COMMENTS and ERRATA – MANUSCRIPTS

Brief descriptions that follow provide insight into the purpose and perspective for each published manuscript. Typographical errors are noted for papers with reprints currently in my possession. Reprints of the following papers were read as published with little or no known correction needed: #1, 2, 5, 7, 11, 13, 14, 17, 18, 20, 21, 25, 26, 28, 29, 33—35, 41–59, 61, 62, 64, 66–74, 77–82, 84.

1. "Pulse Generator with Logarithmic Spacing," IRE Trans vEC-11 Aug 1962, pp 531-534.

This paper was a condensed version of my thesis for the degree *Master of Science in Engineering* at UCLA. I had accidentally discovered a way to generate complete sets of logarithmically spaced pulses, which resulted from automatic switching of resistors in and out of the circuit with a binary chain. Isolated resistance values chosen to match the appropriate interval at counts equal to integer powers of *2* combined fortuitously, with a surprising degree of accuracy for every combination. A solid state circuit was assembled with discrete components and successfully tested, producing laboratory-recorded pulse trains shown. A Taylor series analysis showed why the scheme worked. In that thesis I included a statement to the effect that logarithmic combining character of sequentially shunted resistances hadn't been previously recognized. True, but there had been another work, only tangentially related – having nothing to do with repetitive switching of elements in and out of a circuit by flip-flops, and using none of the analytical validation just described – exhibiting logarithmic combinations in a completely different way with different circuitry. At the time I thought – erroneously – that citing this other work would confuse the issue. With later experience it became clear that citing work, seemingly related but only tangentially – accompanied by a clear description of basic differences – would have strengthened the overall perspective and presentation.

2. "Time-Varying Doppler Navigation Servo," (Co-au) IEEE Trans vAC-9 July 1964, pp 282-285.

Before digitization was feasible in practical mechanizations, analog servos were used to solve the doppler navigation problem with a single scanning beam. For proper weighting a closed form solution was quite useful – a rarity for systems with time-varying parameters.

The only problem with the printed result at the time was, despite all attempts at correction, the editor's insistence on placing a hyphen between the words "single scanning" (as if the word *single* modified the participle *scanning*; actually in the expression *single scanning radar beam* the first three words all act as adjectives modifying the noun *beam*). The hyphen remained – that experience served as my initiation into the "illiterate-but-forceful editor" phenomenon which

- unfortunately plagued a number of my subsequent writings as well
- fortunately did not interfere with most of my later writings (*Institute of Navigation* publications)

3. "Doppler Radar Clutter" (Co-au), IEEE Trans vANE-11 Sept 1964, pp 162-172.

Due to the fourth-power range law, most ground or sea clutter return for high-PRF radars comes from area closest to the transmitter. As a result it was possible to obtain an approximate side lobe high-PRF clutter-to-noise ratio with a constant directivity model. Results were derived by analytically integrating over areas spanned between conic sections (the approach is less successful for low- or medium-PRF radars).. Main beam clutter computation was more complex and less accurate.

There are a few misprints:

- Eq. (20) – replace CM^2 by cm^2 denoting square centimeters (units of $wavelength^2$)
- Eq. (30) – add subscript n to i on left-hand side
- End of *9th* line of Appendix II – "main" (desired expression is "main beam gain")

4. "Simulation of a Minimum Variance Orbital Navigation System," AIAA JSR v3 Jan 1966, pp 91-98.

This paper was actually first presented in 1994. At that time linearization was widely envisioned for matrix extrapolation and gain computation, but various accompanying procedures (e.g., nonlinear vector functions in state *vector* extrapolation and in formation of *a priori* observations – while always using the latest estimates as the basis for linearization) didn't yet have a name (extended Kalman filter; EKF); reported results of accounting for nonlinearities and modeling imperfections were rare. Successful conformance of MonteCarlo results to expected performance here was attributable to (1) high precision used in the vector functions just mentioned and (2) limited duration of the data fit. The paper is cited on page 330 of Jazwinski, *Stochastic Processes and Filtering Theory* plus page 374 of Bryson and Ho, *Applied Optimal Control*.

Formation of the state transition matrix, described verbally on page 94, would have been made explicitly clear if an earlier submittal "Closed Form Keplerian State Transition Matrix" had not been rejected by a reviewer who had no idea that this paper was coming. For those interested, I included a MATLAB version of that algorithm on page 208 of my 2007 book. That MATLAB algorithm, converted from the Fortran code used for this paper, was likewise used for paper #52.

The following typographical errors are in this paper as published:

- *p*.93: First line of Section **Flight Path Geometry** -- "… orbit (see data on page ***95***)"
- *p*.93: Eq. (15) – Remove circumflex (^) above the first two (and not the third) **x**
- *p*.93: Footnote -- "… data on page ***95***"
- *p*.93: Eq. (19), next-to-last term – Remove circumflex (^) above v
- *p*.93: Eq. (21), missing r under the circumflex after the slash (/) ; $/\hat{r}_{m-1}$
- *p*.94: Eq. (36) – Left-hand side should be y_t
- *p*.95: Under Section **Numerical Results** – Change 3.98613 to 3.986008.

5. "Solution to Problem 65-1" (Co-au), SIAM Rev v8 July 1966, pp 384-386.

This was written as a response to what became known as "the Wahba problem" named after the one who submitted a request for a least squares attitude solution from multiple sets of direction cosines. The latter author shown on this response, who generously listed my name first, emphatically deserved to be listed as the principal author – especially since the *SIAM Review* editor summarily deleted my half of the writing (editors, again !) . My half was a solution accounting for

- the fact that only three attitude variables are independent (direction cosines, for example, have orthogonality constraints and sums of squares of quaternion elements must add to one)
- singularity avoidance with nonlinearty effects minimized via repetitive shifts in reference frames.

That usage of independent angles as state variables for attitude was later applied to space dynamics (for both spinning and gravity-gradient stabilized satellites) in paper # 9.

6. "Performance of Strapdown Inertial Attitude Reference Systems," AIAA JSR v3 Sept 1966, pp 1340-1347.

