QUANTUM IMPROVEMENT in AIRPORT SURFACE SURVEILLANCE

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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.

Edwin D. McConkey (MSEE, BSEE and Mathematics, Univ of Michigan, 1964) is a registered professional engineer in the state of Florida. He is manager of the Technical Support Division for Air Transportation Systems Operation at SAIC, with 13 years of experience managing Federal Aviation Administration (FAA), Dept. Of Transportation (DOT), and NASA programs plus 34 years of technical and management experience in R&D, system engineering, and management support for air transportation system programs. Areas of specific expertise include navigation, air traffic control systems, helicopters, and advanced vertical flight aircraft. He has worked on R&D projects including GPS, MLS, and Loran-C, with emphasis on usage in the National Air Space (NAS).

ABSTRACT

The Airport Movement Area Safety System (AMASS) is devised to anticipate runway incursions, so that they can be prevented. This critically important function is planned to operate with inputs from triangulation and/or Airport Surface Detection Equipment (ASDE). Superior performance will clearly result from superior accuracy at the input, followed by rigorous formation of closest approach time and distance for every possible pairing.

CONCEPTUAL BASIS

A major step toward improving performance will be revealed instantly: *transmit measurements, not coordinates and velocity* – with immediate payoff in multiple areas:

- Pseudorange difference accuracies of a meter or two are realistic; with good geometry these can be converted into superb coordinates and velocities.
- Many corrections are eliminated; it is well known that major errors cancel (and an additional tropospheric refinement is available) for separation distances larger than any airport dimension.
- By feeding differential data to a state estimator, position and velocity histories can be formed using standard techniques. As always, this reduces effects of fix errors (already small for a differencing operation), and also provides a basis for dynamic extrapolation (an ***extremely*** important goal is to minimize error growth during incursion prediction).
- When a full fix can't be obtained (*e.g.*, due to obstructed sightlines in some directions), partial information gathered at any time is still fully used.
- Because differencing is performed on scalar measurements of the same type (not on vectors representing coordinates that could be expressed in different datum references), a significant source of potential danger is forever removed – aircraft can now perceive locations in nonuniform datum references with no serious consequence.

Ramifications of these benefits will be discussed in relation to the airport surface surveillance application.

CONCEPTUAL DESIGN DECISIONS

Usage of differential GPS data for airport surface surveillance has already been proposed, and much of the necessary work – including validation as well as configuration definition – has been performed at Lincoln Laboratories [Refs. 1,2]. In addition to data rates and detailed message layouts, very important preprocessing techniques are also included therein. The main modifications needed for extension here are:

- message format changes,
- preparation for double difference formation – with usage of the time tag offset technique in Ref. [1],
- dynamic estimator formulation (or adaptation) for optimally processing the double difference inputs,
- postprocessing for incursion avoidance.

The next four sections address these items. To be thorough, two more topics will be briefly raised:

- Refs. [3,4] introduced a related method 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.
- Integration of double differences with ASDE data can be categorized here as additional available observations for the state estimation algorithm. As pointed out in Ref. [2], ASDE measurements carry no identification tag – and thus impose further preprocessing requirements prior to insertion.

Message Formats

Refs. [1,2] show complete data fields for all 1090 MHZ extended squitter formats; attention is now drawn to airborne and surface messages, both of which allow 17 bits each for latitude and longitude. There are fourteen more bits that can be replaced – 7 bits each for speed and heading in the surface message, or baro altitude + turn + spares in the airborne message. A total of 48 bits can then be used to represent the least significant 12 (surface) or 16 (airborne) bits, for each of four or three SV pseudoranges, respectively. At 1-meter LSB, this provides a range difference of 4.096 Km over an airport surface or 65.536 Km in air. Time tag consumes no significant field width (next section).

Measurement Preprocessing

Pseudoranges received within the aircraft are to be rereferenced in time and position before transmission. A time shift is needed, as in Ref. [1], to permit very short time-tag data fields while still exploiting the transmit schedule randomization that minimizes synchronous interference. The procedure is to convey values that apply to the nearest UTC second (thus also facilitating double difference formation). Time-shift computations will demand slightly more for pseudoranges than for coordinates, but the increase is quite modest. The position shift is a lever arm adjustment to the aircraft mass center, thus eliminating any rotation effects.

Aircraft State Estimation

The dynamic model for relative Cartesian position vector $\mathbf{R}$ and velocity $\mathbf{V}$, driven by an unknown acceleration $\mathbf{e}$, can be symbolized in partitioned form as

$$\begin{bmatrix} \dot{\mathbf{R}} \\ \dot{\mathbf{V}} \end{bmatrix} = \begin{bmatrix} \mathbf{O} & \mathbf{I} \\ \mathbf{O} & \mathbf{O} \end{bmatrix} \begin{bmatrix} \mathbf{R} \\ \mathbf{V} \end{bmatrix} + \begin{bmatrix} \mathbf{0} \\ \mathbf{e} \end{bmatrix} \qquad (1)$$

where $\mathbf{O}$ and $\mathbf{I}$ are null and identity partitions, respectively; $\mathbf{0}$ denotes the null vector. Another state can be added, to account for acceleration or deceleration along the tracked object's instantaneous velocity vector. A related but more complex formulation that includes total acceleration of the tracked object in addition to relative 3-dimensional position and velocity, as well as detailed motion of the origin (a vehicle carrying the tracker processing provisions), appears in Ref. [5]. Myriad variations of these dynamic formulations were used for different applications with radar or optical sensors as the source of discrete observations; some are described in Refs. [6 - 11]. Factorized algorithms from Ref [12] have been used in actual mechanizations.

