GNSS Aided Navigation & Tracking ("GANT") after 10 years

A review by Kepler award winning past Inst-of-Navigation president Chris Hegarty noted: this is not an introductory book.Rather than including many details I relied (some readers would say TOO heavily) on references for most fundamentals. In expressing GPS measurements by Eqs (2.58) and (5.7), for example, I chose implicit rather than explicit representation for SV clock offset and for Earth rotation –
* instead of an explicit separate equation for relativistic effects, I implicitly considered that part of the total overall SV clock error (as many others do)
* instead of a separate Earth rotation term, I treated it as an implicit requirement for consistent coordinate frames in vector subtraction. An explicit separate term confuses some people because, at a glance, it seems to contradict Einstein (we need distance from SV at transmit time to user at receive time, with no further adjustment from motion during transit). The paradox, considered subtle by some, is resolved at https://youtu.be/ F5Xp81ol5c.
That latter issue also arises on page 104, again without a thorough background explanation (which would have been distracting in the middle of a development). In retrospect maybe a footnote citing an appendix or addendum might have been useful.

Likewise useful, possibly, could have been a start-at-the-beginning approach including much of the basic material from my 1976 book (Integrated Aircraft Navigation; "IAN"). That would have been a longer undertaking resulting in a heavier and more expensive book. Without dwelling on that topic now, it is worth recalling tutorials over the past several years that have been divided into two halves, using "IAN" for the first half and "GANT" for the second. Attendees are pleased with that arrangement.

The review by Chris Hegarty also noted presence of several insights that are hard to find or, in many cases, not available elsewhere at all. Those unusual, subtle, and advanced features are the primary subject of what follows. Rest assured that departures from custom stem from performance advantages, and not enacted for the purpose of just being different. A list, including multiple innovations, can illustrate:
* Section 2.6 which lays a foundation for much material following it
* Eq. (2.65) for the level of process noise spectral density (which, without a guide, can otherwise be the hardest part of Kalman filter design)-with follow-through in Section 4.5 (and also with a history of successful usage in tracking as well as navigation, plus other operations beyond)
* Eqs. (3.10-3.12) for wander azimuth immune to numerical degradation
* Section 3.4.1 for easier-than-usual yet accurate position incrementing in wander azimuth
* First bulleted item on the lower half of p.46, which foreshadows major simplifications in Kalman filter models that follow it
* Table 4.2, which is perilous to ignore (http://jameslfarrell.com/gyro-mounting-misalignment/), closely related to reasons why IMU specs should NOT be used to set EKF process noise levels
* How separating position from dynamics accommodates the next item
* Capitalization on Bierman's matrix factorization, a "one-at-a-time" processing of observables sidestepping matrix inversions and facilitating covariance matrix propagation through time, while also allowing prewhitening in Section 5.2 to account for error correlations across measurements in synchronism (though not sequentially correlated measurement errors discussed separately later)
* SEQUENTIAL CHANGES IN CARRIER PHASE (Section 5.6, validated in Table 5.3) removing vulnerability to catastrophic error from undetected cycle slip while also relieving otherwise interoperability problems (Section 7.2.3 and http://www.insidegnss.com/node/3492) -- especially if used with FFT-based processing (Section 7.3 and http://jameslfarrell.com/gpsfft/)

* Commonality of track with short-term INS error propagation (Section 5.6.1), enabling reduction of the latter to a simple intuitive form that is still almost universally overlooked
* Exploitation of the feature just noted, to solve an otherwise challenging design task: setting the levels of process noise spectral densities (second item in this list)
* Multiple RAIM extensions: normalization to unit variance (Section 6.1.1), expansion to include SV offsets with nav solutions unchanged (http://jameslfarrell.com/extended-raim-eraim-ion-gps-1992/ and Section 6.1.2), fault exclusion with scalar (rather than 2x1 vector) parity Section 6.1.3), and extension of all these to differential operation (Section 6.2)
* Single-measurement RAIM, Section 6.3 and http://jameslfarrell.com/single-measurement-raim/
* Computational sync, Section 7.1.2
* Whatever tracking applications of Chapter 9 (also validated in operation) fall within your scope (http://jameslfarrell.com/book-on-tracking/)
* Alpha-beta-gamma trackers -- http://jameslfarrell.com/kalman-filter-or-suboptimal-does-it-matter/
* Realistic free-inertial coast limitations, (Matlab program & closed form solution in Appendix II)-see also http://jameslfarrell.com/wpcontent/uploads/2013/08/GNSS2010.pdf
* Practical realities, Appendix III