Noncommutativy of finite rotations was of course well known in strapdown's early days, but not the long term effect of endless accumulations from small rotations, imperfectly reported due to sampling and/or quantization. A "bull-by-the-horns" simulation determined both true and computed attitude matrices for up to a million iterations, and extended the scope to include several motion-dependent inertial instrument degradations (see paper #80) which, aside from gimbal displacement, were correctly represented. With answers thus made available, an analytical model could be derived. Agreement between that model and the simulation results was successfully attained and demonstrated for a host of error sources, including numerous rectification effects

I recall very few errors in this printing. All I notice at this time are a missing vertical bracket on the extreme left of Eq. (9) and a slipped character at the bottom of the footnote on the last page.

7. "Alignment Methods for Strapdown Inertial Systems" (Co-au), AIAA JSR v3 Sept 1966, pp 1432-1434.

   3-dimensional attitude can be initialized from measurement of two angles about noncollinear axes. My contribution to that paper was expression for first partial derivatives of the attitude matrix w.r.t. the angle states (derived as simple functions of that matrix's columns), also used in paper #9.

8. "Analytic Platforms in Cruising Aircraft," AIAA J Aircraft v4 Jan 1967, pp 52-58.

   Similarities of gimballed and analytic platform overall error propagation characteristics were known at the dawn of the strapdown era. The multifaceted impact of rotation-sensitive inertial instrument errors, however, imposed a new set of conditions. Experience and insight gained from the simulation in paper #7 was applied – beyond attitude determination, to full INS performance characterization – in the presence of motion-sensitive instrument errors.

   I remember this as an admirably clean job of final printing; the only error I have marked is a missing tilde (~) above $\mathbf{A}_0$ in Eq. (18).

9. "Attitude Determination by Kalman Filtering," AUTOMATICA v6 May 1970, pp 419-430.

   This work, performed under a study contract sponsored by Goddard Space Flight Center, was actually completed in early 1967 and accepted as a Ph.D. dissertation (University of Maryland). Modern estimation, somewhat unfamiliar to many researchers at the time and not applied to attitude determination before 1967 – was shown to offer success in space, given the proper reference frame (local for gravity-gradient stabilization; inertial with shifting reference for spin-stabilized satellites). As a useful feature of the analysis, first partial derivatives of the attitude matrix w.r.t. the angle states were shown to be simple functions of that matrix's columns {Eqs. 14-16}. Many years later I learned that this method was dismissed as "ad hoc" by a noted author – who then presented "his own" formulation *identical* to mine except for usage of rows instead of columns (due to his choice of opposite direction for the transformation). Sorry I was unaware of that criticism for so long; my response would have been informative.

   Printing this in 1970 was a tall order but the only remaining typographical errors appeared on page 424. In the notation $[B_m]^T\,[B_m]$ of the footnote in the left-hand column, the second B_m should have a circumflex over it, to denote apparent value. Also there are four instances of abbreviating "meters" with "mr" instead of "m" in the right-hand column.

10. "Natural Frequencies of a Flexible Gravity-Gradient Satellite" (Co-au), AIAA JSR v5 May 1968, pp 560-569.

    The X-shaped Radio Astronomy Explorer (RAE) gravity-gradient stabilized satellite, with post-deployment end-to-end lengths exceeding the height of the Empire State Building, produced deformation dynamics inseparable from its rotational dynamics. For example, its moments of inertia changed about as slowly as its attitude librations – but that only begins to describe the nonrigid dynamics' complexity. After extended intensive study (see the next two papers and papers #14-16), a reliable characterization was obtained. The satellite was designed with a damper having one angular degree of freedom. The main results of this paper were

    - derivation of a strained equilibrium state as the proper basis for defining flexural dynamics
    - usage of **QR** matrix decomposition to determine motion eigenfrequencies and eigenvectors
    - individual boom bends combined into *satellite* deformations (Fig.2, page 563; co-author's idea, so I made him principal author), with separate constituents coupled to rotation and translation
    - proof that, although the damper could suppress the rotation-coupled flexural deformations, it was ineffective for the translation-coupled flexural deformations.

    Fortunately there was some intrinsic damping provided by the booms' material composition.

Decoupling from orbital motion, quite helpful, is entirely permissible. For all practical purposes, the coupled rotational/deformational motions were separated from orbital dynamics; the satellite's composite mass center (expressed as functions of the state and of various first-cantilever mode shape integrals) had the same translational motion as it would have had if it were a small rigid sphere.
Given its complexity, this paper was printed accurately. Errors noted are

- *p*.561, in definition of ξ – "vector" - not "vectorr"
- *p*.562 – delete the extraneous sixth line from the top of the right-hand column
- *p*.563, Eq. (8) – the integral's upper limit l is missing
- *p*.563, Table 3 – exponents missing from first integrand; "… / μ^2, … / μ^4 "
- *p*.564, Eq. (19) – wrong algebraic signs for last term in first and third component.
- *p*.566, Eq. (40) – transpose operator ^{T} missing from first vector **N** of second term on right

11. "Digital Program for Dynamics of Non-Rigid Gravity-Gradient Satellites" (Co-au), NASA CR-1119, Aug 1968.

The Lagrangian analysis for the paper just described (# 10) was sufficiently complex to warrant a completely independent means of validation. In marked contrast to the elastic continuum used for the Lagrangian analysis, the discretized model represented each boom by rigid segments connected by torsion springs. The goal wasn't (and couldn't be) a reduction in complexity (either model was extremely complicated), but independence. The discrete model was fully documented in this report.

12. "Solar Pressure and Thermal Effects on the Radio Astronomy Explorer" (Co-au), AAS/AIAA Astrodynamics Conference, Jackson Lake Lodge WY Sept 1968. ASS Paper #68-126.

The elastic continuum dynamics were complicated enough even without external influences, but those effects could not be ignored. The main complication came not just from the physics, but the inescapable dependence of the effects on incidence angle – which varies not only with instantaneous state but along the length of each boom. Did it anyway.
Typographical errors were relatively few for this complexity level:

- Units for Eq. (15) are large Calories per square meter per second
- Eq. (20) is missing a subscript (I) on the left-hand side
- discussion preceding Eq. (71), values of $d_{21} = - d_{12}$ and $d_{21} = - d_{12}$ – replace 2/3 by 4/3
- Eq. (B-6) – delete vertical bar on extreme left to produce vector n_u times its norm

13. "Comment on 'Evaluation of the Computational Errors of Strapdown Navigation Systems'," AIAAJ v7 March 1969, pp 571-572.