As with any estimation algorithm, the definition is incomplete until the observables are also described. The immediate approach was already revealed as a combination of differential GPS methods with dynamics of the type just described. From one (simplified) perspective, then, the method proposed here is an extension of work performed for other applications – augmenting radar data (in this case from ASDE) with differences between GPS pseudoranges seen by a tracked object and those seen from a ground station (and those differences are again differenced between SV's in ground processing). From another perspective, the work herein is an extension of work performed at Lincoln Laboratories [Refs. 1,2]. The main difference is that pseudoranges – rather than coordinates – constitute the information to be communicated, for all of the reasons previously listed.

Postprocessing of State Estimator Output

When there are K aircraft within a limited volume there are $K(K - 1)/2$ pairs to check for possible collision. For each pair a relative velocity $\mathbf{U}$ and range vector $\mathbf{S}$ are formed by subtracting outputs of the individual Kalman estimators. By re-applying an expression in Ref. [6] to relative position and velocity between any pair of vehicles, the difference vectors are then used to form a line-of-sight (LOS) rate vector $\mathbf{S} \times \mathbf{U} / (\mathbf{S} \cdot \mathbf{S})$ and range rate $\dot{S} = \mathbf{S} \cdot \mathbf{U} / |\mathbf{S}|$. The ratio of $|\mathbf{S}|$ to closing rate $(-\dot{S})$ could then be used to estimate time remaining before a collision occurs – realistic only if LOS rate magnitude falls below a designated threshold – but a more rigorous formulation is prescribed herein. Both the time and the distance of closest approach will be formed from $\mathbf{U}$ and $\mathbf{S}$, exemplified as follows:

With no acceleration / deceleration it is seen that, for a vehicle pair with closing range rate, closest approach is τ seconds in the future, at which time the separation distance (and thus its square) must be a minimum:

$$d/d\tau\{(\mathbf{S}+\tau\mathbf{U})\cdot(\mathbf{S}+\tau\mathbf{U})\}=0;\quad \tau=-\mathbf{U}\cdot\mathbf{S}/|\mathbf{U}|^2$$

$$\equiv-\mathbf{u}\cdot\mathbf{S}/|\mathbf{U}|,\quad \mathbf{u}=\mathbf{U}/|\mathbf{U}|;\quad \mathbf{U}\cdot\mathbf{S}<0 \tag{2}$$

When that occurs, the distance becomes just

$$|\mathbf{S}+(-\mathbf{u}\cdot\mathbf{S}/|\mathbf{U}|)\,\mathbf{U}|=|\mathbf{S}-(\mathbf{u}\cdot\mathbf{S})\,\mathbf{u}| \tag{3}$$

which of course is $|\mathbf{S}\times\mathbf{u}|$, the separation vector component normal to the relative velocity. Because it is perpendicular to that relative velocity, it never shrinks even as the other separation vector component (parallel to the relative velocity) goes to zero. Closest approach distance for this simplified case is therefore $|\mathbf{S}\times\mathbf{u}|$, at $-\mathbf{u}\cdot\mathbf{S}/|\mathbf{U}|$ seconds in the future, for closing range rate ($\mathbf{u}\cdot\mathbf{S}<0$). The presence of acceleration / deceleration adds complexity, but closest approach time and distance can still be expressed – repetitively because of changing dynamics – in terms of difference vectors from the Kalman estimator outputs. Wherever projected closest approach distances fail to exceed separation requirements, by amounts above error limits accounting for the Kalman estimator covariances, an incursion alarm is needed.

Computational requirements

If there are 100 total surface vehicles (including departing aircraft, landing aircraft, trucks, etc.) with ASDE and/or pseudorange measurements, then there are 100 Kalman estimators to be maintained and up to $(100)(99)/2$ – almost 5000 – possible pairs to be considered. From successful multi-target tracking at White Sands in the 1970s it is stated without any hesitation that 100 Kalman filters will not tax computer resources today. Nor will conditional postprocessing (contingent on range rate's algebraic sign) for less than 5000 closest approach times and (squared) distances to be compared vs. specified minimum values. In return for these modest computational tasks, the method described herein affords these benefits:

- *Efficiency*. Calculations just described are direct and economical. No new provisions are needed.
- *Accuracy*. Locations can be within a few meters; velocities will be on the order of that figure divided by Kalman filter averaging time (several seconds).
- *Reduced sensitivity to interference*. Partial fixes are utilized and no DGPS corrections are needed.
- *Consistency*. Every vehicle detected is handled with the same optimal path estimation technique.
- *Rigor*. Closest approach time and distance are just the criteria needed, and even their covariances can be taken into account.
- *Thoroughness*. All pairs containing at least one aircraft moving at 20 Kt or more are scrutinized.

