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Integrity Coasting Concept for General Aviation Users of the Ground Based Regional Augmentation System

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ABSTRACT

It is now widely established that high performance navigation can be achieved by integrating GPS and low-cost inertial Micro-Electro-Mechanical Sensors (MEMS) measurements. However, the high noise and drift rates of these low-cost sensors, and their subsequent inability to coast for sufficient periods during GPS outages has hampered their widespread uptake in general aviation aircraft. The Ground Based Regional Augmentation System (GRAS) will bring high-integrity GPS navigation to General Aviation aircraft, however the potential exists that the GRAS signal could be lost for seconds or minutes at a critical time due to terrain masking or aircraft manoeuvres. A system is therefore needed which can coast through short-period GRAS outages, whilst taking advantage of the superior integrity provided by the GRAS Signal in Space (SiS) when it is available. This paper presents simulation results for a high performance navigation system utilising low-cost MEMS inertial sensors and the GRAS. The system utilises the high accuracy and integrity of GPS navigation when the GRAS SiS is available to calibrate the inertial system parameters, and is then able to coast the navigation solution with high-integrity for short periods if the GRAS signal is not available.

KEYWORDS: Aviation, GRAS, Augmentation, Inertial, MEMS

1 INTRODUCTION

The United States Global Positioning System (GPS) is now in widespread use in aviation throughout the world for primary and supplemental means navigation. In order to use the positioning information provided by the GPS for safety critical applications, augmentation systems are required to guarantee its integrity. Integrity is the ability of a system to provide timely warnings to the user when its information should not be used for navigation. Current users of the GPS primarily rely upon autonomous integrity monitoring systems such as Receiver Autonomous Integrity Monitoring (RAIM), which is self contained within the GPS receiver, or Aircraft Autonomous Integrity Monitoring (AAIM), which uses measurements from other aircraft sensors, to verify the GPS integrity. RAIM and AAIM systems can be used for En-Route, Terminal and Non-Precision Approach (NPA) navigation.

In 2003, ICAO recommended that Approach with Vertical Guidance (APV) become the minimum navigation performance standard (previously it was NPA) (ICAO 2003). Since the current RAIM and AAIM algorithms cannot provide the required GPS integrity, ICAO stated that external augmentation systems would be required (ICAO 2005). In the United States, the Wide Area Augmentation System (WAAS) has fulfilled this requirement, and APV approaches are now available at many airports across the U.S. The WAAS is a Space Based Augmentation System (SBAS) which consists of 38 reference stations, 2 master stations, and a geostationary satellite sub-system to transmit augmentation information to users throughout the region (Enge, Walter et al. 1996). Ground Based Augmentation Systems (GBAS) are also under development to provide precision approach capability.

The Ground Based Regional Augmentation System (GRAS) has been under development in Australia to meet similar requirements to the WAAS. A GRAS provides GPS integrity monitoring and differential corrections to users throughout a large geographic region through a network of ground monitoring stations, and ground-based VHF data link transmitters (GRAS VHF Stations or GVS). The system has particular advantages for nations where a navigation service must be provided, but where the large commissioning and maintenance costs of a Satellite Based Augmentation System (SBAS) cannot be justified.

One of the perceived limitations of GRAS is that the data link signal is limited to radio line-of-sight. At major aerodromes, this is unlikely be a problem, since a GVS will likely be located at, or close to, the aerodrome (possibly in conjunction with a GBAS). However the further the user is from the GVS, the higher they must be to receive the signal. At smaller regional aerodromes, this may lead to the loss of the signal at critical times (such as during an instrument approach).

This paper examines the operational use of GRAS at regional aerodromes for general aviation (GA) users, and establishes the scope of any limitations. A solution is proposed through the use of emerging Micro-electromechanical Sensor (MEMS) technology, which has the potential to bring high performance integrated navigation systems to GA at an affordable cost.

In this paper a description of GRAS is first presented, followed by an examination of an operational scenario where the GRAS signal may be lost. This helps to determine the system requirements of the integrated system under consideration. This is followed by a discussion of the proposed navigation system architecture, including integrity monitoring architecture. Results are presented which test the potential performance of a GRAS-Inertial navigation system, plus the characteristics of a proposed integrity monitoring approach. Finally, a discussion of the results and future work is presented.

2 DESCRIPTION OF GRAS

2.1 GRAS Overview

GRAS is a unique GPS augmentation system being developed by Airservices Australia in conjunction with industry as an alternative to SBAS. A schematic representation of a GRAS network is shown in Figure 1(RTCA 2005). The reference and master stations of SBAS and GRAS are effectively equivalent. However rather than users receiving the augmentation data via a satellite data link, it is transmitted via a network of terrestrial VHF stations. The grid-based ionospheric corrections generated by the reference station network are converted to a regional ionospheric correction at the GRAS VHF Station (GVS). This is combined with the other correction parameters in to a single pseudorange correction. The associated integrity parameters are also calculated and transmitted to the user.

As with SBAS, GRAS is designed to support navigation performance up to Approach with Vertical Guidance (APV) or even Category 1 Precision Approach (CAT-1). From a navigation service point of view GRAS has several potential advantages over SBAS systems including

- Common avionics between GRAS and GBAS;
- The ability to seamlessly transition to a GBAS mode when entering the terminal area (Gate-to-gate operations);
- The potential to protect against local atmospheric disturbances, such as severe localised ionospheric gradients;
- The ability to quickly deploy and maintain a system to service a region.

