Inertial Measurement Technology in the Satellite Navigation Environment

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Inertial measurement technology can make a valuable contribution to the development of autonomous, sole-means Satellite Navigation Systems. The integration of inertial measurement technology and GPS can enable a significant performance improvement to the various configurations of GPS, WAAS and LAAS. This paper provides a conceptual discussion of the safety and performance benefits that inertial measurement and integration technology can bring to the satellite navigation environment.

KEY WORDS

1. Inertial Navigation. 2. GPS. 3. Integration

1. INTRODUCTION. The integration of inertial measurement technology (IMT) and GPS has many benefits for improved safety and performance. In this paper, the following topics are addressed: the need for a back-up to GPS/WAAS/LAAS; the benefits of using IMT for navigation, precision approach and interference suppression; the potential cost of a sole-means avionics retrofit and its effect on schedule; the applicability of various qualities of IMT; development schedules and costs; a transition strategy and the obstacles to the successful implementation of an inertial back-up.

2. DEFINITIONS AND ASSUMPTIONS. In this paper, the term 'sole-means' is used as a synonym for 'the only navigation system installed in the aircraft' and the term 'sole service' for 'the only navigation service provided by the FAA'. Any review of the back-up options for Satellite Navigation Systems (SNS) is hindered by the lack of comprehensive operational requirements. It is clear that the needs of light aircraft operating in Alaska are not the same as those of a B747 descending into Chicago; however, the differences are not well documented. This is particularly relevant in the case of loss of GPS functionality, whether due to interference, jamming or other cause.

It will be assumed that any outage is limited to a single, unintentional, interference source affecting an area of radius of 100 nm or less. This assumption is made on the basis that most commercial aircraft can be equipped with a high performance IMT back-up to GPS. This back-up will provide a typical airline aircraft with the capability to fly for an hour without GPS and still maintain RNP 1. The ability of the aircraft to safely exit an area of jamming, or continue its original mission without disruption, will help remove the motivation for, and hence the threat of, intentional jamming.

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3. THE NEED FOR A BACK-UP. The author's review of the implications of the Johns Hopkins University Applied Physics Laboratory (JHUAPL) GPS Risk Assessment Study (GRAS) highlighted the following inferences:

(a) The time required to implement the GRAS recommendations will impose a significant schedule slip on the GPS/WAAS/LAAS programme.
(b) A SNS back-up is a permanent requirement.
(c) Air Traffic Control (ATC) is not a cost-effective back-up.
(d) Improving the jamming/signal ratio is very effective against unintentional interference.
(e) It is not advisable to commit the civilian aircraft fleet to an electronic warfare race with hackers and terrorists.

These inferences point to the requirement for some combination of back-up means and service. The candidates for all phases of flight except precision approach are: VOR/DME, Loran-C, IMT and ATC. IMT can augment the precision approach performance and reduce the cost of WAAS and LAAS, but it cannot act as a landing system back-up. The candidates for precision approach are ILS, MLS and Transponder Landing System (TLS).

4. THE BENEFITS OF INERTIAL MEASUREMENT TECHNOLOGY AS A BACK-UP. IMT is the optimum long-term choice for a navigation back-up because:

(a) IMT can improve the performance (and the cost) of GPS/WAAS/LAAS in three areas: navigation, precision approach, and interference suppression.
(b) The alternatives to IMT give no benefit except in a GPS/WAAS/LAAS outage.
(c) IMT can obviate the need for ground-based navigation systems.
(d) IMT provides its benefits worldwide.
(e) IMT is immune to disruption from sources outside the aircraft.

4·1. *Navigation.* Litton Aero Products has developed, and patented, a GPS/Inertial integration algorithm designated AIME™. This algorithm is currently embedded in the LTN-101 Global Positioning Air Data Inertial Reference System (GPADIRS) in use on the Airbus family of aircraft. AIME™ technology integrates the inertial element of the LTN-101 and the LTN-2001 GPS. Certification of the LTN-101 and AIME™ algorithm with the GPS elements of the Collins and Sextant Multi-Mode Receivers (MMRs) is nearing completion at Aerospatiale. The LTN-101 (including the AIME™ algorithm) was certified to the performance levels shown in Table 1. These performance levels are consistent with the requirements for a sole-means system.

Table 1. LTN-101 certification parameters.

	Availability	Continuity* (Note)	Integrity	Accuracy
LTN-101/AIME™	$1–10^{-5}$	$1–10^{-5}$/hr	$1–10^{-7}$/hr	RNP 0·3

* The failure of IRS is random amongst aircraft and consequently 10^{-5} is acceptable for sole-means. The 10^{-7} requirement applies to situations where multiple aircraft in the same area are likely to be affected by the same failure.