This method, then, offers maximum capability for providing prompt dependable incursion warnings.

OPERATIONAL CONSIDERATIONS

Currently, surveillance services in the National Airspace System are provided primarily by secondary surveillance radar with backup from primary radar. Over the next two decades this situation is intended to change dramatically with a transition to airborne, GPS-derived position and velocity transmitted to ground tracking facilities via data link. Methods employed at present for airport surveillance include Airport Surface Detection Equipment (ASDE) radar, visual observation of surface traffic by the air traffic controller in airport towers, and pilot broadcast of intentions on aircraft communications frequencies for non-towered airports. Future enhancements to this system will include the Airport Movement Area Safety System (AMASS) – which will add secondary radar inputs to the aircraft position determination process and provide the controller with decision-making tools to assist in identifying potential conflicts. Enhancements planned over the next decade include aircraft position determination from multilateration using aircrafts' secondary radar beacon transponders. ASDE and AMASS will be implemented only at high activity airports (*e.g.*, ASDE will be fully implemented at only 34 high-activity airports in the United States).

Airborne GPS-Derived Surveillance Plans

Clearly the architecture of the National Airspace System (NAS) is moving toward greater reliance on GPS-based automatic dependent surveillance (ADS). The current draft (Version3.0) of the NAS architecture currently being circulated by FAA for industry comment indicates that the FAA's future surveillance system, both for airborne and airport surface operations, will transition to an ADS-based system over the next two decades A major improvement in airport surface surveillance capability is expected to come from GPS capability in the aircraft coupled with an ADS data link. Current plans call for GPS-derived position and velocity of aircraft to be sent over data link to a ground surveillance facility – for integration with reports from other aircraft – while processors assess traffic flow and prepare display data for air traffic controllers equipped with decision-making tools, for assessing collision threats and avoidance maneuvers. Quality of GPS-derived position and velocity surveillance data will vary with airborne GPS equipment and airports' ground infrastructure capabilities. Augmentation with either Local Area Augmentation System (LAAS) or Wide Area Augmentation System (WAAS) offers significant increases in both accuracy and integrity of the GPS data. LAAS, which provides the greatest accuracy enhancement, is planned to be available at high-activity airports. WAAS is planned to be available throughout the United States, to enhance accuracy and integrity of GPS in multiple domestic flight domains: enroute, terminal, and surface.

Future Outlook

In order to obtain benefits of enhanced GPS through LAAS or WAAS, airborne GPS equipment must be capable of receiving and processing the corrections. Many operators, *e.g.*, those purchasing new aircraft, could be expected to obtain this capability. However, many older aircraft and some general aviation aircraft may have only unaugmented GPS systems. Also, some may not have data link capability, and still others may not have GPS capability. Thus the present plan (aircraft-derived GPS position and velocity transmitted via data link) requires NAS to accommodate a broad variety of airport and aircraft capabilities. With data refined by LAAS, by WAAS, or no augmentation, surveillance capabilities could be degraded to the lowest common denominator - services based on capabilities of the unaugmented aircraft.

For reasons already identified in other sections of this paper, transmission of uncorrected pseudoranges from aircraft and from other vehicles operating on the airport surface would pave the way for data of consistently high accuracy and integrity (*i.e.*, double differences) to support airport surface surveillance of all GPS/data link equipped vehicles. Following through with closest approach computations would provide as complete a protection against incursions as humanly possible. Although not emphasized herein, the approach is readily extendable to other operations as well (*e.g.*, TCAS with maneuvers in the horizontal plane – for which the tracking computations would be performed in air, as in Ref [5]).

CONCLUSIONS

Adaptation of the Mode S squitter approach in Refs. [1,2] – but with transmission of raw pseudoranges rather than coordinates and velocity – will facilitate closest approach predictions, enabling runway incursion protection that is extremely efficient, accurate, uniform, rigorous, thorough, and robust (less vulnerable to multipath and signal blockage).

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ADDITIONAL ITEMS ARISING in VERBAL DISCOURSE :

***How much** improvement will the proposed approach provide?* The amount of improvement depends on the severity of signal blockage and multipath degradation – which will vary from one airport to another. With increasing severity of signal loss and/or degradation, there will be decreasing accessibility of accurate coordinates. Also, even with modest degradation, optimal velocity estimates are not achievable by stitching together coordinates of varying accuracy.

How does the proposed approach reduce multipath? It doesn’t lessen the amount but it reduces the effect. By conveying pseudoranges rather than coordinates, we can selectively reject suspicious data while retaining the good data.

Why bother to predict closest approach between aircraft on different runways at opposite ends of an airport? The proposed approach considers every possible pairing of objects. If known circumstances preclude collision of a particular pair, calculations for that pair can be skipped, and the computation cycle can proceed to the next pair.