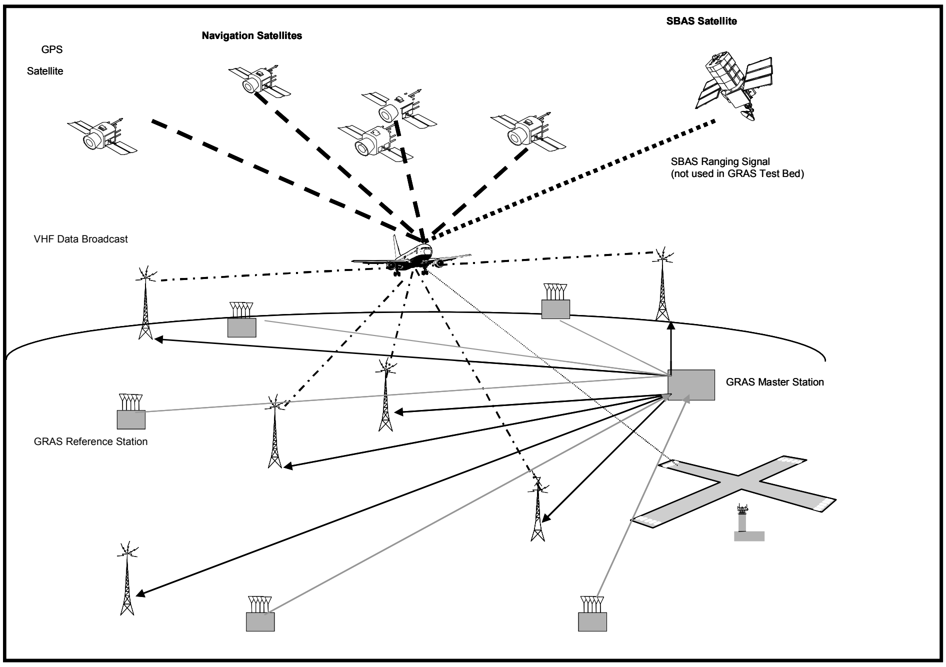

Figure 1: Notional GRAS Architecture (RTCA 2005)

2.2 GRAS Limitations

One of the perceived limitations of GRAS lies in the data link technology. Since GRAS utilises a ground based VHF broadcast, signal reception is limited to users within a radio line of sight to the transmitter. Consequently a large number of stations may be required to service a region as large as Australia, diminishing the cost advantages. This has particular implications for those utilising a GRAS Approach with Vertical Guidance (APV) service, where the GRAS SiS may be lost during the approach, as the aircraft approaches the ground. It is important to remember that this limitation is already experienced by users of the VHF voice network. In this paper, the point at which the GRAS Signal is lost will be termed the Loss of GRAS Integrity (LOGI) point.

Two Scenarios are considered where the loss of the GRAS signal may occur. Firstly, the loss of GRAS whilst En-route, and secondly whilst conducting an instrument approach.

1. Loss of GRAS Augmentation whilst En-Route or in the Terminal Area

   This situation is not critical, and navigation would revert to the current situation where horizontal navigation and integrity is provided by GPS with Fault Detection and Exclusion (FDE). Several studies (Van Dyke 2000) and practical experience have shown that the availability of GPS with FDE is very high with the current GPS constellation, and outages are typically of short duration – in the order of minutes. Similarly, vertical navigation would continue to be achieved via barometric altimetry. Future GNSS such as GPS-III and Galileo will likely lead to a further improvement in this situation over the next decade, even if stricter en-route navigation requirements are adopted.

2. Loss of GRAS augmentation during an instrument approach

   This situation is more critical. Depending on the weather conditions, if the GRAS

> augmentation is lost above the decision height and prior to establishing visual reference with the landing airfield then a go-around or diversion may be necessary. The current situation is that vertical navigation is achieved using barometric altimetry, leading to decision heights in the order of 400-1000 feet above ground level (AGL). With a GRAS APV service, decision heights as low as 250 feet can be achieved, with the added safety of having positive vertical guidance (i.e. a vertical deviation indicator). As per the ICAO recommendations, it is expected that APV services will become the minimum for future air navigation. Note that an APV approach is a *geometric* approach path which will not necessarily coincide with a barometric approach which follows a *pressure* gradient. Secondly, the decision heights are determined as much by horizontal integrity as vertical integrity, since the horizontal performance defines the size of the required Obstacle Clearance Surface (OCS) required for the approach (FAA 1999).

One of the methods proposed to overcome these small gaps in a GRAS VHF coverage is the use of auxiliary systems such as inertial navigation. In particular, the advances provided by Micro-electromechanical Sensors (MEMS) in recent years have the potential to bring sophisticated high performance navigation systems to the General Aviation (GA) community at an affordable cost. Indeed these devices are already in widespread use in Experimental and Sport aviation, where they are used in many popular ‘glass-cockpit’ attitude reference systems. The development of an advanced integrated navigation system for GA users has other important benefits, such as the provision of attitude information and high bandwidth positioning information which can be used by Highway-in-the-Sky systems, Synthetic Vision Systems (SVS) , flight directors and autopilots, all of which will improve flight safety.

Two concepts which are useful when defining navigation performance using inertial systems are now discussed for background information. These are the concept of variable approach minima, and a missed approach time (MAT).

2.3 Variable Approach Minima

Current approach minima are dictated by the navigation performance available to an average system, amongst the other factors such as surrounding terrain. For example, the minima for a RNAV(GNSS) approach is limited by the integrity of stand-alone GPS, and Barometric Altimeter, in addition to local terrain and aircraft performance. Typical vertical minima for such an approach are in the order of 400-1000 feet AGL. APV approach vertical minima are similarly determined by the accuracy and integrity available from augmented GPS (e.g using GRAS or WAAS). Such approach minima are in the order of 250-300 feet AGL.

However, in between, there is obviously a large discrepancy. If GRAS SiS is not available at altitudes down to the decision height at a given aerodrome, then the user must revert to GPS Stand alone integrity (ie FDE) and Barometric altimetry for vertical guidance. Thus an approach with suitable minima may not be available. Additionally, in reverting to a Non-Precision Approach standard, the user loses positive vertical guidance which seriously degrades safety margins and may force the aircraft to divert.

Imagine however a system which if the integrity information was lost, the approach could continue to some point in the future, such that visual with the runway could be established. This point would have a minima dictated by the real-time accuracy and integrity of the navigation system. This is the concept of the Variable Approach Minima. Such a concept allows for a minima which is somewhere between the optimal APV minima, and a non-optimal NPA/barometric minima. Additionally, positive vertical guidance should also be provided in this mode.