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The LTN-101 is currently approved as primary means, worldwide, down to RNP 0·3 (Non-Precision Approach (NPA)) without use of a coverage prediction programme for constellations with more than 22 satellites. The system is able to coast through complete GPS outages as shown in Figure 1.

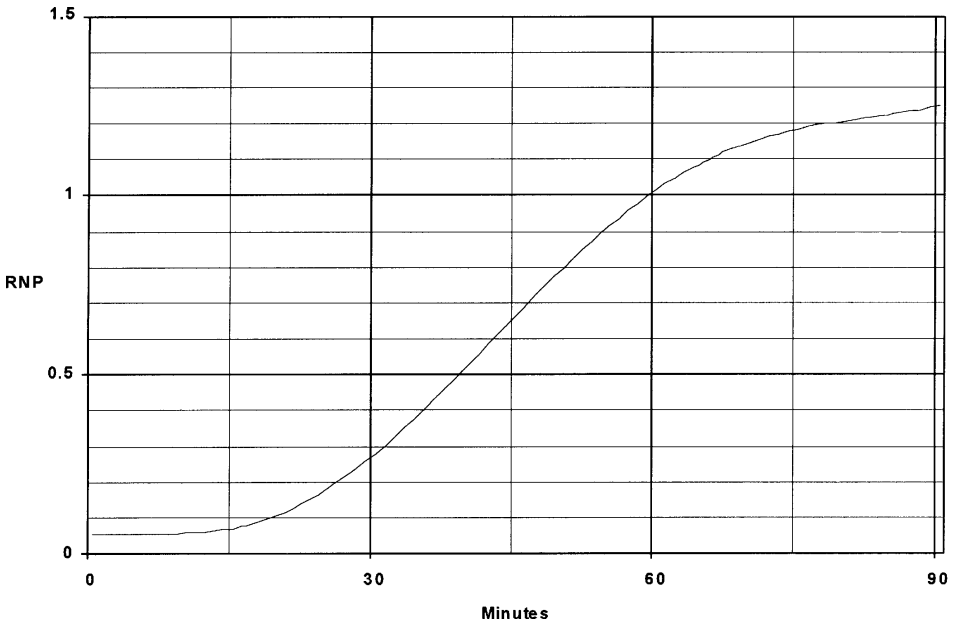


Figure 1. LTN-101 AIME™ navigation coasting performance (2σ radial). (It should be noted that performance is somewhat conditioned by coasting entry parameters. This figure gives an estimate of expected performance.)

Although the patented AIME™ algorithm is currently mechanised in the LTN-101, it could be implemented in any manufacturer's Inertial Measurement Unit (IMU), GPS or Flight Management System (FMS), or in a stand-alone module connected appropriately to these systems. However AIME™ technology is mechanised, its performance depends on the quality of the inertial instruments. The LTN-101 IMU has gyros with performance in the order of 0·01°/hr and accelerometers in the 50 μG range.

The AIME coasting capability, shown in Figure 1, does not require input from WAAS or LAAS and, in the event of a GPS outage, provides jet transport aircraft with the ability to travel approximately 300 nm (in the worst case, assuming loss of GPS at take-off) before losing even RNP 1. This has two beneficial effects: it gives aircraft the ability to escape the area affected by interference, and it provides time for ATC to arrange to cope with any residual problems.

In assessing the impact of loss of GPS, it should be noted that not all aircraft would be at the centre of the affected area. Some aircraft might have to travel a considerable distance to escape, some might be able to complete their planned flight using IMT coasting and others would have only a short distance to travel to GPS coverage. It is possible that some aircraft would be unable to maintain the required RNP and require ATC assistance, but the workload on ATC would be much lighter than if all

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aircraft became instantaneously lost. The use of AIME™ coasting capability ensures that GPS outages have very little impact on aircraft safety assuming that ATC can inform aircraft of the area affected and how best to escape the interference.

If the Air Transport (AT) fleet were equipped with AIME™ coasting capability, the following benefits would ensue:

(a) The potential for intentional jamming would be greatly reduced.
(b) General Aviation (GA) aircraft would be able to operate safely with a limited back-up, if indeed any back-up is required.
(c) If Loran were the chosen back-up for GA, then VOR/DME/NDBs could be decommissioned.
(d) The criticality of achieving 50–60 dB of anti-jamming (AJ) would be reduced – no AJ would be acceptable, some AJ would be better.