Paper #6, before its Journal appearance, was first supposed to be presented at a conference more than a year earlier (an airline strike interfered). This note was an attempt to make up for the absence, by comparing different approaches to error propagation analysis.

14. "Dynamics of a Libration-Damped Discretized Cruciform Structure" (Co-au), AIAA Structural Dynamics and Aeroelasticity Specialists Conference, New Orleans LA, Apr 1969.

The satellite model described in paper # 11 was programmed, with results presented in this paper.

15. "Continuous and Discrete RAE Structural Models" (Co-au), AIAA JSR v6 Apr 1969, pp 414-423.

The Lagrangian approach of papers # 10, 12 and the discretized model of # 11,14 were shown to be in close agreement, over a wide variety of conditions. The model was then deemed ready for usage in an estimation scheme wherein continuous histories for attitude and boom tip deflections would be obtainable from highly intermittent observation data (next paper).

Only two errors appear in the Journal printing:

- *p*.421, Fig. 4 – The highest label on the right-hand side should be X_4 (rad)
- *p*.423, third line below Eq. (A7) – ψ (*external*) force, not Ψ (Lagrangian generalized force)

16. "Optimal Estimation of Rotation-Coupled Flexural Oscillations" (Co-au), AIAA JSR v6 Nov 1969, pp 1290-1298

Brief glances at tip deflections (while over monitoring stations), plus attitude and damper angles, were planned inputs to a program for rotation-coupled deformation offsets from the strained equilibrium state (papers # 10, 12). After all the preparation and programming, TV cameras at the base of the booms failed.. Without the tip deflections, the dynamic histories could not be provided. Consequently the distortions in antenna patterns due to bending of the "lower V" (for low-frequency Earth radiation monitoring) and the "upper V" (for space monitoring) could not be provided.

This paper had four typos in the proceedings of the 1969 JACC (Boulder CO),

- Eq. (1) – replace k by κ (kappa)
- Eq. (18) – lower case $\hat{y}_m$
- Eq. (33) – last $\underline{L}$: move vertical bar appearing before it to after it, to indicate norm of the entire vector in the denominator
- in TYPICAL RESULTS section – change mass (5 Kg) to 4.22 Kg

and three printing errors in the AIAA JSR version,

- *p*.1291 – remove dot above vector of generalized coordinates
- *p*.1292 – postmultiplying vectors in Eq. (7) should be $\mathbf{p}'_{i0}{}^T$ and $\mathbf{p}'_{iI,j}{}^T$
- *p*.1292, Eq. (8) – vector of generalized coordinates: add double dot above it after matrix [*m*] and single dot above it after matrix [*d*]

17. "Comment on 'Gyro Misalignment and Encoder Quantization Effects During Multi-Axis Evaluation of Strapdown Gyros'," IEEE Trans vAES-6 Sept 1970, pp 707-708.

This comment was written before I realized how common it is for authors to see their work rediscovered and presented as new results.

18. "Comment on 'Nonlinear Filtering Techniques with Application to Strapdown Computation'," IEEE Trans vAC-16, June 1971, pp 266-267.

The paper being critiqued here actually considered applying modern estimation to every attitude computer iteration. The idea was impractical, especially with the limited computational capability of its time – and remains impractical now – but more serious was an unbalanced comparison of

- modern estimation with knowledge of covariances between angular rate components, versus
- conventional attitude updating *without* knowledge of those covariances

I objected to the unbalance, since the analytical model developed for paper #6 enables compensation of noncommutativity error with conventional attitude updating when the covariances are known.

19. "Statistical Bit Synchronization in Digital Communications," (Co-au) IEEE Trans vCOM-19 Aug 1971, pp 487-491

Modern estimation was applied to synchronization extracted from bit transitions only (with no separate synchronizing signal). Both initial acquisition (block) and subsequent track (recursive) modes are included, followed by various suggestions helpful in practical usage. The paper is cited in the bibliography for Chapter 14 (page 636) of Spilker, *Digital Communications by Satellite*.

There is one misprint: *p*.487, last sentence of first paragraph on left-hand side – "offers" not "offer"

20. "Digital Mechanization for Single Beam Doppler Navigation," ION Nat'l Air Meeting, Atlanta GA, Mar 1972.
    Digitization removed limitations such as restrictive beam sequences and periodicity needed for validity of solutions in earlier analog mechanizations (such as paper #2). In addition, the door was opened for mixing the radar observations with properly weighted data from other sources.

21. "Synthetic Aperture Imaging with Maneuvers" (Co-au), IEEE Trans vAES-8 July 1972, pp 410-418.
    High-resolution synthetic aperture radar mapping (SAR) was originally "side-looking radar" (SLR), with requirements for a tight autopilot to restrict motion along a narrow path, and with processing done by lenses plus analog film drive mechanisms. The principal author of this paper (J.H. Mims) singlehandedly redefined SAR for the age of digitization. That is no exaggeration; I saw top recognized SAR experts initially dismiss maneuvers while mapping, especially with forward squint ("common knowledge" a year later). It was my privilege to furnish nav support for this effort.

22. "Effects of Navigation Errors in Maneuvering SAR" (Co-au), IEEE Trans vAES-9 Sept 1973, pp 758-776.
    This paper's purpose, evident from its title, was severely compromised by a multitude of misprints – far too numerous to be listed. That publication must have been behind schedule; I received galley proofs *after* the due date for their completion. The Chief Editor openly admitted "We printed a mess" – but not the Associate Editor, who published a retort when I objected to the impossible deadline. A footnote on page 261 of *Integrated Aircraft Navigation* answers that retort.
    For those interested in this subject, the paper contains a large number of figures (which are valid though not all numbered correctly), and many (though not all) equations are printed correctly. More important, paper #38 revisits the topic – this time with strapdown mechanization.

23. "Optimal Air-to-Air Tracking for WX Radar (U)" (Co-au), Tri-Services Radar Symposium, West Point NY, July 1974 (CONFIDENTIAL).
    Although this paper could easily be declassified now, I don't feel free to go into detail.