2.4 Missed Approach Time

Another important concept is that of a Missed Approach Time (MAT) as defined by Anderson (Anderson 2003). The missed approach time relates to the point in time at which the accuracy provided by the navigation system no longer provides the required navigation performance to complete the approach. This is illustrated in Figure 2 where the loss of GRAS integrity occurs just after the Final Approach Fix (FAF). The system protection level begins to degrade and the point in time at which the HPL reaches some limit is the Variable MAT (VMAT) or Variable Missed Approach Point (VMAP). This point is related to the variable approach minima, since the HPL limit is determined as a function of the required HPL at the projected altitude of the aircraft. The approach minima would then be the altitude at which the HPL limit or VMAT is reached.

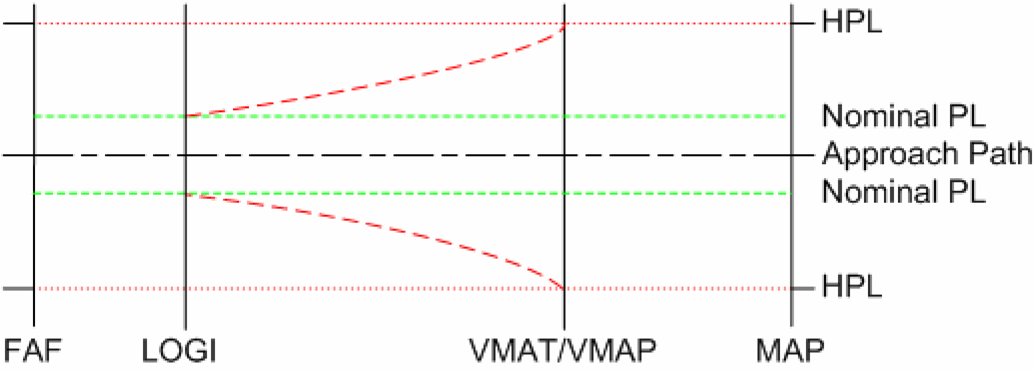

Figure 2: Variable Missed Approach Time (VMAT)

2.5 Case Study – Coen, Northern Queensland

In order to examine the application of variable approach minima and missed approach time, a case study is used to establish the system requirements. The area of interest is northern Queensland, which is one of the proposed areas to be used for GRAS operational certification in the coming years. It is planned to physically test this scenario during these GRAS trails.

GVS sites are planned to be co-located with existing voice VHF outlets at Cairns (Mareeba), Cooktown, Kintore and Weipa. Figure 3 depicts the potential GRAS coverage scenario in this region (not to scale; the vertical and earth curvature has been exaggerated for clarity). The aerodrome of interest is Coen which is a small regional airport currently serviced by regular public transport (RPT) and charter operators. In the figure, the textured blue area indicates regions where the GRAS Signal is available, and white areas where the signal is blocked by the curvature of the earth.

Using the VHF line of sight range equation (ARRL 1988), it is found that the GRAS signal from Kintore would be lost or become unreliable at altitudes below approximately 1000 feet above ground level (AGL) which is about 1500 feet above mean sea level (AMSL). The signal from Weipa would be lost at altitudes below about 5000 feet AGL. This has not taken into consideration any signal blockage due to mountainous terrain. This example would be typical of many secondary aerodromes throughout Australia if a GRAS were to be installed nation wide.

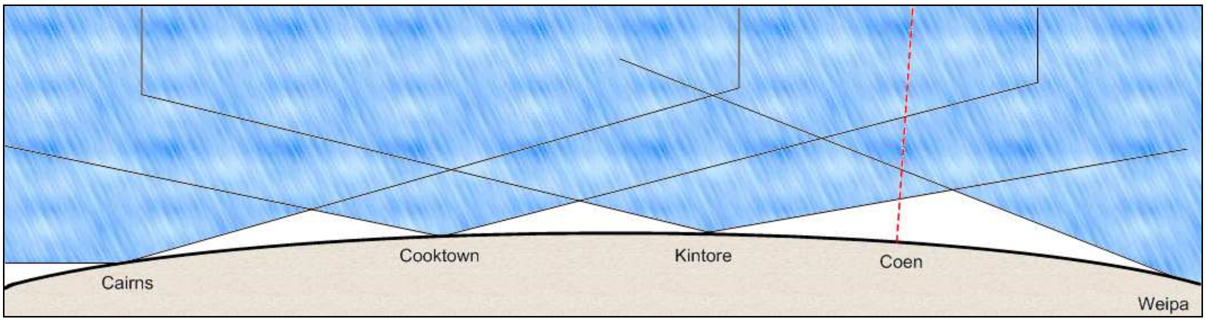

Figure 3: Potential GRAS Signal Coverage in North Queensland

By examining the existing RNAV(GNSS) approach plate (Figure 4) for Coen, it can be seen that the GRAS signal from Weipa would not be available during the approach, and the signal from Kintore would be lost at some point on the final approach segment, with approximately 2-3nm to run on the approach.

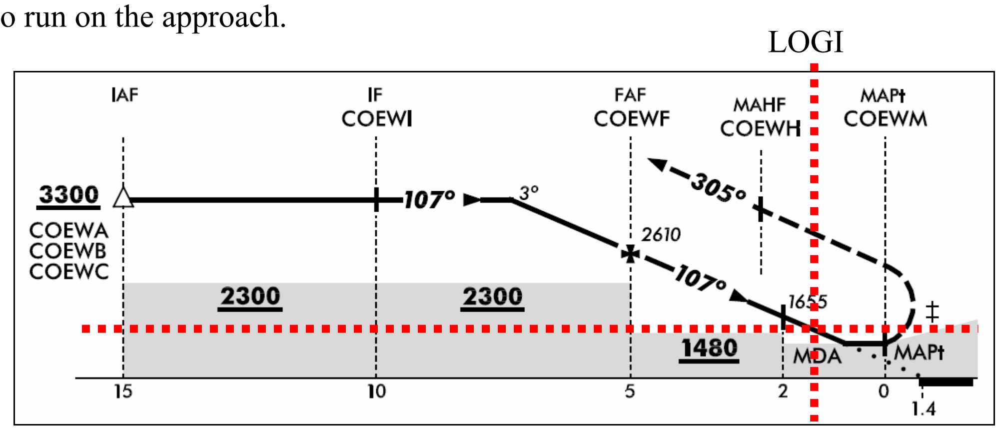

Figure 4: Coen RNAV(GNSS) Approach

At an approach speed of 90 knots (typical of many regional charter aircraft), this distance would be covered in 120 seconds. This finding represents the typical desired period of time that an integrated system should be able to navigate with high integrity following the loss of the GRAS signal. The next section discusses an integrated system which is proposed to meet this requirement.