The probable mix of GA and AT aircraft in busy or complex airspace requires detailed study to ensure that no local equipage or other regulations for GA would be necessary in such areas.

4.2. *Precision Approach.* For both WAAS and LAAS, the vertical requirements are the most difficult to meet. A 3D-AIME™ implementation is being developed, which provides a vertical reference from an independent dissimilar system. Initial flight tests have already demonstrated its feasibility. With SA off, the 3D-AIME™ mechanism is projected to be able to provide the following capabilities:

(a) Without WAAS/LAAS, ILS, or other ground aids:
  (i) CAT I vertical accuracy of 4 m 95%, with vertical alert limit (VAL) 9 m.
  (ii) CAT II vertical accuracy of 2 m 95%, with VAL 4 m when the second frequency (L5) becomes available.
(b) With WAAS/LAAS:
  (i) An accurate integrity check and back-up from an independent dissimilar system.
(c) Performance increases as indicated in Table 2. It is estimated that 3D-AIME™ technology will increase the accuracy of WAAS and LAAS as follows:
  (i) WAAS CAT I to CAT II, without extra GEOs or ionospheric correction improvements.
  (ii) LAAS CAT I to CAT III, without LAAS improvements, airport pseudolites (APLs) or extra satellites.

Table 2. Projected 3D-AIME™ performance v. GPS/WAAS/LAAS. (These values were derived from the References.)

	Vertical performance (m)		Horizontal performance (m)		Approach category	
	GPS	3D-AIME™	GPS	3D-AIME™	GPS	3D-AIME™
GPS SA ON	200	7·8	100	70	IPV	IPV
GPS SA OFF	68	4	34	16	IPV	CAT I
GPS SA OFF + 2nd freq.	20	2	10	5	IPV	CAT II
WAAS	7·6	1·5	7·6	4	CAT I?	CAT II
CAT I LAAS	4·0	0·6	4·0	3	CAT I	CAT III

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4.3. *Interference Suppression*. Anti-jamming AIME™ (AJ-AIME™) technology implements deep coupling of the inertial and the GPS tracking loops to provide low-cost interference suppression. The main objection to deep coupling has been that it correlates the solutions from different tracking loops rendering the pseudo-range measurements no longer independent. In this circumstance, RAIM and other integrity detection schemes are ineffective. Applying the AIME™ principle of parallel Kalman filters for each tracking loop solves this problem and allows deep coupling to be used without sacrificing integrity. The AJ-AIME™ implementation could provide 20–30 dB J/S. Simultaneously, the tightly coupled element of the basic AIME™ algorithm will still continue to provide high navigation availability, integrity and continuity plus the ability to coast through areas where GPS jamming is still effective. The improvement of J/S ratio reduces the radius of any potential loss of signal and makes the measures described in the navigation section above even more effective.

5. COST AND SCHEDULE ISSUES. The schedule for implementation of GPS sole-means avionics will be governed by user acceptance and realisation of cost benefits. As costs rise without concomitant increases in benefits, the schedule will be prolonged. It is tempting, when reviewing the programme, to look only at the capital cost of the new equipment. Even if it were possible for GPS to be true sole-means of navigation (no back-up), the equipage issue would be significant. It is not just a case of installing GPS and un-installing all other radio navigation aids. Reorganising an aircraft's avionics to achieve sole-means could be a costly exercise. Most or all of the following sub-systems may require modification: flight warning computer, radio management panel, FMS (continuity & criticality), database (integrity), multi-function display unit, system power supplies, maintenance computer and cockpit warnings. Such tasks invoke significant costs both for modifying existing equipment and aircraft downtime. The cost of implementing sole-means GPS in some aircraft may not be acceptable to the aviation community, whatever back-up strategy is chosen. The above are components of the cost of sole-means, but they are not prerequisites to the Free Flight and safety benefits of GPS. The benefit the user derives from sole-means is saving the cost of replaced avionics and concomitant maintenance and training. If the short-term cost of modification outweighs the long-term value of these savings, there will be little motivation to retrofit.

The sooner acceptable end-state avionics architectures can be specified, the sooner new aircraft can be delivered with the appropriate configuration. For existing aircraft, the motivation to retrofit reduces with aircraft age and remaining service life with its current owner. The retrofit costs may cause the transition to GPS sole-means to be more protracted than expected. A realistic assessment of the schedule implications of the JHUAPL GRAS and the aircraft modification requirements puts achievement of the end-state at least 10–15 years away, whatever the end-state architecture.