24. "Dynamic Scaling for Air-to-Air Tracking" (Co-au), NAECON Symposium, Dayton OH, 1975.
    Digitization offered an opportunity to substitute vector tracking for the older separate range and angle track loops. Usage of a stable (e.g., INS) reference frame is especially beneficial at short ranges, where acceleration in the line-of-sight (LOS) frame is largely an artifice produced by LOS rotation. Digital capability was still fairly primitive at the time; airborne computation was not floating-point. There were eight range scales (from less than 1 nmi to nominally 80 nmi). Every variable in the Kalman filtering algorithm had to be automatically rescaled shortly before or after octave boundary crossings (some hysteresis was purposely used, to prevent repetitive switching near octave edges). Vector tracking was sufficiently new in the early 1970s to warrant concentration on its theory. Process noise spectral densities controlled Kalman filter effective memory duration ("data window"). For typographical errors, Figure 4 should have been entitled "Position Dynamics" and the "Estimator-controlled tracker" label should more clearly point to the dotted plot. Also, the denominator of Eq. (24) should be the squared absolute value of the range vector (denoted there with an underline).

25. "Fixed Point Single Precision Estimation" (Co-au), AIAA/AAS Astrodyn. Conf., San Diego CA, Aug 1975.
    Adaptive scaling usable for predominantly single-precision computation (except for products in cumulative additions and for retention of double-precision numerators of quotients) was successfully applied to orbit determination. Convergence enhancements included stepped measurement variance multipliers to ease initial transients and data window control by process noise.

26. "Keeping Pace with Avionics Innovations," NAECON Symposium, Dayton OH, 1977.
    Early digital implementations often were mere digitized imitations of analog designs. Several avionics functions were discussed as candidates to capitalize on increased capabilities.

27. "Thermal Curvature of Satellite Booms," AIAA J v15 Sept 1977, pp 1331-1333.
    A closed-form solution was derived with the arc length constraint taken into account.
    One misprint: *p*.1332, Eqs. (9) and (10) – all of *4Kh* should be enclosed in parentheses {as Eq. (8)}.

28. "Air-to-Air Designate/Track with Time Sharing" (Co-au), NAECON Symposium, Dayton OH, 1978.
    A fast-switching electronically steerable array antenna beam can suddenly dart from one direction to another, removing the severe data rate limitations of mechanical scanning. Tracking of multiple objects, with updates allocated according to tracked object type, then reduces multitarget tracking to the equivalent of a single-object task plus simple bookkeeping. Simulation was done in preparation for later testing at White Sands where, on more than one occasion, four objects (two missiles and .two aircraft) were successfully tracked together in real time.

29. "Transfer Alignment for Precision Pointing Applications," NAECON Symposium, Dayton OH, 1979.
    The reference frame of a strapdown slave IMU is driven toward that of a master INS primarily by velocity matching (with adjustment of course for the INS-to-IMU lever arm). Ramifications of the well-known limited azimuth observability are discussed with the added complication of nonrigidity (e.g., due to aeroelastic deformation). – which, not surprisingly, further reduces the already limited observability in azimuth.

30. "Simulation of Tracking Radar in the Presence of Scintillation" (Co-au), NAECON, Dayton OH, 1980.
    Amplitude scintillation is among the most serious degradations in a lobing radar. When UP/DOWN or LEFT/RIGHT received signal echoes are compared to indicate tracked object's direction relative to the overlapping radar beams, quasi-random changes in radar cross-section hinder the interpretation of relative strengths. Tracks are maintained, but not without substantial cross-range errors from extraneous variations. Instead of obtaining consecutive full FFT blocks for each direction (e.g., 64 radar pulses with LEFT shift followed by 64 with RIGHT shift), a fast-switching electronic "squint control" can interleave the directions (e.g., odd for LEFT and even for RIGHT; an acknowledgement at the end identifies the inventors, who are not the authors). Realistic simulation models, with variations that can exceed 20 dB in a few milliseconds, show that this "sequential monopulse" approach can overcome the interference – while avoiding monopulse radar channel imbalances..
    One misprint: the index subscript on the right of Eq. (7), and the mention of it three lines above that equation, should be "K" in the notation used for this paper.

31. "Retention Probability in a Track-While-Scan Radar," IEEE Trans vAES-17 Jan 1981, pp 139-144.
    The probability of a missed detection can change with every radar pulse (e.g., due to changes in radar-to-target distance). The probability that a run of *K* missed detections ends on scan # *j* or # *j+!* or # *j*+2 or ··· quickly becomes intractable as a Boolean expression. A simple reexpression as the probability that a run of *K* missed detections ends *for the first time* on scan # *j* or # *j+!* or # *j*+2 or ··· makes the events mutually exclusive, so they can be added with no further complication. Furthermore, each of these individual (first-time) cases can be expressed as products of probabilities for independent events. A computational procedure is fully defined, with sample results from a programmed recursion algorithm.

A radar expert questioned feasibility of the high data volumes shown at the time, but I was not free to divulge the explanation: A patent by the inventors was pending wherein the radar antenna could point to any tracked objects *during transit times*, as long as the beam returned on schedule to capture each echo. Fast switching of an electronically steered array removed earlier design limitations. Two misprints: Item (2) after Eq. (8) – o**n** scan j and last line of page 142: – "the**n**" (not "the").

32. "Track Mechanization Alternatives" (Co-au), NAECON Symposium, Dayton OH, 1981.

Usage of Cartesian states for radar-to-target relative position, relative velocity, and total target acceleration is shown to provide major advantages in multiple facets of operation. Linearity of dynamics can coexist with near-linearity of observables when the Cartesian states are first transformed into range/Az/Elev axes (through known attitude and sensor pointing angles) – a benefit still largely unappreciated to this day. Methods for stabilization are given that circumvent potential "loop-within-a-loop" problems encountered in other mechanizations.

Typographical errors include

- three lines before Eq. (3-1) – change "proportioned" to "proportional"
- five lines before Eq. (3-5) – change "appropriated" to "appropriate"
- Eq. (3-5) – the vector following [$\mathbf{T}_{b/G}$] must have components (in order) X_1 , X_2 , X_3
- third line down from heading for Section 3.4 – add comma after "matrices)"
- second line of paragraph 3 in Section 3.4 – delete first two words "location, INS"
- third line above last paragraph of Section 4.0 – comma (not semicolon) after "availability"

33. "Time-Varying Weights for Optimal Control with Inequality Constraints" (Co-au), AIAA J G&C, v4 Sept-Oct 1981, pp 566-568.

