JTIDS RELNAV REDEFINED

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BIOGRAPHY

James L. Farrell (Ph.D., U. of MD, 1967) is ION's Air Nav representative, a senior member of IEEE, a former AIAA local board member, a registered professional engineer in Maryland, and a member of TRIANGLE plus various scholastic honorary fraternities. Experience includes teaching at Marquette and UCLA, two years each at Honeywell and Bendix-Pacific plus 31 years at Westinghouse in design, simulation, and validation of modern estimation algorithms for navigation and tracking [e.g., F16 AFTI, B1 radar, SDI; fire control system design, generation of test data for bench validation; INS update and transfer alignment algorithm design, development of programs for USAF-WPAFB (fire control evaluation) and NASA (estimation of orbit, attitude, satellite deformation); missile guidance optimization, MLE boundaries] plus digital communication design (sync, carrier tracking, decode). He is author of *Integrated Aircraft Navigation* (Academic Press, 1976; now in paperback after five printings) and of various columns plus over 50 journal and conference manuscripts. Active in RTCA for several years, he served as co-chairman of the Fault Detection and Isolation Working Group within SC-159.

C. Gary Stephens (ASEE and BSEE, Johns Hopkins University) has over 30 years of engineering experience in research, development, evaluation and test of DOD plus commercial communications, navigational and radar systems. He worked for 15 years at ITT as a conceptual design engineer, system engineer, and engineering manager developing radar and spread spectrum COMM systems, and for 7 years as engineering director at SASI, involved in the Navy Tactical Data System, Low Cost Link11, FLTSATCOM, JTIDS, MILSTAR, and NARACS. As a member of Joint Services COMM Working Group he evaluated Link 16 VMF messages and protocols. For 10 years he has been at ARINC, now as principal architect for Improved Data Modem (HAVEQUICK and SINCGARS radios for F-16, A-10, and H-64), while evaluating encryption capability for ACARS – an air-to-ground data link for flight operations and ATC services.

ABSTRACT

Significant improvement is needed for friendly aircraft surveillance in general [Ref. 1] and for Joint Tactical Information Distribution System (JTIDS) RELNAV performance in particular. This paper describes a patented means of accomplishing that objective. One component of the plan involves concepts underlying the estimator formulation and algorithms, including consideration of implications regarding computational load. The other component is a straightforward – but strikingly effective – modified selection of information to be shared. A planned demo program will establish feasibility.

INTRODUCTION

Replacement of the existing JTIDS RELNAV method In Multifunctional Information Distribution System (MIDS) can use a rigorously correct and computationally stable program based on raw uncorrected pseudorange differences (C/A only), and/or time-of-arrival (TOA) data – that is, the new rationale can use pseudorange information from GPS, participants' coded transmission TOAs, or both. Because the current configuration already uses TOA information, emphasis here can be placed on the processing of GPS pseudoranges. Algorithms planned for usage will combine features from the vastly successful array of differential GPS applications with tried-and-true air-to-air tracking techniques. All computations can be done in COTS hardware. The result will be strikingly better performance with minimal impact on communication link capacity demand. Dramatic benefits to other nav applications (*e.g.*, carrier landing) are also achievable.

The concept described in this manuscript was derived by adapting capabilities already known. The author's involvement in modern estimation for Air-to-Air track with multiple targets goes back over two decades (Refs. [2—6]), and differential techniques exploited herein have been successfully employed in myriad applications, too numerous to list. Then where is the departure from standard practice? Here's the answer:

Transmit* <u>*pseudoranges*</u> *not* <u>*coordinates*</u>*! This seemingly unspectacular feature can in fact offer dramatic solutions to several existing limitations. The next section describes these limitations, identifies the information to be transmitted, and reveals how the proposed approach can provide vital performance benefits.