These were preceded by a few innovations in the 1976 book, not all of which appear in "GANT" --
* extension of the previously known Schuler phenomenon, following through to provide a full closed form solution for tilt and horizontal velocity errors throughout a Schuler period (Section 3.4.2)and reduction to intuitive results for durations substantially shorter
* exact difference in ellipsoid radii, facilitating wander azimuth development offering immunity to numerical degradation even as the polar singularity is reached and crossed (Section 3.6)
* analytical characterization for average rate of drift from pseudoconing (Section 4.3.4), plus connection between that and the gyrodynamics analysis preceding it with the Goodman/Robinson classical coning explanation- http://jameslfarrell.com/coning-in-strapdown-systems/
* expansion of the item just listed to an extensive array of motion-sensitive errors for gyros and accelerometers, including rectifications (some previously unrecognized) throughout Chapter 4
* Eq. (5-57), repeated in "GANT" as Eq. (2.65) for process noise settings.

While providing "IAN" as a reference for the introductory segment of a tutorial, I point out its limitations following from decades of subsequent advances. Discussion of Figures 1-13 and 1-14 need revison in terms of using complementary filtering (Brown/Hwang). Areas of further change include, not surprisingly, mechanization (e.g., obsolescence of DDA descriptions in Section 3.5), refinement of some computational steps (e.g., from Section 5.4.3), addition of satellite navigation (embryonic in the mid-1970s). At the same time there are issues, some subtle and others peripheral, useful to some but not necessarily all:
* rotation about an arbitrary axis via Eq. (2-48)
* reflections (Section 2.4)
* intrinsic precession analysis carried beyond the usual angular rates to a closed form expression for the attitude matrix (Appendix 2.A.2)
* evolute of the standard ellipsoid (Section 3.A)
* gyrodynamics (Section 4.2)
* a host of inertial instrument motion-sensitive and rectification errors (Chapter 4)
* modeling principles (pages 177-179) emphasizing caution in state augmentation

* a thorough illustration of measurement bias estimation without state augmentation (Appendix 5.B)

THIS IS WORTH SCRUTINY

Certain items among these are important enough to justify revisiting the opportunities they offer. In many cases their adoption would solve critical problems that have plagued operational systems. Often their absence is due to expediency ("keep it simple") carried to excess, forfeiting dramatic improvements available through moderately increased effort.

INTERFACES AND TIMING

A host of practical considerations in Chapter 10's half-dozen pages, plus another dozen pages in Appendix III, present configuration principles that can make or break a system's performance.
See also http://jameslfarrell.com/wp-content/uploads/2010/06/IONGPS90.pdf and - http://jameslfarrell.com/wp-content/uploads/2010/05/robust.pdf

PROCESS NOISE SETTINGS

Although the rationale was explained in both books ["IAN" Eq. (5-57) and "GANT" Eq. (2.65)], its significance has escaped most designers. A short Matlab program in a recent manuscript (abstract at https://www.ion.org/gnss/abstracts.cfm?paperID=5210) provides a transparent simple illustration.