6. THE APPLICABILITY OF IMT. The problems with IMT as the general solution to the navigation back-up are that IMT is currently too costly for GA aircraft and the majority of commuter and regional aircraft are not IRS equipped. The quality of the inertial system has a different effect on each area: navigation, precision approach and interference suppression. The area most impacted by inertial quality is navigation. Only four technologies (spinning mass, hemispherical resonant, ring laser

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and, in the future, fibre-optic) are capable of producing gyros for inertial navigation. There is no likelihood of any of these technologies leading to an inertial navigation system that GA could afford. Inertial quality still equates to system cost. If the gyro performance requirements are reduced, cost falls and more aircraft are candidates for the technology. However, coasting performance, and the ability to escape an outage, reduce with gyro performance and cost. The application of IMT to the sole-means task will be dealt with in the next two sections.

7. INERTIAL NAVIGATION QUALITY. The term 'inertial navigation quality' is used to describe systems with gyro performance of 0·01°/hr and better. The term 'sub-inertial navigation quality' is used to describe systems with gyro performance between AHRS (1·0°/hr) and IRS (0·01°/hr); typical performance would be 0·1°/hr. Sub-inertial navigation quality systems are not adequate to fulfil the conventional IRS role but are differentiated from AHRS by their capability to perform coarse navigation and to gyrocompass.

Inertial navigation quality instruments are used on all major air transport aircraft. In the later models, IRS is not just required for navigation but is designed into critical functions such as flight control. Current IRS technology will continue to be a requirement for AT aircraft and will form part of the end-state architecture. The issue here is whether the industry chooses to take maximum advantage of IMT.

The historical decline in the relative cost of IMT has enabled its application to smaller aircraft. Currently, inertial quality systems are used as alternatives to Attitude and Heading Reference Systems (AHRS) on regional aircraft such as the Canadair RJ and SAAB 2000. The market motivations for adopting the IRS as opposed to AHRS are: avoidance of generic AHRS errors (heading splits…) and associated delays and maintenance actions, independence from radio navigation data, and the need for inertial quality data to support Head-Up Guidance System (HUGS) operations.

The increasing penetration of IRS into the regional aircraft market indicates that the benefits of IMT are recognised by operators, and they would not be deterred by the cost of a single inertial installation, were it necessary for sole-means. When considering the overall cost of retrofit to sole-means, the differential between AHRS and IRS is probably a minor component. A further consideration when reviewing the acceptability of IRS to the regional and commuter user is the quantity of systems required per aircraft. At the higher end of the AT fleet, three systems per aircraft is the rule. In regional aircraft, two systems per aircraft is a more common occurrence, but some operators opt to fit a third IRS to guarantee dispatch reliability.

While two sources are required for the basic attitude source, it is probable that only a single IRS would be needed to form the back-up system for regional and commuter aircraft (i.e., the lowest cost configuration might be one AHRS and one IRS). A single serviceable IRS with AIME™ integration of GPS produces the required coasting accuracy and availability (but not the integrity and continuity to be the only attitude system carried on the aircraft). While GPS is available, the AIME™ algorithm will ensure the integrity of the IRS. If the IRS fails in flight, the user will be informed. In the case of a GPS outage there are three possibilities for an aircraft equipped with a single IRS back-up: a fully functional back-up – (assuming an MTBF of 10000 hours – it is likely all aircraft, within a given outage, will be in this state), a detected failed back-up (there may be a few aircraft in this condition), an undetected failed back-up

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providing hazardously misleading information (the probability of this occurring while the AIME™ algorithm is functioning in GPS coverage is minimal.)

In the case of an outage, the few, if any, aircraft with detected failures can be taken care of by ATC and the probability of an undetected failure will be acceptable. During the coasting period, in an aircraft with multiple inertial systems, the systems would be compared to eliminate the probability of an undetected failure and maintain system integrity. The comparison strategy obviously does not work for a single system. However, there is a good possibility that the required integrity is available without inter-system comparison because:

(a) The probability of being in an outage is low.
(b) The probability of a single IRS developing an undetected failure is low.
(c) The simultaneous probability of both occurrences is acceptable.

The requirement for a single IRS back-up, the declining relative cost of IMT and further cost reductions associated with a larger market for IMT would make the technology accessible to all regional and commuter aircraft without undue financial burden. While it is possible to resolve the issues of sole-means for commercial aircraft fairly quickly, the same is not true for GA. Even a single inertial is still too expensive for all but the most sophisticated GA aircraft. Unless an affordable back-up can be developed, either it will have to be acceptable for GA to operate without a navigation back-up, or it will be necessary to retain a subset of the current radio navigation architecture.