Optimization problems with hard-limit constraints frequently offer a design choice between two undesirable alternatives (i.e., accept the nonlinearity or find a linear solution that grazes the limit).. Both can be avoided by using a surprisingly rare device: a time-varying weighting function. An example is shown wherein a previously documented classic case is improved by this method.

34. "Integrated and Transferable Hardware/Software Checkout" (Co-au), NAECON Symposium, Dayton OH, 1982.

A methodology is offered that can integrate three functions previously performed separately: design validation, software verification, and hardware testing. Not surprisingly, extensive process control (e.g., including freeze/step capability) and routing of time-aligned raw data exemplify the flexibility needed for success.

One typographical error is noticed – Figures 4 and 5 are transposed.

35. "Application of VLSI to Strapdown" (Co-au), NAECON Symposium, Dayton OH, 1983.

Digitization of both inertial navigation provisions (with strapdown) and antenna controls (with electronically steerable arrays) presents an ironic performance problem for airborne radar: While older analog servos maintained desired beam pointing accuracy in the presence of severe aircraft rotations, time lags accompanying typical data rates preclude the customary degree of tight control. Procedures prevalent at the time (extrapolation or interpolation for time-alignment) were cumbersome and, with hundreds of deg/sec roll rates or several hundreds of deg/sec/sec rotational accelerations, imprecise. Exploitation of newly available fast computing capability was advocated as a way to overcome inaccuracy due to latency. To this day, the limitation has not been completely solved for the most severe dynamics.

36. "Integrated Tracking Software for Multimode Operation," AIAA Digital Avionics Systems Conference (DASC), Baltimore MD, December 1984.

The formulation described in papers #24, 28, and 32 was combined with various design features noted and applied to three modes (air-to-air; air-to-ground with target motion; air-to-ground stationary). All dynamics estimates (velocity and acceleration; position errors were too small to be significant) obtained were shown to be accurate after pull-in transients of duration commensurate with initial settings.

There are two typographical errors, both on the right-hand column of the first page:

- end of eighth line down – change "#2" to "#3"
- 13th line down – read as " ··· range from the sensor ··· " (delete the word "target")

37. "The Enhancement of Armored Vehicle Fire Control Systems Using VHSIC Technology" (Co-au), ADPA Symposium on Fire Control Systems, NSWC, White Oak MD, Apr 9-10, 1985.

Not being principal author, and under the impression that this publication was somewhat sensitive, I never tried to receive a copy of this reprint.

38. "Strapdown INS Requirements Imposed by Synthetic Aperture Radar," NAECON Symposium, Dayton OH, 1984 – Also AIAA J G&C, v8 n4 Jul-Aug 1985, pp 433-439. Superseded by pp 177-198 of Advances in Aerospace Systems - Dynamics and Control Systems, v33 pt 3 C.T. Leondes (ed), Academic Press, 1990.

SAR degradation effects were assessed for a wide variety of inertial instrument error sources (actually a couple dozen). It was (and is) acknowledged that vibration patterns assumed were purely hypothetical. The methodology should be used with realistic vibration data to be made available for specific applications.

Scope and presentation improved with each revision of this paper. The only known misprints are in the first (NAECON) version.

- In Section 3.4, under "G-SENSITIVE DRIFT" the units are deg/hr/g, not deg/hr/g^2
- the left-hand side of Eq. (21) is velocity error *rate*; add a dot over the tilde.

39. "SDI Terminal Stage Tracking," ION 42nd Annual Meeting, Seattle, WA, June 1986 (SECRET/NOFORN).

No discussion is given here for this paper.

40. "7-State Tracking Results," ION Nat'l. Technical Meeting, Anaheim CA, Jan 1987 (SECRET/NOFORN).

No discussion is given here for this paper.

41. "Airborne Transfer Alignment & SAR Motion Compensation," ION 43rd Annual Meeting, Dayton OH, June 1987. Also NATO AGARDograph No. 314, C.T. Leondes (ed.)

To show effects of imperfect motion compensation, SAR processing algorithms were performed on simulated point-reflector responses. Smearing of energy across nearby cells (from low-frequency errors or biases) and levels of scattered energy in remote cells (from high-frequency errors) were expressed in dB relative to peak. Presentation concluded with discussion of operational implications.

42. "Radar Signal Processor Testing via Digital Simulation [VAXAR]," (Co-au) ADPA Annual Technical Meeting, Ft. Eustis, VA, Nov 18-19, 1987.

The task of integrating simulation, code, and hardware bench checkout was performed as described in this paper. I&Q responses from radar reflectors were computed from instantaneous positions in dynamic scenarios and fed to an array processor's input buffer at real-time speeds. Correct operation demands correspondence of relevant range-gated FFT outputs to the radar reflector configuration.

One experience exemplifies how this simulation/bench test integration complements other validation steps: A SAR image's failure to produce a correct reflector pattern was traced to the hardware processor's inability to perform two particular microcode instructions in succession without a "no-op" (literally a no-operation) in between them. Catching that minuscule detail at the bench saved an unknown (but assuredly large) amount of struggling with relatively inscrutable flight test data.

43. "A Critical Examination of Sensor Fusion," ION 44th Annual Meeting, Annapolis MD, June 1988.

A classic issue in constructing tracks from sequences of image frames is the association problem (which artifacts in different frames came from the same object?). With a dense array of sensor responses, the variety of plausible interpretations can make solution intractable. Registration of images in raster form can remove many extraneous associations. That effort requires establishing correspondence between pixels of different sizes, shapes, and orientations.

Locus lines for image cells from optical sensors (lines of constant azimuth and constant elevation) were compared vs. radar range circles and isodops. Especially at low depression (sub-horizon) angles the effect of terrain slope is

- appreciable but modest for radar
- strikingly dramatic for optical sensors.

Implications of the latter's sensitivity include difficulty in registering images obtained from terrain with unknown slope and/or undulations. Any degradation, however, pales in comparison with attempts to correlate dense responses from single sensor data alone.

44. "Airborne Transfer Alignment Simulation Results," Position Location and Navigation Symposium (PLANS), Orlando FL, Nov. 1988.

The formulation in paper #29 was tested in simulation in two forms. The first assumed perfect synchronization of all data involved in the algorithm. Comparison was made *vs* a case wherein data from two IMUs – with independent time bases – had to synchronized computationally. That familiar but cumbersome (pre-GPS) operation more than doubled (nearly tripled) the amount of code needed. Also clearly shown was inadequacy of 16-bit word lengths for velocity components.