CENTRAL ROLE FOR ACCURACY OF DYNAMICS

A video description of 1-sec carrier phase data usage at
http://www.youtube.com/watch?v=b0LAnM47_c4
led to a comment (accepted before I stopped all spam by disallowing all comments) highlighting an issue that needs to be more widely understood.
http://jameslfarrell.com/1-sec-carrier-phase-again/

SEPARATE ESTIMATION OF DYNAMICS FROM PRECISE POSITION

Even with position from ambiguity-resolved carrier phase, segmentation (separation) is beneficial;
when ambiguity resolution fails, ONLY position is destroyed while dynamic history REMAINS VALID.

RE-EXPRESSION OF MEASUREMENTS AS OBSERVED AT C-G

Sensors are commonly placed at mounting sites (e.g., nose of aircraft for radars) experiencing rapid dynamics from rotation but unrelated to translational motion of the vehicle itself. The history of motion conforms to a simple and smooth dynamic model at the mass center, far better than an often wavy path experienced at a sensor mounting site (Section 7.2.2). Keeping lever arm adjustments separate reduces estimation modeling error effects.

HOW A COMPLEX TOPIC WAS RESOLVED

The sequential correlation issue is a very deep one, addressed in Refs. [21-23] of page 106. The latter two handle it in different ways, and the first one (Jazwinski) shows both methods. For completeness, Addendum 5.B circumvents all limitation with a run using block instead of sequential processing. That enabled me to include sequential correlation effects via off-diagonal elements in the block matrix partitions shown on page 94. Section 5.6 discusses practical limits of long data block durations. As noted there and also in my IoN-GNSS-17 paper cited below, theory promises spectacular performance NOT reached in the real world. Even the best IMUs with precise data bases for vertical deflections won’t maintain leveling to within

microradians. Even if they did, minuscule bumps-&-wiggles of a spaceborne antenna phase center would intervene at some point.
My cm/sec RMS results in Chapter 8 can be (and have been) improved to a few mm/sec. After that I don’t know (the smaller the gremlins, the more there are).

APPLICATION TO TRACKING: The 1-sec phase increments producing cm/sec velocity in flight for nav (directed by Ohio U. Prof. Frank vanGraas) was later adopted and successfully validated in flight for tracking (directed by Ohio U. Prof. Maarten Uijt de Haag). Chapter 9 describes a wide variety of additional tracking applications with stabilization and related operations.

Examples covered by all preceding discussion above are not exhaustive, but they are sufficient to drive home an important point: THERE'S A LOT TO ALL THIS -- and creatures-of-habit, by clinging to over simplified methods, are surrendering much of what's offered by current (and even yesteryear's) capabilities. While some mathematical sophistication is needed, no more than the required amount is useful, and no amount of it will be adequate without proper insight.

The last item I'll introduce here is a paper based on a lifetime spent in this activity. Instead of reading it, many will prefer to watch the video at https://youtu.be/9UKuOTnQa5w. Either way conveys what concerns a small but growing number of us: our industry generates tons of literaturenbut abundant brilliant advances are not evident from operational performance. Reasons for it and answers to the situation necessitate a plan for action. In addition to my "two-cents' worth" (involving civil plus defense-&-aerospace) there are others, each with another set of examples; the collection would span this space much more thoroughly. Whether from triumph-of-profit-over-engineering, inadequate training of designers, or decision-makers' lack of sufficient experience and insight, all result in painfully evident failure to harness capability available for decades. Widely documented deficient performance in operational systems has produced too many missed opportunities; evidence abounds --
* the incredibly slow pace to address vulnerability clearly shown in the 2001 Volpe report
* the five-year Loran shutdown with (again incredible) destruction of valuable infrastructure
* cost overruns, schedule delays, and inadequate technical performance in the defense industry (GAO-08-467SP report from year 2008 provides just one description
* bizarre enough to repeat: http://jameslfarrell.com/defense-secretary-hates-gps/
* http://www.insidegnss.com/node/5567
* interfaces 'cast in concrete" that hamstring subsequent design, allowing achievement of only a minor fraction of intrinsic capability
* etc.

The end of the video just cited, and others I uploaded to youtube, offer conceptual remedies for some facets. Small pilot programs are preferable to throwing billions at problems.