8. SUB-INERTIAL NAVIGATION QUALITY. The civil aviation community is waiting to be told that silicon gyro technology will reduce the cost of inertial navigation quality systems to the price range appropriate to GA ($5000). Unfortunately, the potential for this technology to achieve navigation grade within ten years is very low and the probability that it can be integrated into a $5000 system is lower still. Currently the best manifestation of Micro Electro-Mechanical Systems (MEMS) technology is claimed to be achieving 1°/hr across the required temperature range. To achieve inertial navigation quality requires a hundred-fold improvement in performance. With each new performance improvement comes the potential to observe previously hidden error sources. There is no theoretical obstacle to achievement of navigation grade silicon gyros, but neither is there any evidence that it is practically possible.

In addition to the low probability of being able to achieve navigation performance, there is a cost reduction issue. The requirement is to reduce cost by a factor exceeding ten. Even assuming the inertial instruments are free, this would be a significant task requiring very high levels of integration and highly automated manufacturing. Amortisation of the non-recurring costs associated with such developments, in a low-cost system, is not possible without large sales quantities (100 000 units or more). Manufacturers will be unlikely to make this kind of speculation without a market guarantee and a reasonable assurance that the performance requirements are achievable.

It is unrealistic to expect a full inertial quality system to be available for $5000 in any relevant time frame; fortunately, it's also unnecessary. All that is required, and all that it is reasonable to expect, is sub-inertial grade performance augmented by AIME™ technology. Experience with AIME™ and MEMS leads to the belief that the AIME™ algorithm can be used to calibrate a MEMS gyro with a 0·1°/hr stability

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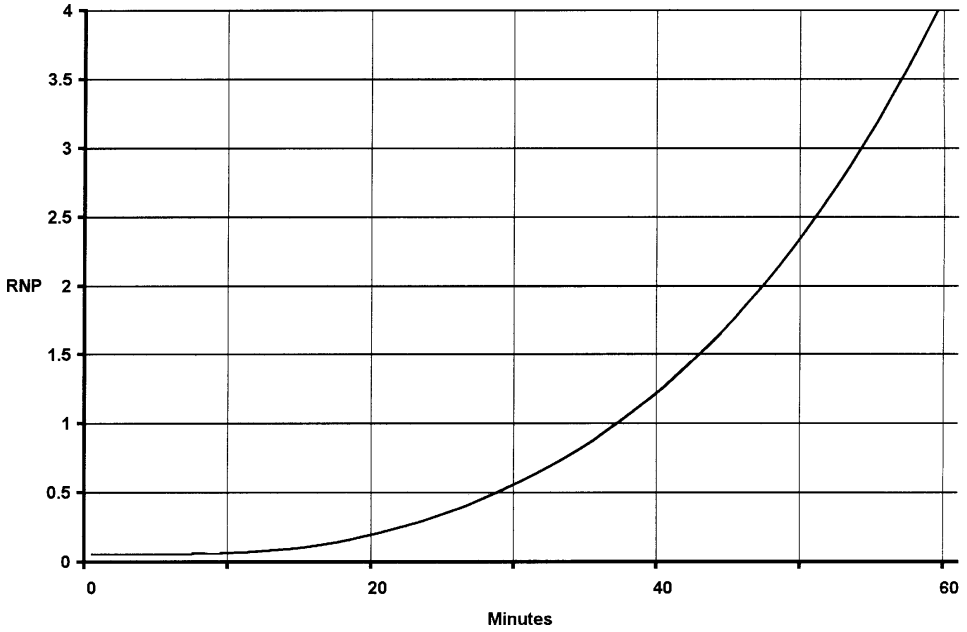


Figure 2. Sub-inertial navigation quality – AIME™ navigation coasting.

(turn-on to turn-on) to 0·01°/hr (in-run stability for 20 – 30 min). This performance is not adequate to allow such a system to substitute for IRS in its conventional jet transport role but is adequate to allow significant coasting capability in the case of an outage (see Figure 2 and Table 3) and the use of 3D-AIME™ and AJ-AIME™ technology.