45. "Biased and Unbiased Estimates in GPS Processing," ION 45th Annual Meeting, Alexandria VA, June 1989.

An earlier paper by another author had raised the possibility of using biased estimation for integrity monitoring. This later paper (#45, June 1989) showed that the only offset needed was not a bias but a straightforward accounting for the initial estimation error covariance matrix.

46. "Ridge Regression: A Cautionary Note," ION 46th Annual Meeting, Atlantic City NJ, June 1990.

The issue noted in the preceding paper was revisited (due to a repeat publication), with the same conclusion. This subsequent paper (#46, June 1990) acknowledged that there is a place for biased estimation, but integrity monitoring is not the right application.

47. "That All-Important Interface," (Co-au) ION GPS-90, Colorado Springs CO, Sept 1990.

Output specifications for radio navaids and other information sources related to navigation were derived long before modernization. Urgency of their updating, already noted long ago, continues to increase with every innovation.

48. "Passive Ranging for Target Tracking," (Co-au) ADPA Avionics Technical Symposium, McDonnell-Douglas Auditorium, St. Louis MO, Nov. 1990 (SECRET/NOFORN).

No discussion is given here for this paper.

49. "The Expanding Role of Sensor Fusion," ION 47th Annual Meeting, Williamsburg VA, June 1991.
The topic of paper #43 is discussed with words and diagrams only; no mathematics.

50. "Receiver Autonomous Integrity Monitoring (RAIM): Techniques, Performance, and Potential," (Co-au) ION 47th Annual Meeting, Williamsburg VA, June 1991.
Detection capability for excessive error was compared *vs* requirements; and found wanting for sole means in operations of interest. Parameter values, methods, and findings from several other references were cited. Alarm rate was shown to be quite sensitive to small deviations from perceived RMS error. Probability density for variances was used to derive a probability density function for the ratio of (assigned / true) RMS error, which was then used derive the confidence coefficient applicable to testing with a conservative representation. Performance for a baseline fault detection algorithm was illustrated in terms of best, worst, and average protection radii; it was explained why needs must be met in all instances; rather than averaging over space-time.

51. "Statistical Validation for GPS Integrity Test," (Co-au) ION GPS-91, Albuquerque NM, Sept 1991 (also IONJ v39 n2 1992, pp 205-216 <u>and</u> "Redbook" of Selected Papers vV 1998, pp 89-100).
Inescapable usage of perceived (rather than unknown true) error characteristics (just raised in paper #50) leads, upon further exploration, to a compounding quite familiar in the field of quality control. The design parameters (RMS values, and even the probabilities themselves) are random. These probability-of-the-probability issues can be resolved rigorously by usage of confidence levels. Ramifications on testing are demonstrated through comparing "top-of-the-head" estimates against (1) gaussian approximations and (2) binomial distributions. For officially sanctioned tests, numbers of allowable events shrink from seven to one and from five to *none*, dramatizing the non-intuitive nature of these results.

52. "Tracking of Ballistic Objects at High Altitudes," ION Nat'l. Tech. Meeting, San Diego, CA, Jan 1992.
The orbit estimation approach used in paper #4 was reprogrammed in MATLAB, combined with a NASA-documented Lambert algorithm, and applied to post-ascent path determination for a ballistic object illuminated by radars with limited field-of-regard. RMS position and velocity time histories were shown for various cases. Parabolic models (included for comparison only) were shown, not surprisingly, to give unsatisfactory results.

53. "Extended RAIM (ERAIM): Estimation of SV Offset," ION GPS-92, Albuquerque NM, Sept 1992.
Classic approaches to RAIM prescribe multiple trials, with each candidate satellite taking turns "sitting out this dance" in the role of the suspect. The exact same trials can be performed with each suspect, instead of being left out, retained with its error added as an augmenting state. This paper shows that, with the beneficial addition of SV error estimates, the set of resulting navigation solutions is completely unchanged. A more important benefit, however, is realized in isolation or exclusion. With six SVs and the augmented state (five components instead of four), there is only a parity scalar (instead of a vector). A biased SV produces a bias in the parity scalar itself – for every trial *except*, appropriately, the one wherein the suspect is the satellite with the offset.. The capability naturally extends to procedures for more than one biased SV (e.g., by using seven pseudoranges to estimate six states including each trial pair of SV biases), always with a scalar parity.

54. "Advances in Passive Tracking," (Co-au) Joint Services Data Exchange, Palm Springs CA, Oct 1992 (ITAR RESTRICTED).
No discussion is given here for this paper.

55. "System Integration: Performance Doesn't Measure Up," NAECON Symposium, Dayton OH, 1993.
A blunt (i.e., non-diplomatic; therefore "unprofessional") assessment of what passes for integration in the defense industry – almost fifteen years before the February 2008 GAO report.

56. "Baseline Fault Detection and Exclusion Algorithm," (Co-au) ION 49th Annual Meeting, Cambridge MA, June 1993.
A plan offered as a baseline for FDI/FDE. As of 2009 the industry has not accepted one; suppliers can prescribe their own acceptance tests.

57. "Integrity Testing for GNSS Sole Means," (Co-au) ION Nat'l. Tech. Meeting, San Diego, CA, Jan 1994.
Blind test sequences with rigorous confidence-based demands were recommended to validate GPS receiver integrity. Tests advocated were to verify absence of failures from previous occurrences (e.g., computational breakdown for cardinal directions and other known problems). The plan never gained acceptance.

58. "A Quantitative Measure of Integrity Error," Position Location and Navigation Symposium (PLANS), Las Vegas NV, April 1994.
Although pilot training has long emphasized GO/NO_GO decision-making, there is no reason why testing must be similarly limited. Failure to issue an alert after only slightly exceeding an allowable limit is currently penalized as much as a far greater error. This paper offered a draft plan to remedy that deficiency.

59. "Integrated Nav: the 2nd Edition I Never Wrote," ION 51st Annual Meeting, Colorado Springs CO, June 1995.
History of nav integration was briefly summarized, with description of how an update (not planned) could be more thorough.