NEW RELNAV RATIONALE

Deficiencies in grid placement and quality indicators are definitely not intrinsic; they can be cured by changing the fundamental approach. Existing JTIDS grid positions do not capitalize on knowledge of covariances from participants' estimator algorithms. Instead of forming residuals directly by comparing observed *vs* anticipated GPS pseudorange, the existing system uses coordinates computed from those GPS pseudoranges (a procedure needed only for grid initialization and – if there is not tight GPS/INS integration – for ownship nav). Major sacrifices in accuracy result:

- When a full set of GPS data can't be acquired, information gathered at that time point is lost (Opportunity #1: modern estimation has always been able to make the most of partial information).
- Likewise unused is information from participants showing inferior quality indicators (Opportunity #2: *everyone's* pseudoranges are fully acceptable for differencing *vs*. own-ship values; participants do not have to know their own positions in order to provide useful track data).
- Sightlines to SVs will never be mutually orthogonal, but coordinates are computed simply by matrix inversion. Without usage of covariances this is tantamount to assuming that all coordinate directions are determined to the same accuracy and at the same sensitivity – thus ensuring improper gains (Opportunity #3: usage of pseudorange differences as observables inherently accounts for geometry).
- As coordinates based on different datums are brought into the process, the inversion further heightens the nonuniformity of *pseudomeasurement* variance (Opportunity #4: each participant will use his own perceived datum in the formation of pseudoranges differences; *no* grid degradation).
- The existing process intrinsically ignores all correlations between errors in computed coordinate directions, further contaminating the weighting for estimation (Opportunity #5: this limitation clearly vanishes in the proposed scheme – while also providing cancellation of major error sources).

Drawbacks just described vanish when each participant constructs his own grid, with data received from *all* other participants (no data need be rejected). A participant's perceived location in his own grid will not affect his placement in grids constructed by other participants. Due to the differential approach, errors in ownship location and perceived azimuth will affect neither relative positions nor grids constructed by other participants. A participant can use any datum without affecting any other. In view of all these benefits, combined with spectacular successes already realized elsewhere by differential operation, it is surprising that this approach is not already used for RELNAV. There was a recent related method for similar applications [Refs. 7,8] based on decomposition of coordinate solutions; tests provided a 50% improvement for static receivers. Here we eschew usage of nav solution data, choosing only raw measurements instead.

CONCEPT and IMPLICATIONS

Performance goals cited here are adequately supported by pseudorange differences accurate to one or two meters; thus no consideration is given to carrier phase, integer ambiguity resolution, nor two-frequency operations. Because of inherent error cancellation in differential operation, uncorrected data will be completely acceptable; there is no need for keyed receivers. Each member (whether ground or airborne) present in any scenario is assumed to be equipped with a multichannel GPS receiver, plus secure COMM provisions needed to transmit and receive pseudorange information — with unique identification — plus computing provisions adequate for deriving all flight paths of interest from double differences. It is immediately recognized that differencing will involve *intermittent* time-tagged receptions and, while each receiver is required here to provide uniform observation times for its own SV's, no synchronism is expected across receptions at different locations. Thus, each airborne member will form a time history of pseudorange from its mass center (thereby removing rotation effects) to each visible SV. To obtain receiver-to-receiver differences, that time history is easily interpolated to the instant of reception for each communicating member. Those results are of course repeated for each SV used by both – so that double differences are formed by subtraction, in accordance with normal procedures.

Ramifications of requirements just stated impose no stringent demands on equipment. Uncorrected C/A code data; adjustments for lever-arm (needed to reference pseudoranges to the mass center) and for asynchronism of multiple SV receptions – no real cost or design burden. Computing provisions and software for bookkeeping and interpolation should not raise any concerns; about the only load that may encounter resistance is the need for multitarget tracking by individual scenario members. The next section places the need for multiple track file data – which, after all, must be supplied by one means or another – into a perspective appropriate for today's capabilities.

POSITION, VELOCITY, and ACCELERATION of a TRACKED OBJECT

In most systems, velocity history is not obtained by direct observation but inferred from position-dependent measurements separated by known time intervals. It is further noted that the position reference need not be stationary. In tracking applications the origin can move with a supersonic jet, carrying a means of dead reckoning (*e.g.*, an Inertial Navigation System; INS) plus sensors for receiving observables from external trackable objects – whose states are being estimated while moving independently of the platform carrying the means of processing the measurements. Motion in each of three mutually orthogonal directions can be characterized in conformance to standard kinematics so that if, between time t_{m-1} and t_m, ownship INS velocity changes by an amount q_m, then the relative (tracked object minus ownship) velocity would be expected to change in accordance with