There is always significant technical risk associated with gyro development, but the use of AIME™ calibration to achieve the required performance for relatively short periods of time dramatically reduces the risk. The uncertainties in this strategy are minimal compared to the full inertial navigation quality option and the intrinsic costs are less. At the $5000 price level, factors such as environmental protection (thermal, electromagnetic and vibration isolation) become significant cost drivers. The protection required by a 0·1°/hr gyro is correspondingly less than that required for a gyro with an order better performance. Yazdi *et al.* (1998), which is a review of MEMS micro-machined accelerometers and gyroscopes, states that:

> Inertial sensors have seen a steady improvement in their performance, and today, micro-accelerometers can resolve accelerations in the micro-g range, while the performance of gyroscopes has improved by a factor of 10 every two years during the past eight years.

Figure 17 of Yazdi *et al.* (1998) provides a trend line for random angle walk for bulk and surface machined MEMS gyros. Performance between 10^{-2} and 10^{-3} $°/\sqrt{\text{hr}}$ is consistent with 0·1°/hr bias stability. Extrapolation from the trend lines shows bulk gyros achieving the desired level of performance by the year 2001 and surface gyros by 2003. Although the 0·1°/hr gyro strategy considerably lowers the performance risk and has an impact on recurring cost, cost remains an issue. The capital expenditure necessary to achieve the needed cost still requires a reasonable guarantee of a market large enough for acceptable amortisation. The 0·1°/hr performance level is not an

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arbitrary choice; it is the minimum gyro performance necessary to achieve gyro-compassing and independence from a magnetic flux valve. Should it prove impossible to achieve even this level of performance, there is a workable, but not optimal, fallback position

It is estimated that the AIME™ algorithm can be used to increase the performance of a 1°/hr MEMS gyro to about 0·1°/hr for the first 20–30 min without GPS. Analysis has shown that this still does not produce useful coasting performance. However, if the system is augmented, (using a long baseline (1 m), differential, GPS antenna, airspeed and magnetic heading), it is estimated that the coasting performance shown in Figure 2 can be achieved. This level of performance may well be sufficient for GA aircraft; however, it needs significantly more study.

While 1°/hr (after AIME™ calibration – 0·1°/hr) performance may be marginal for navigation, it is suitable for both 3D-AIME™ and AJ-AIME™ operations. This fallback option invokes the same cost versus market size considerations discussed above but has some added cost risk because of the requirement for augmentation. Given some way to assure potential manufacturers of an adequate market, the sub-inertial navigation quality strategy is realistic and practical and has a viable fallback strategy in case gyro performance predictions prove optimistic.

9. INERTIAL/AIME™ DEVELOPMENT SCHEDULE AND COST.

The AIME™ algorithm is developed and fully functional. To implement AIME™ technology it is necessary to decide in which module to locate it.

9.1. *Existing IMT Equipped Aircraft*. For aircraft currently equipped with IMT, the candidate hosts for the AIME™ algorithm are the FMS, MMR or a standalone Line Replaceable Unit (LRU). Modifying existing inertial systems to accommodate the AIME™ algorithm is not likely to be cost-effective, nor is there any possible motivation or benefit associated with replacing the existing inertial systems (except in the case of a few obsolete spinning wheel systems).

9.2. *Existing Non-IMT Equipped Aircraft*. For those aircraft not currently equipped with IMT, it would be more cost-effective to implement AIME™ technology in the new inertial system (for considerations associated with 3D-AIME™ and AJ-AIME™ operations). Selection and implementation of the host would probably take two years from turn on to certification.

9.3. *3D-AIME™ Development*. 3D-AIME™ technology is in the early R&D phase and would require at least four years from turn on to certification. There are two considerations with the 3D-AIME™ upgrade strategy. Firstly, in most modern aircraft the IRS is intimately associated with the flight control system used for precision approach. There are justifiable engineering concerns with using the IRS to both create the demand for the flight control system and to assist in following that demand. Secondly, existing IRS may not provide data of sufficient quality and rate to implement the 3D-AIME™ algorithm. Neither of these considerations is likely to prove fatal for the following reasons: 3D-AIME™ technology is not an essential element of sole-means – it cannot replace ILS, MLS or TLS as a back-up – its benefit is the extension of the GPS/WAAS/LAAS capability; for new aircraft architecture these concerns can be appropriately dealt with by design; the 3D-AIME™ algorithm can be mechanised with low-cost 1°/hr gyros. In the event that the AT community decided that the benefits were significant, the cost of adding an additional inertial system dedicated to 3D-AIME™ operations would not be prohibitive. This additional

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Table 3. Current and projected inertial/AIME™ technology and performance.