3 GRAS-INERTIAL INTEGRATION

This section discusses the proposed integrated GRAS-Inertial navigation architecture which is proposed to meet the needs of GA users. The complimentary error characteristics of GPS and Inertial measurements are widely recognised, and the integration of the two measurements in a complimentary filter yields a high performance navigation system in terms of accuracy, bandwidth, and resistance to interference (Brown and Hwang 1997; Farrell and Barth 1999). However limitations exist when the integrity of the integrated signal needs to be validated, since undetected errors in the GPS signal can adversely affect the navigation solution. The use of the GRAS provides significant benefits, since the GPS measurements can be incorporated into the navigation solution with high confidence. This facilitates the continuous online characterisation of the aiding sensor errors such that when they are called up on to provide aiding in the event of the loss of GRAS augmentation, more confidence can be placed in their accuracy.

The provision of high quality navigation information from an integrated GPS-Inertial navigation system has several other important benefits for GA users. This includes the provision of data for "Glass Cockpit" attitude display, flight directors and 3 axis autopilots, which in turn facilitates curved approaches, head up displays, synthetic vision and highway in the sky displays. The flight safety foundation has identified that these advanced displays can also help to reduce the incidence of Controlled Flight into Terrain accidents (Daniel 1999).

3.1 Navigation System Architecture

The proposed navigation system architecture is shown in Figure 5. This architecture represents a tightly coupled GPS-Inertial system in which the integration filter combines the measurements from a MEMS Inertial Measurement Unit (IMU), dead-reckoning sensors, and GRAS augmented GPS to produce estimates of the vehicle position, velocity and attitude. The integration filter detail is shown in Figure 6.

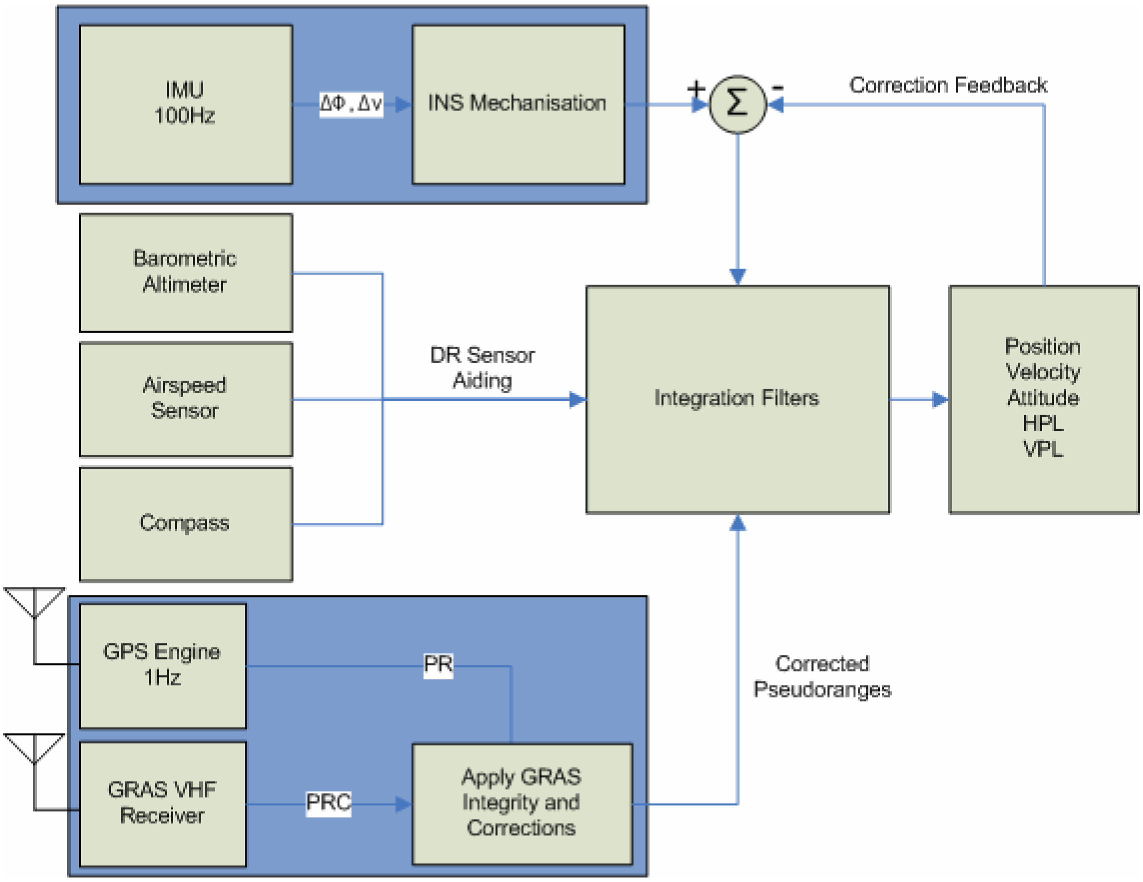

Figure 5: Navigation System Architecture

The IMU component measures platform rotational rates (ΔΦ) and accelerations (ΔV) at a high data rate (>100Hz). Rudimentary low-pass filtering is normally applied at the outputs of most commercial devices on the market which limits the bandwidth in the order of 50Hz. High bandwidth (comparable with optical gyroscopes) MEMS gyroscopes are not available commercially, however it is anticipated that such devices will be available in the future as the technology matures. The trade-off of higher bandwidth sensors is higher noise, so a balance must be established between the required sensitivity, and overall system performance.