$$v_m = v_{m-1} - q_m \qquad (1)$$

while, with characterization of INS velocity change – not at all critical – as varying linearly with time during the interval, relative (from ownship to tracked object) position would be expected to change according to

$$r_m = r_{m-1} + v_{m-1}\,(t_m - t_{m-1}) - q_m\,(t_m - t_{m-1})/2 \qquad (2)$$

if nothing is known about the tracked object's acceleration. When the formulation is extended to include that, however, Eqs. (1,2) must be generalized. Now let all states at time t_m be denoted as double-subscripted components of a 3×1 vector $\mathbf{x}_m$ – the first subscript indicates time and the second is *1*, *2*, or *3* for position, velocity, or acceleration, respectively. Recalling that motion is being characterized in only one direction thus far, the three kinematically related states represent that directional component of relative (receiver-to-tracked-object) position, relative velocity, and total (not relative) acceleration of the tracked object. The expression used to propagate state *vector* estimates between successive measurements is then based on Eq. (5-64) – *not* (5-63), which does not perform as well – of Ref. [9];

$$\begin{bmatrix} \hat{x}_{m1}^{(-)} \\ \hat{x}_{m2}^{(-)} \\ \hat{x}_{m3}^{(-)} \end{bmatrix} = \begin{bmatrix} 1 & t_m - t_{m-1} & \tfrac{1}{2}(t_m - t_{m-1})^2 \\ 0 & 1 & t_m - t_{m-1} \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \hat{x}_{m-1,1}^{(+)} \\ \hat{x}_{m-1,2}^{(+)} \\ \hat{x}_{m-1,3}^{(+)} \end{bmatrix} - \begin{bmatrix} \tfrac{1}{2}\,(t_m - t_{m-1})\,q_m \\ q_m \\ 0 \end{bmatrix} \qquad (3)$$

Covariance matrix propagation during the same interval of course uses the same transition matrix but a random – not the deterministic INS-derived – forcing function.

For the immediate example that would be provided by a 3×3 "plant noise" matrix **E** having only one nonzero value E_{33} — a spectral density derived from the effective data averaging time span T and measurement error variance σ^2 on the basis of Eq. (5-57), Ref. [9]:

$$E_{33} = (\,20\,\sigma^2 / T^5\,)\,/\,g^2 \quad (\text{g/sec})^2/\text{Hz} \qquad (4)$$

Note that this term easily absorbs any imperfection in the INS velocity history. It is also realized that this formulation could have omitted q entirely, using the above term to represent all necessary acceleration information. Usage of relative acceleration states, however, would have sacrificed detailed knowledge of INS velocity history, characterizing ownship acceleration instead with the random model used for the tracked object. To avoid that unnecessary performance degradation the dynamic model used for state vector extrapolation has a forcing function with nonzero mean — thus, unlike position and velocity, target acceleration states are total rather than relative.

An additional clarification is now in order. Years of tracking experience have shown that, where practical, it is expedient to separate estimator axes — so that three principal directions could be found to represent full 3D motion. The dynamic model would then utilize separate 2-state (for position and velocity), or 3-state estimators (for position, velocity, and acceleration), of the type just described, for each axis. There are cases allowing this channelization {*e.g.*, radar tracking with all axes monitored at comparable data rates and accuracies while line-of-sight (LOS) rotation is gradual} — but that expedient would unduly degrade performance in this application. Here we capitalize on coupling across axes from multiple changing projections in sensitivity as measurement directions rotate. To maintain that coupling, the dynamic model for relative Cartesian position $\mathbf{R}$ and velocity $\mathbf{V}$ vectors, and total acceleration $\mathbf{Z}_\mathbf{T}$ of the tracked object (driven by both unknown acceleration **e** and a known INS velocity change), is symbolized in partitioned form as

$$\begin{bmatrix} \dot{\mathbf{R}} \\ \dot{\mathbf{V}} \\ \dot{\mathbf{Z}}_\mathbf{T} \end{bmatrix} = \begin{bmatrix} \mathbf{O} & \mathbf{I} & \mathbf{O} \\ \mathbf{O} & \mathbf{O} & \mathbf{I} \\ \mathbf{O} & \mathbf{O} & \mathbf{O} \end{bmatrix} \begin{bmatrix} \mathbf{R} \\ \mathbf{V} \\ \mathbf{Z}_\mathbf{T} \end{bmatrix} - \begin{bmatrix} \mathbf{0} \\ \dot{\mathbf{q}} \\ \mathbf{0} \end{bmatrix} + \begin{bmatrix} \mathbf{0} \\ \mathbf{0} \\ \mathbf{e} \end{bmatrix} \qquad (5)$$