Instrument type	Availability (years)	Normalised system price	Non-rec. cost ($M)	Gyro bias °/hr inherent/ AIME™ calibrated (30 min)	Accel bias μG (1σ) inherent/AIME™ calibrated (30 min)	Coasting capability (min)		
						RNP 0·3 (NPA)	RNP 1	RNP 4
ZLG™/RLG	Now	1	20	0·01/0·005	50/20	30	60	300
FOG/SiAc™	Now	0·35	20	1·0/0·1	50/20	10	15	25
MEMS (Mk 1) augmented	3	0·1–0·2	25	1·0/0·1	50/20	10	20	40
MEMS (Mk 2)	5	0·07–0·14	30	0·1/0·01	50/20	20	35	60

system could not be substituted for one of the existing IRS since its measurement accuracy would be inadequate for flight control applications.

9.4. *AJ-AIME™ Development*. The AJ-AIME™ mechanisation has a similar issue to 3D-AIME™ mechanisation. It will require very high rate data that cannot be extracted from current IRS. The AJ-AIME™ algorithm can cohabit with the 3D-AIME™ algorithm and also only requires 1°/hr gyros.

9.5. *Implementation of AIME™ in a separate LRU*. At first review, this requirement for a separate system may seem to be a significant drawback, but consideration of the overall picture reveals an interesting option. The basic AIME™ software needs a host. It is not practical to consider embedding it in existing IRS since the software certification costs would be prohibitive. Significant modifications to the FMS are equally likely to prove troublesome especially if the certification categories do not match. The MMR is the most likely choice for a host, but software modification of an existing landing system is not likely to be easy. The cleanest engineering solution, and probably the lowest cost option, is to implement the AIME™ computer in a separate LRU. It would be relatively easy to create a modular system capable of accommodating combinations of inertial quality platforms and the three varieties of AIME™ technology. In the case of an inertial equipped AT aircraft with no requirement for 3D-AIME™ or AJ-AIME™ operations, the system would simply consist of an AIME™ computer and the relevant interfaces. The system would take input from the existing IRS and GPS and output AIME™ calibrated navigation data. To upgrade to 3D-AIME™ technology would require the addition of the appropriate software, approach database, the radar altimeter input and a low quality MEMS platform. The AJ-AIME™ mechanism could be similarly implemented. Such a system would allow a progressive growth path with relative ease. Costs could be minimised by using common modules for the entire fleet, from AT through GA. It would also be possible to attach a flat panel display and have the system simultaneously fulfil the role of standby attitude reference – or, in the case of GA, primary attitude reference. Table 3 documents the potential time frame and recurring and non-recurring costs associated with the development of the instruments and systems described above.

9.6. *Funding*. The gyro development schedule is funding dependent. If the gyro development schedule is delayed, the ground-based radio navigation back-up for GA will have to be maintained for longer than anticipated. There is the potential for a trade-off between the cost of funding, or otherwise motivating, an acceleration of gyro development and the cost to maintain the GA radio navigation infrastructure.

10. A TRANSITION STRATEGY. Current transition planning and studies are concerned with how much of today's navigation infrastructure can be removed and when. This may not be the crucial issue. The decommissioning of ground-based navigation aids can be carefully controlled, but retrofitting the AT and GA fleets on the basis of cost/benefit motivation is not so easy. The highest probability of success can be achieved by defining an end-state requirement, developing motivational benefits for achievement of the end-state, providing sufficient schedule to achieve the end-state and announcing a shutdown schedule for alternatives.

The transition strategy needs to address both retrofit/upgrade and new aircraft. The sooner an end-state architecture can be established the sooner new aircraft manufacturing can be switched to sole-means. Unless a subset of the current radio-

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navigation infrastructure is to be permanently retained, the only acceptable solution currently identified is GPS/Inertial. Disregarding the precision approach and interference suppression benefits of GPS/IRS integration (which can be developed as incremental upgrades), the technology exists today to achieve sole-means of navigation. Costs may decrease, components may become more integrated, but the overall architecture will still be valid in 20 years.

The ability to define a viable and credible end-state architecture is critical in an industry where a relatively simple complete fleet retrofit takes at least five years. As indicated above, the retrofit programme for sole-means may be fairly complex whether IRS is involved or not. To accomplish the transition, the industry needs time, an unwavering target and motivation. It is neither necessary nor cost-effective to impose a homogenous back-up strategy on all aircraft types and operations. The requirements for inertial back-up in various applications are proposed in Table 4.