In a high integrity system, it is also required to ensure that the inertial sensor measurements are not faulty. Whilst this can be achieved using dual-redundant IMUs, better fault detection performance can be achieved using a redundant skew-axis configuration which allows fault detection with a minimum number of sensors (Sturza 1988). The trade-off of this approach is a dilution of precision in the individual sensor measurements which reduces the signal to noise ratio. Unfortunately there are no commercial Inertial Measurement Unit products currently available on the market in a skew axis configuration, thus if this approach is adopted a customised solution would need to be developed.

Three auxiliary sensors – barometric altimeter, airspeed sensor and compass – are proposed to be used. It has been shown that the integration of dead reckoning (DR) sensors (airspeed, heading, altitude and altitude rate) can significantly improve the coasting performance of low-cost inertial devices (Berman and Powell 1998; Poh, Koh et al. 2002). These sensors are already available on many GA aircraft, and the cost of adding these sensors is relatively low compared with the inertial sensors. The barometric altimeter is required to stabilise the vertical INS channel, and in addition is required for en-route and terminal area navigation. The integration of DR sensors will further improve the navigation system integrity and reliability.

Finally, a GPS engine and VHF data radio complete the major hardware components. This sub-system will output GRAS corrected GPS pseudoranges, plus the GRAS parameters used to determine the integrity protection limits.

All of the sensor information is processed in the integration filters, discussed in the next section.

3.2 Integration Filter Processing

The integration filter (Figure 6) implements a tightly coupled state estimator (i.e. the integration is performed in the pseudorange domain) in a complimentary filter configuration. This approach is considered the best practice approach if access to the GPS receiver measurements is available (Farrell and Barth 1999). The state vector is shown in Eq. 1 and consists of 4 position states, and 4 velocity states. The state vector tracks the full state estimates, not incremental quantities, as shown in Brown (1997), which has advantages when calculating the solution integrity (discussed below). The state transition and process noise matrices are shown in Eq. 2-3 also following Brown.

The nomenclature used is as follows:

$\hat{\mathbf{x}}$	System State Vector
k	Time Instant
$\boldsymbol{\varphi}$	State Transition Matrix
Δt_{GPS}	GPS Time Step
S_p	Power Spectral Density of INS Error Driving Noise
$\mathbf{z}$	Measurement Vector
$\mathbf{P}$	State Covariance Matrix
$\mathbf{Q}$	Process Noise

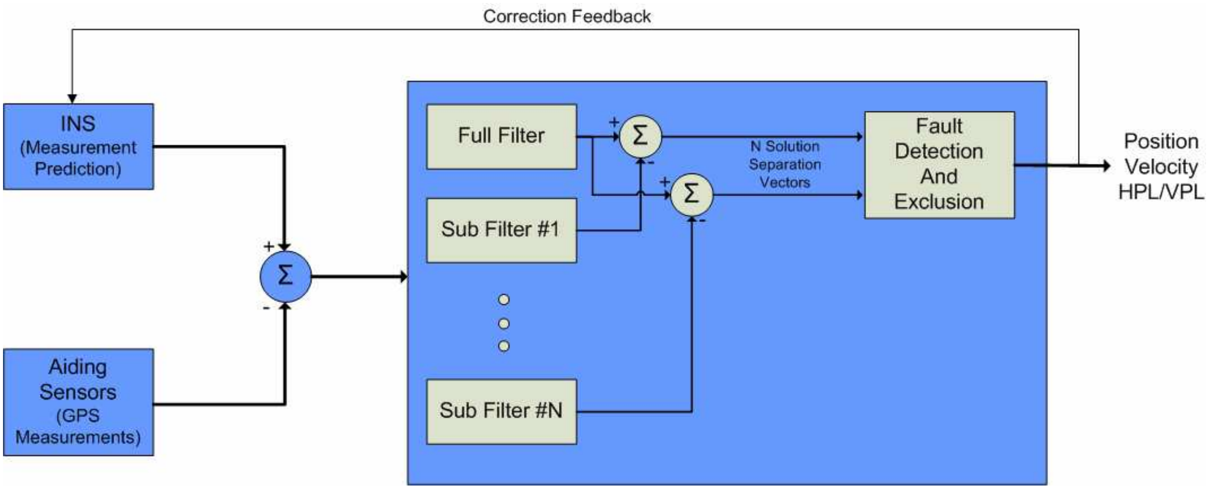

Figure 6: Integration Filter Architecture

For the simulations performed in this paper various sensor errors (inertial, barometric and pseudorange bias) are not modelled since these are well studied in the literature. These errors will be modelled in the full system to ensure filter consistency. Additionally the integration of DR sensors is not considered in this paper; however this is also well studied by the literature(Berman and Powell 1998; Poh, Koh et al. 2002) and will be implemented in the full system. One factor which has not yet been determined is the correlation time of the residual GRAS errors which needs to be considered in the integration filters. It is anticipated that these will be similar to the WAAS; however experimental testing will be required in an operational system to validate this assumption.

$$\hat{\mathbf{x}} = \begin{bmatrix} 3 \times \text{Position (ECEF)} \\ 1 \times \text{Receiver Clock Bias} \\ 3 \times \text{Velocity (ECEF)} \\ 1 \times \text{Receiver Clock Drift} \end{bmatrix} \tag{1}$$

$$\boldsymbol{\varphi}_{POS,VEL} = \begin{bmatrix} 1 & 0 & 0 & 0 & \Delta t_{GPS} & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & \Delta t_{GPS} & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & \Delta t_{GPS} & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & \Delta t_{GPS} \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \tag{2}$$

$$Q = \begin{bmatrix} \frac{S_P \Delta t_{GPS}{}^3}{3} & 0 & 0 & 0 & \frac{S_P \Delta t_{GPS}{}^2}{2} & 0 & 0 & 0 \\ 0 & \frac{S_P \Delta t_{GPS}{}^3}{3} & 0 & 0 & 0 & \frac{S_P \Delta t_{GPS}{}^2}{2} & 0 & 0 \\ 0 & 0 & \frac{S_P \Delta t_{GPS}{}^3}{3} & 0 & 0 & 0 & \frac{S_P \Delta t_{GPS}{}^2}{2} & 0 \\ 0 & 0 & 0 & S_F \Delta t_{GPS} + \frac{S_G \Delta t_{GPS}{}^3}{3} & 0 & 0 & 0 & \frac{S_G \Delta t_{GPS}{}^2}{2} \\ \frac{S_P \Delta t_{GPS}{}^2}{2} & 0 & 0 & 0 & S_P \Delta t_{GPS} & 0 & 0 & 0 \\ 0 & \frac{S_P \Delta t_{GPS}{}^2}{2} & 0 & 0 & 0 & S_P \Delta t_{GPS} & 0 & 0 \\ 0 & 0 & \frac{S_P \Delta t_{GPS}{}^2}{2} & 0 & 0 & 0 & S_P \Delta t_{GPS} & 0 \\ 0 & 0 & 0 & \frac{S_G \Delta t_{GPS}{}^2}{2} & 0 & 0 & 0 & S_G \Delta t_{GPS} \end{bmatrix}$$