60. "JTIDS RELNAV Redefined," (Co-au) ION Nat'l. Tech. Meeting, Long Beach, CA, Jan 1998.
This paper advocated replacement of coordinates by uncorrected pseudoranges in JTIDS message content. That simple step was shown to offer a substantial list of major advantages.
It was gratifying to see W.R.Fried (Mr. JTIDS) respond by discussing these benefits. God bless him.
For typographical correction: MIDS stands for Multifunctional Information Distribution System.

61. "Quantum Improvement in Airport Surface Surveillance," (Co-au) ION Nat'l. Tech. Meeting, Long Beach, CA, Jan 1998.
This paper advocated replacement of coordinates by uncorrected pseudoranges in airport surface surveillance messages. That simple step was shown to offer a substantial list of major advantages. One question I failed to answer clearly was how, with no detection nor compensation for multipath, vulnerability to multipath could be claimed. The answer is simply the ability to reject some of the data without rejecting all of the data.

62. "Radical Streamlining of GPS/INS," ION GPS-98, Nashville TN, Sept 1998.
Operation with frequent updates available is now dominant. Yesteryear's widely accepted dynamic formulation was simplified substantially for that majority.. Adjustment terms added to specific force for expressing acceleration in the slowly-varying nav reference frame – on the order of a few milli-*g* – are significant but their imperfections are smaller than typical accelerometer errors (and therefore negligible). This and various other simplifications, useful for most applications – later verified in van tests plus flight tests – were defined with full justification and explanation of benefits.

63. "Comments on 'Summary of RTCA SC-159 Working Group Activities'," (Co-au), IONJ v44 n4 1997, p 497.

Recall paper #57. This letter was prompted by rejection of rigorous test requirements.

The only error in this communication was the typesetter's mangling of a temporary (ill-chosen) name for my one-man corporation. To make a long story short, the Bureau of Trademarks disallowed usage of *Navaide*; I finally ended up as *Vigil, Inc.*

64. "DoD Methodology, Past vs. Future," ION Nat'l. Tech. Meeting, San Diego, CA, Jan 1999.

This critique of DoD practices was even-handed. Examples from Army (IMU mounting on tank hulls – useless for F/C), Navy (training range tracking with primitive concepts, redundant states, no integrity monitor), and USAF; (overlooked limitations of IMU/ESA asynchronism and latency for beam stabilization) were criticized with equal force.

65. "IMU Coast : Not a Silver Bullet," (Co-au) ION 55th Annual Meeting, Cambridge MA, June 1999.

This paper was prompted by advocacy, by authors with prestige and credibility, of coasting for substantial periods during GPS outages. With flight safety on the line, I felt compelled to take that notion and kill it deader than a doornail. A typical value for only one error source (gyro cross-axis sensitivity) in a standard holding pattern was enough to make the point.

Since this paper was not submitted in PDF format, there were minor spacing differences; not all equations look right in the *Proceedings*. This type of problem is remedied on this CD (see the limits of the definite integral in the last equation of Appendix A for this paper herein).

66. "Send Measurements, Not Coordinates," (Co-au), IONJ v46 n3 1999, pp 203-215.

Papers #60 and #61 were combined, with added interpretive discussion, for IONJ.

67. "Multi-Target Tracking in the Littoral Environment" (Co-au), IEEE Radar Conf., Washington D.C., May 2000.

Performance of a "garden variety" track-while-scan (TWS) radar was exemplified in a representative near-coastline situation with hundreds of responses, may of them extraneous. The only extension needed for real-world operation is replacement of the linearized measurement model, by partial derivatives based exclusively on the first vector at the right-hand side of Eq. (9.33) in *GNSS Aided Navigation and Tracking* (NavtechGPS sole distr.).

68. "Modern Generic IMU Interface Standard" (Co-au), IAIN World Congress, San Diego, CA, June 2000.

After introductory discussion this paper presents a long list of features needed for modern operation, and another long list of operations to be performed. It is shown how major changes to accepted standards are required to satisfy those needs.

69. "Navigation and Tracking," Chapter 14 of Avionics Handbook (2000), also Chapter 19 of 2nd Edition (2007), Cary Spitzer (ed.), CRC Press.

The chapter presents a tutorial-oriented summary of modern estimation applied to navigation (estimation of "ownship" state history) and tracking (estimation of "everyone else's" recent history).

70. "GDOP and RAIM in Differential Operation," ION Nat'l. Tech. Meeting, Long Beach, CA, Jan 2001. Also IONJ v48 n3 2001, pp 195-203.

The common practice of across-SV differencing, for the purpose of removing user clock error, produces correlations between measurements. In both GDOP and RAIM formulations, accounting for those correlations enables correct answers to be obtained by a modest increase in computations.

71. "Carrier Phase Processing Without Integers," ION 57th Annual Meeting, Albuquerque NM, June 2001.

Sequential changes in carrier phase – *not at all synonymous with deltaranges* – provide precise dynamics without cycle ambiguity resolution. Triple differencing – across satellites, receivers, and 1-sec intervals, adjusted for SV excursions during those intervals, are prepared for operational usage.

72. "GPS/INS - A Very Different Way," (Co-au) ION 57th Annual Meeting, Albuquerque NM, June 2001.
Methods devised in papers #62 and #71 were successfully applied to van tests at Ohio University, where this work was sponsored. Test conditions and resulting plots were documented in detail.

73. "Comment on 'Performance Analysis of a Tightly Coupled GPS/Inertial System for Two Integrity Monitoring Methods'," IONJ v48 n2 2001, pp 131-132
This comment was written to oppose long free-inertial coast periods in NAS (see #78 below.)

74. "GPS for Avionics Synchronization," ION GPS-2001, Salt Lake City UT, Sept 2001.
From the various available means of interpolation (transforms, splines, etc), parabolic blending afforded completely acceptable accuracy with minimal latency. The formulation was taken from a cited reference and presented, followed by successful results using a gyro time history segment from the same Ohio University test data source previously documented.

75. "GPS/INS - Streamlined," IONJ v49 n4 2002, pp 171-182.
Developments from papers #62 and #71 were combined and, due to Selective Availability removal, extended to operation without a ground station. Estimates of dynamics, thus formed from sequential changes of across-SV differences, were used as feedforward inputs to an integrator with narrowband corrections obtained from pseudoranges.
Errata: Adjustment by $\boldsymbol{\omega}_R \times \mathbf{R}$, present in the conference version, was inexplicably omitted from my *IONJ* submission. Also, as noted in the 2007 book, θ is a scalar, not a vector.