Thus a potential transition strategy is as follows:

(a) Allow ATA and AOPA to specify the interim back-up they prefer. This will presumably turn out to be DME and/or Loran and ILS.
(b) Define a GPS/IRS architecture suitable for the end-state.
(c) If both DME and Loran are selected as back-ups, then announce the complete withdrawal of DME in 10 years and Loran in 15 (it takes GA longer to convert than AT and the low-cost inertial technology needs development time).
(d) Implement WAAS and LAAS in such a way that benefits would accrue to the user equipped with integrated GPS/Inertial. This would save development cost for WAAS and LAAS and provide motivation to the community to transition early to the end-state.

If such a strategy was implemented:

(a) The architecture for new build aircraft could be rapidly modified.
(b) The technology could be applied to retrofit commercial aircraft in a reasonably short timeframe (5 to 7 years). Those AT aircraft not adopting the IRS back-up would adopt Loran.
(c) The technology would slowly move down market as the relative cost of IRS reduced.
(d) Complete transition could be accomplished in 15 years.

The permanent retention of a subset of the ground-based navigation infrastructure, the only alternate strategy, is the worst-case outcome for this inertial back-up strategy. The major risk associated with this strategy is the time frame for the development of gyro technology for GA applications. The only consequence of a slip in the inertial schedule would be the extension of the GA element of the ground-based back-up (which would be no worse than the end-state of the alternative strategy). However, the proposed strategy would have removed most commercial aircraft from the threat zone and the industry would have had considerable experience in operating GPS as sole-means for the AT community. Given those circumstances, it might be possible for at least the lower end of GA to operate without a back-up or with a reduced capability system based on lower quality (cost) inertial instruments.

11. CONCLUSIONS. The Johns Hopkins University Applied Physics Laboratory (JHUAPL) GPS Risk Assessment Study (GRAS) identifies the need for a back-up if GPS is to be used as sole-means. The back-up identified is ATC, but this

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Table 4. Inertial back-up equipage.

Application	Inertial back-up system			Upgrade schedule
	Quantity	Grade	Availability	
Large, long-range jet transport	2	High (0·01°/hr–50 μG)	Now	7–10 years ● Existing IRS retained, dual AIME™ modules added. ● Low cost MEMS added to AIME™ modules for 3D and AJ-AIME™ operations if required.
Small, medium range jet transport	2	High (0·01°/hr–50 μG)	Now	7–10 years ● Existing IRS retained, dual AIME™ modules added. ● Low cost MEMS added to AIME™ modules for 3D and AJ-AIME™ operations if required. ● Dual full quality IRS replace AHRS on non-inertial aircraft – 3D and AJ-AIME™ technology incorporated into full quality system if required.
Regional and commuter air transport	1	High (0·01°/hr–50 μG)	Now	7–10 years ● Existing IRS retained if fitted, single AIME™ module added. ● Single full quality IRS replaces one AHRS on non-inertial aircraft – 3D and AJ-AIME™ technology incorporated into full quality system if required. ● Dual systems would be required if 3D-AIME™ technology used for standalone precision approach.
IFR GA	1	Low (0·1°/hr–50 μG)	5 years	10–15 years ● Single low quality MEMS platform added with 3D and AJ-AIME™ technology if required.
VFR GA				Not required.

is inappropriate and not cost-effective in today's airspace environment. The practical choices for back-up are as follows:

(a) Navigation – VOR/DME, Loran or INT.
(b) Precision Approach – ILS, MLS or TLS.

IMT is the optimum back-up for the navigation phases of flight because it brings the following benefits:

(a) IMT can improve the performance and cost of GPS/WAAS/LAAS for navigation, precision approach and interference suppression
(b) IMT serves a useful purpose at all times. The alternatives offer no benefit except in a GPS outage
(c) IMT can obviate the need for ground-based navigation systems
(d) IMT provides its benefits worldwide
(e) IMT is immune to disruption from sources outside the aircraft

The implementation of sole-means is likely to be expensive, whatever back-up strategy is chosen. GPS/WAAS/LAAS can be used to capture Free Flight benefits without being sole-means. The motivation to retrofit to sole-means will be low without some form of incentive. The AIME™ GPS/Inertial implementation capable of achieving sole-means NPA worldwide is already certified and in revenue service. The AIME™ algorithm can be implemented in a variety of systems including IRS, FMS, MMR or a standalone module.

The transition to sole-means GPS will take at least 10–15 years. Initially, DME and Loran will serve as the back-up for AT and GA, respectively. Inertial back-up can be implemented in a sequential fashion starting with the largest, most capable, AT aircraft and moving towards the bottom end of GA as the inertial technology becomes available.

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