(3)

The EKF measurement equation is given by Eq (4). The measurement passed to the Kalman filter equations is the difference between the actual measurement (pseudoranges and doppler velocity or carrier phase) and the predicted measurement, calculated from the full state vector. The standard EKF prediction and update equations are then given by equations 5 - 9.

$$\mathbf{z}(k) = \mathbf{z}_{meas}(k) - \mathbf{z}_{predict}(k) \tag{4}$$

$$\hat{\mathbf{x}}^{-}(k) = \boldsymbol{\varphi}(k)\hat{\mathbf{x}}^{+}(k-1) \tag{5}$$

$$\mathbf{P}^{-}(k) = \boldsymbol{\varphi}(k)\mathbf{P}^{+}(k-1)\boldsymbol{\varphi}^{T}(k) + \mathbf{Q}(k) \tag{6}$$

$$\mathbf{K}(k) = \mathbf{P}^{-}(k)\mathbf{H}^{T}(k)\left(\mathbf{H}(k)\mathbf{P}^{-}(k)\mathbf{H}^{T}(k) + \mathbf{R}(k)\right)^{-1} \tag{7}$$

$$\hat{\mathbf{x}}^{+}(k) = \hat{\mathbf{x}}^{-}(k) + \mathbf{K}(k)\mathbf{z}(k) \tag{8}$$

$$\mathbf{P}^{+}(k) = \mathbf{P}^{-}(k) - \mathbf{K}(k)\mathbf{H}(k)\mathbf{P}^{-}(k) \tag{9}$$

The GPS design matrix (**H**) and measurement noise matrix (**R**) are formed following Brown (1997) using doppler velocity aiding.

3.3 Inertial Coasting

The ability of a GPS-Inertial system to 'coast' a position solution upon the loss of GPS aiding is a significant advantage. However, the achieving high-reliability coasting performance is not guaranteed. Farrell (1999) highlights the problem of errors introduced by misalignment error and provides an analysis of this problem for aircraft in a holding pattern. It is shown that even with a navigation grade INS, positioning errors can quickly grown to hundreds of meters after only a few turns.

The two dominant error sources in MEMS devices – noise and bias instability - are undergoing continual improvement; however misalignment is often not considered. For the few products that do quote a misalignment, or even cross axis sensitivity, it is in the order or percent whereas navigation grade devices are in the order of parts per million. Therefore, for truly low-cost devices, even if noise and gyro instability can be accounted for, it is unlikely that pure inertial coasting performance can be relied upon to provide any type of useful performance. Temperature induced bias changes are also of concern in aviation, where temperature gradients of up to 5˚C per minute can be experienced, for example during decent to the airport. Abdel-Hamid conducted extensive testing and showed that the statistics of individual sensors, including variation with temperature, are not necessarily the same, and individual calibration needs to be carried out to ensure optimal performance (Abdel-Hamid 2005). This study identifies the need for further understanding and improvement of MEMS device characteristics under different environmental conditions.

3.4 Integrity Architecture

When the GRAS signal is available, it provides an integrity flag for each GPS measurement in view. This integrity flag guarantees that the GPS signal-in-space is correct, and integrity bound are calculated from other parameters transmitted in the GRAS message. Walter (1995) explains that receiver based integrity monitoring is recommended even in the presence of the augmentation signal since the integrity flag does not protect against localised errors which may be introduced to the GPS ranging measurement by the local environment (e.g. interference or multipath), or receiver faults. It is therefore still required to show that the final solution meets the integrity requirements (RTCA 2001).

If the GRAS signal is lost, then an alternative integrity scheme is required to prove the integrated positioning solution integrity. Two primary techniques have emerged to address this problem for integrated navigation systems on airliners – A Solution Separation approach, proposed by Brenner (1995) and Autonomous Integrity Monitored Extrapolation (AIME) proposed by Diesel and Dunn (1996). The former method is somewhat more analytical (Lee and O'Laughlin 2000) and has been chosen as the baseline integrity scheme for this study, despite the fact that it generally produces higher protection levels than its counterpart. Importantly, these techniques have been originally designed for providing integrity in the En-route through to NPA flight phases – not for precision approach since airliners generally rely upon Instrument Landing System (ILS). It is therefore required to carefully validate the application of these approaches to precision approach and landing, paying particular attention to the detection of multiple satellite faults which may affect the positioning accuracy.

The basis of the solution separation approach is finding the disagreement between filter solutions when certain measurements are excluded. In the case of the integrated GPS-Inertial solution, one solution is calculated for each GPS measurement where one measurement is left out, plus a solution calculated using all measurements. The test statistic in the solution separation approach is formed by the difference vectors of each sub solution to the full solution. A threshold is set based on the expected chi-square statistics of the solution.

In this system, the filter solution is an Extended Kalman Filter (EKF), where the system is linearised about the current inertial position estimate. The filter corrections are fed back to the INS, since a MEMS INS will quickly drift from the nominal trajectory. If the filter estimates are inconsistent, then the protection levels may break down since the filter covariance may not bound the true system errors. Therefore extensive consistency validation is required for an operational system.