76. "Strapdown at the Crossroads," ION 58th Annual Meeting, Albuquerque NM, June 2002. Also IONJ v51 n4 2004, pp 249-257.
Strapdown inertial navigation, once considered highly complex (it emerged when computing speeds were limited) still retains some of its original complexity (e.g., separation into "fast" and "slow" time), now unnecessary. Direct processing of raw inertial instrument outputs is described in the simplest possible way, with equations plus corresponding "cookbook" task lists. Comprehensibility is facilitated by showing the full raw-input-to-final-output (3-dimensional position/velocity/attitude) in one diagram. Every effort was made to commend earlier achievements from limited technology, but some traditionalists were not happy to see this paper.
A printing error in the Journal's Eq. (A-8) – the algebraic sign for q_3^2 in the (3,3) element should be +.

77. "Unfinished Business: Glaring Absences from the Achievement List," Position Location and Navigation Symposium (PLANS), Monterey CA, April 2004.
Ingrained habits continue to impose significant but completely unnecessary burdens on system performance and cost. Both defense and commercial applications are adversely impacted. Effects on several facets of operation (testing, collision avoidance, time stamping of data, low-cost inertial systems, integration, integrity) are discussed, with recommended remedial actions specified.

78. "Modular Program for Evaluating IMU Coast Performance," (Co-au) ION 60th Annual Meeting, Dayton OH, June 2004.
Recommendations for coasting through GPS outages (recall #73 and also #65) appeared in important places (e.g., ION, ATC Quarterly). This time I added more details and suggested one simple test: Cut off INS updating immediately before a 90° or 180° heading change (consider procedure turns or course reversals) and continuously compare free inertial *vs* GPS.
Requiescas in pace, long-term free-inertial coast in crowded airspace.

79. "Full Integrity Testing for GPS/INS," ION Nat'l. Tech. Meeting, San Diego, CA, Jan 2005. Also IONJ v53 n1 2006, pp 33-40.

The customary way of performing snapshot parity tests prescribed factoring the sensitivity matrix (**H**) into its orthogonal and upper-triangular constituents. Unless the data vector error covariance matrix can be expressed as the product of a scalar × an identity matrix, that is suboptimal. To obtain optimal performance, factoring must be performed on a product, **H** premultiplied by that covariance matrix's inverse square root. The result is then consistent with optimal estimation, and the parity test then conforms to an intuitively simple normalized residual calculation.

80. "Inertial Instrument Error Characterization," ION 61st Annual Meeting, Cambridge MA, June 2005. Also IONJ v54 n3 2007, pp 169-176.

A wide variety of motion-sensitive gyro and accelerometer errors can be represented by using a vector and a matrix of coefficients. Every component of angular rate has its phase-quadrature waveform (e.g., with all sine terms replaced by cosines), and the same is true of specific force. There are then twelve components of a complete motion vector, for formation of an inner product with the coefficient vector (to express effects of imperfect scale factor, mounting misalignments, etc.). For all motion constituent *products* (e.g., for g^2-sensitive errors etc.), there would theoretically be 144 coefficients! Fortunately most of those can be ignored (mainly due to redundancy from symmetry and reciprocity). When all essential products are tabulated, the only coefficients needed are for familiar motion patterns such as vibratory rotation about – or translation motion along – a skewed axis, plus coning, cylindrical motion, and intrinsic coupling between rotation about one axis and translation along an orthogonal axis. These are the major performance-limiting phenomena.

81. "Carrier Phase Coherence as a Sequential Correlation Issue," Joint IEEE-PLANS / ION 62nd Annual Meeting, SanDiego CA, April 2006.

Changes in carrier phase over 1-second – *emphatically not the same as the less accurate deltarange* – are quite useful for maintaining precise dynamics, with or without inertial augmentation. One potential complication is tight sequential correlation between errors in successive differences {e.g., [phase(3) - phase(2)] and [phase(2) - phase(1)] clearly share a common component} . Analysis based on block processing covariances shows, fortunately, that the sequential correlations are not highly influential for data spans of practical duration. Because SV excursions must be taken into account, intuitive formulations produce a small-difference-of-large-numbers problem. That is circumvented through Taylor series expansion.

82. "Velocity and Acceleration from Unaided Carrier Phase," Joint IEEE-PLANS / ION 62nd Annual Meeting, SanDiego CA, April 2006.

Velocity formed from sequential phase change history (preceding paper), fed to an integrator with pushdown memory, will produce position information with a slow drift. Closing the loop with pseudoranges will keep position accurate while velocities are precise (on the order of cm/sec with an IMU, or dm/sec stand-alone, RMS). Analytical support and flight test verification are included.

83. "ADSB (2nd-) Best Foot Forward?" (Co-au), Journal of Air Traffic Control v50 n3 Summer 2008, pp 17-18.

This paper uses an assertive tone, in an effort to make a compelling case for exploiting firmly established but unused capabilities for mutual surveillance. With familiar provisions (Mode S squitters, GPS receivers), all participants could track all other participants. Collision avoidance, applicable to both 2-dimensional (runway incursion) and 3-dimensional (in-air collision, near-miss) minimization, would be enhanced considerably by transmitting uncorrected pseudoranges instead of coordinates (as in paper #66).

Some “surprises” unfortunately found a way into the printed paper. We have, for example, *pseudo-ranges* (hyphenated) instead of, simply, *pseudoranges* and *what is called GPS double differencing* instead of, simply, *double differencing*. In addition, the discussion beginning with “Accurate Knowledge of Aircraft Velocity ··· “ was supposed to begin a new section, rather than a continuation of the bulleted list. Despite these unwarranted changes, the paper largely reflects the intended message. One last explanation: Mention of an on-screen demonstration (using OpenGL graphics with programming by my son) was intended for a presentation in person, not a Journal submission.

84. "Robust Design for GNSS Integration," ION-GNSS 2008, Savannah GA, Sept. 2008

Aircraft with several meters wing span don’t have to be located to within 1-cm while moving at hundreds of knots. Accuracy for dynamics will outweigh instantaneous position precision in many operations – especially when sub-wavelength position comes with vulnerability to false indication of successful cycle ambiguity resolution. Examples are discussed wherein acceptance of a meter position error is a small price to pay for assurance of validity.