where $\mathbf{O}$ and $\mathbf{I}$ are 3×3 null and identity partitions; $\mathbf{0}$ is a 3×1 null vector. These expressions plus the usual kinematical adjustments are easily converted into software to support both vector- (using $\boldsymbol{q}$) and matrix extrapolation (using a probabilistic representation of **e**) before each observation – the former is augmented to account for slow rotation of tracked object's lift vector. With addition of well known characterizations for GPS double differences and for TOA data, the estimation algorithm is defined.

The straightforward character of the requisite computations is important here. Major portions of the pertinent software have appeared many times in myriad applications (Refs. [2-6]); only the joining of the two areas (multiple airborne target tracking and double differences) will produce innovation. For the RELNAV approach being proposed, the simplicity is important — because each participant is assigned the task of maintaining a track file on every coded message source. The uninitiated might balk at that but, after a multitude of repeated exercises (from timing-and-sizing of computations to flight validation at White Sands), it is quite clear that the load is reasonable. A ten-target capacity was practical two decades ago. This is a classic opportunity to exploit advances in computational capability – using the vector tracking formulation in Refs. [2-6] and [9], combined with the factorized approach of Ref. [10].

Discussion would be incomplete here without acknowledging two familiar system characteristics, practically ignored thus far. Neither TOA information nor quality indicators have yet been given a role in the proposed implementation. TOA data can be used for verification; the GPS double differences alone provide excellent observability for location of all friendlies with respect to ownship. Quality indicators – though clearly inappropriate as gatekeepers for friendlies' data – can still perform an important function in the transfer of target information. When a target is sighted from multiple participants, those with the best nav data (azimuth as well as location) are most credible – all other things being equal. That last caveat refers to the possibility that the supplier of target information may or may not be using the same reference datum as the recipient. In any case it is reiterated here that, for knowledge of friendly participants' relative location, only raw uncorrected GPS pseudoranges are needed. MIDS needs to exploit that capability (as the Navy's Cooperative Engagement Capability; CEC is doing), and to exploit the experience gained from years of tracking in high dynamics.

Finally it is explained that the proposed approach is not intended to stamp out any possibility of ownship nav update using TOA data – but that must be done carefully. Even uncorrected C/A code GPS data provides respectable nav fixes; attempts to improve perceived ownship geographic position and/or azimuth by TOAs from aircraft using a different datum reference can degrade accuracy if not appropriately de-weighted. Absence (or – due to COMM capacity constraints, unavailability) of datum type can preclude the optimal updates that would normally be realized; that is one reason for emphasizing RELNAV in this manuscript. There are important – and subtle – opportunities to achieve error cancellation in targeting as well; that topic will be deferred to another forum.

OPERATION and CONCLUSIONS

A dramatically improved RELNAV scheme still calls for transmitting data (with identification) in assigned time slots, with values in correspondence to those slot times – but instead of Precise Participant Location and Identification (PPLI), pseudorange-modulo-RANGE replaces coordinates in the message. For 2^W meters maximum RANGE and 1-meter LSB, $W \times$ (number of satellites *used*) bits will be occupied by position information. Dynamic allocation of slots can be influenced by needs for passivity and response to maneuvers. Significantly, there can be no loss in visibility due to substituting raw data for coordinates; any participant visible enough to convey coordinates is visible enough to convey – and receive – pseudorange data. Quality indicators will restrict target transfer but not RELNAV.

Preprocessing demands are minimal (*e.g.*, adjusting pseudoranges to values extant at aircraft mass center, to eliminate rotation effects; interpolation of ownship pseudoranges, to values extant at slot time). Flexible postprocessing opportunities include formation of total tracked object velocity (by adding ownship's INS output to the relative velocity) and/or dynamic quantities of interest (*e.g.*, range rate, line-of-sight rate) at any data rate needed by any subsystem (Ref. [2]). The flexibility will support not only MIDS but also carrier landing and other potential extended applications.

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