The solution separation vectors are formed by differencing the outputs of the full filter with each sub filter following the approach presented by Young and McGraw (2003).

$$\boldsymbol{\beta}_j(k) = \hat{\mathbf{x}}_0^+(k) - \hat{\mathbf{x}}_j^+(k) \tag{10}$$

The separation covariance is then calculated from the sub filter covariance

$$\mathbf{B}_j(k) = \mathbf{P}_j^+(k) - \mathbf{P}_0^+(k) \tag{11}$$

Finally, the test statistic is then formed by

$$\lambda_j(k) = \boldsymbol{\beta}_j^T(k) \cdot pinv(\mathbf{B}_j(k)) \cdot \boldsymbol{\beta}_j(k) \tag{12}$$

In Eq. 12 '*pinv*' is the Moore-Penrose generalised inverse. Young and McGraw discuss mechanisms to avoid any numerical instability or inconsistency in the test statistic, which can occur if the solution covariance, **B**, is ill-conditioned. Each 'λ_j' is χ^2 distributed and a test statistic is chosen to satisfy the probability of false alarm and probability of missed detection requirements. The Horizontal Protection Level (HPL) is determined from the solution separation statistics and is discussed by Brenner (1995) and Young and McGraw (2003).

3.5 Summary

This section has proposed a GRAS-Inertial integration scheme for General Aviation aircraft, with protection provided against short period GRAS outages. This architecture is realisable with hardware components which are currently available, and can be assembled in an integrated system at an affordable cost to the G.A. community.

Two questions are posed. Firstly, what are the characteristics of the integration filters when the GRAS differential corrections are lost (i.e. how quickly does the performance degrade)? Secondly, if navigation reverts to GPS-Inertial following the loss of GRAS, can an APV navigation standard still be achieved? The answer to these questions affects the ability of an aircraft to complete an approach following the possible loss of GRAS. The results section of this paper considers these questions.

4 RESULTS

4.1 Loss of GRAS Correction

The short-term loss of the GRAS correction signal is a far more likely scenario than the total loss of GPS signals. This analysis considers the effect of losing the GRAS correction on the GPS-Inertial EKF estimation performance (i.e. filter covariance estimate). After the filter was initialised and allowed to stabilise, additional pseudorange noise was introduced at T=500s to simulate the effect of the loss of the GRAS corrections. The results are shown in Figure 7. In this figure, two different quality INS systems are considered – a high quality INS and a low-quality MEMS based INS. The driving noise, S_P, for the high quality INS is set to $(0.05)^2$ and an order of magnitude worse for the low-quality INS.

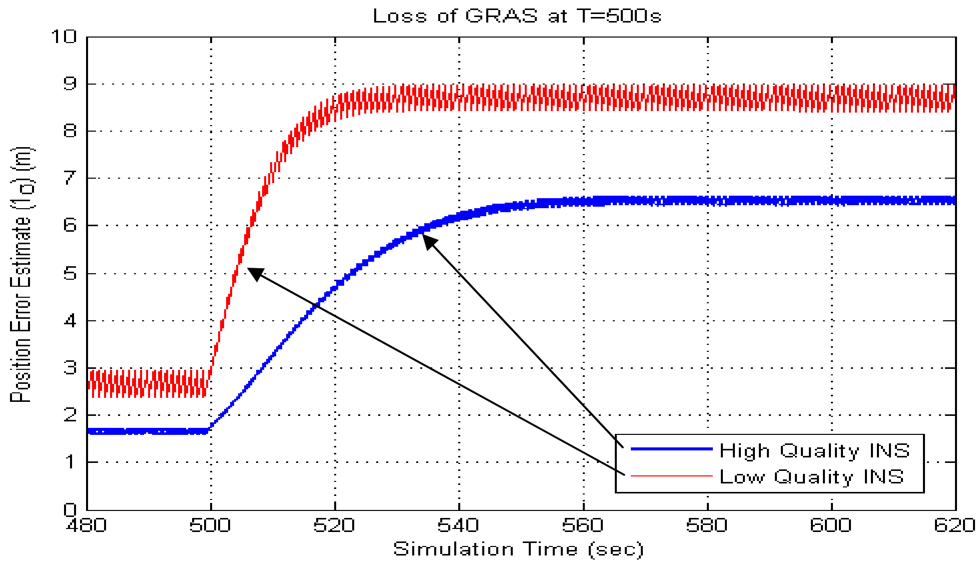

Figure 7: Estimation Error with Loss of GRAS

From Figure 7 it is observed that the navigation uncertainty gracefully degrades upon the loss of the GRAS correction (at t=500sec). During this period, the navigation system is effectively coasting on the inertial sensors, since minimal weighting is being applied to the "now uncertain" GPS signals. The high quality INS simulation degrades to a standard GPS/INS solution in approximately 40-50 seconds, whereas the low-quality INS simulation degrades much more rapidly, in about 10 seconds. As expected, the length of time that the system takes to degrade to a standard GPS/INS solution is determined by the quality of the inertial sensors used in the integrated system. From this result, it is observed that this level of performance falls well-short of the desired 'coasting' time of 120 seconds, however at least the benefit of short period accuracy is obtained. This result also shows that in order to complete the approach, then the integrated GPS-INS navigation solution will need to be relied on following the loss of GRAS, and hence will need to meet the requirements for APV.

This also demonstrates the inherent advantage of the tightly coupled GPS-Inertial integration, where the user can take advantage of the inertial system's measurement to smooth out poor GPS performance for short periods. To take full advantage of this effect, and to ensure filter consistency, the user must have good knowledge of the expected measurement noise. That is, if additional GPS measurement noise goes undetected, this can adversely affect the estimation performance.

4.2 Fault Detection Characteristics

These results investigate the behaviour of the solution separation statistics with varying quality of INS. In Figure 8 the solution separation residual, λ, for each satellite is shown. Ramp failures in the GPS signals in the range 0.1m/s – 2m/s are considered the most difficult to detect (RTCA 2001).

In this example, a ramp fault of 0.1 m/s was introduced on to one satellite measurement (Blue line) and an arbitrary detection threshold set at 10. This example demonstrates the degree to which the faulty measurement is incorporated into the full position solution prior to the fault being detected and excluded. Figure 9 shows the same experiment repeated with a lower quality INS corresponding to a tactical grade MEMS IMU. In this case it is seen that since the INS is of poorer quality, the faulty GPS measurement is incorporated sooner resulting in a faster growth of the residual. This results in the fault being detected sooner, although the position solution is more adversely affected.

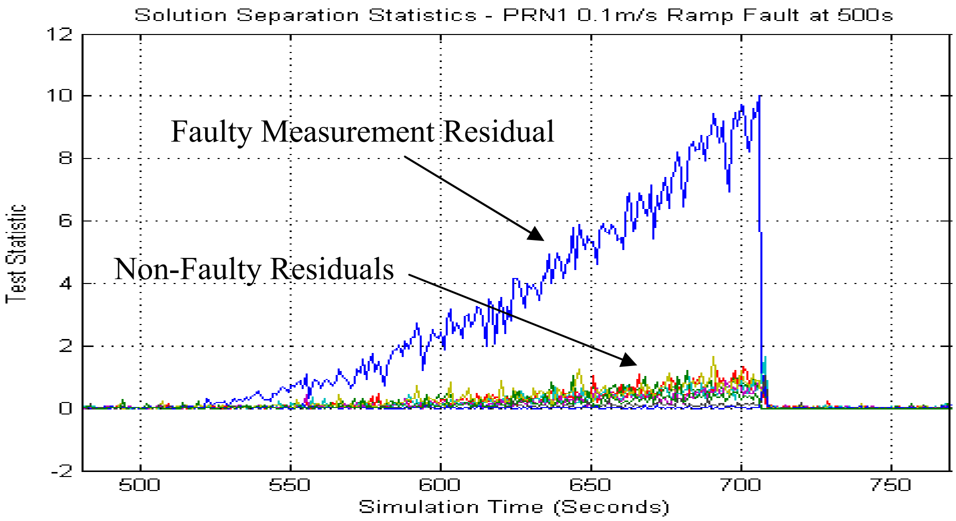

Figure 8: Solution Separation Residuals – High Quality INS

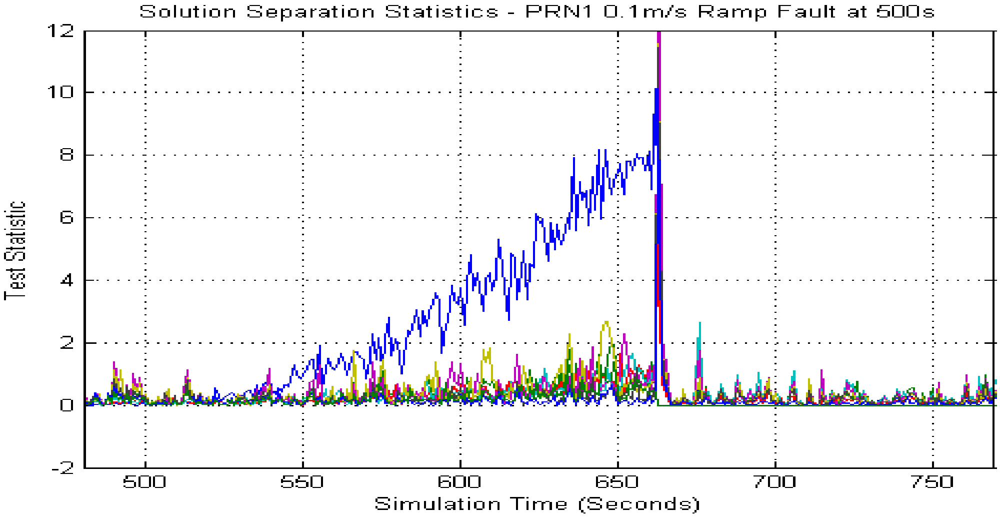

Figure 9: Solution Separation Residuals - Low Quality INS

An interesting observation from these results is that once the faulty measurement is excluded, the solution quickly returns to the nominal estimate, and the effect of the faulty GPS measurement is quickly diminished. This is an important result since it means that if a GPS fault is detected, it will not take long to re-establish a 'healthy' filter estimate, meaning that the approach may be re-attempted.

Figure 10 shows the effect of the introduction of an extremely slowly growing ramp fault at 0.01 m/s.

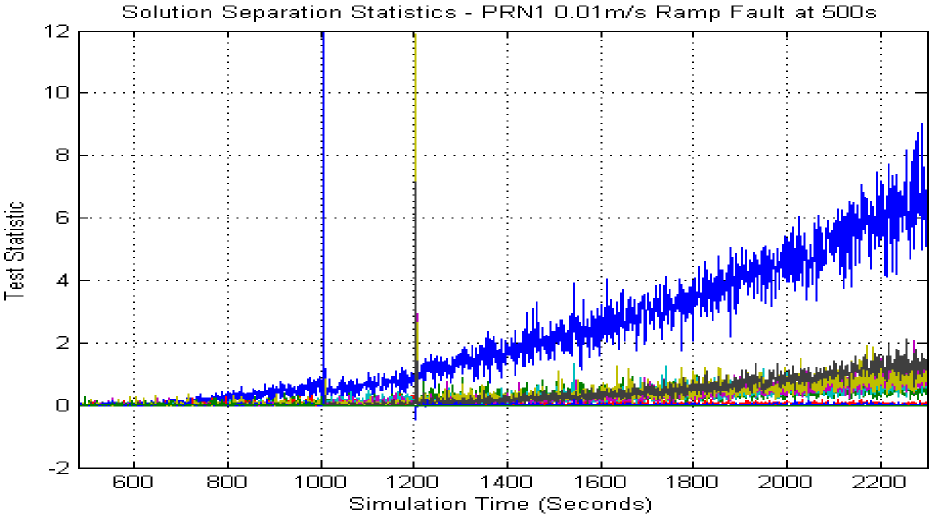

Figure 10: Slowly Growing Ramp Fault

The significance of this result is that a slowly growing ramp fault will not affect the navigation solution significantly in the time frame of interest (120 seconds in this case). That is, the aviation user would expect to become visual with the runway within a few hundred seconds of losing the GRAS augmentation signal. Any slowly growing GPS fault will not significantly affect (i.e exceed the APV requirements) the navigation system accuracy in this relatively short time-frame.

5 CONCLUSIONS

This paper has presented preliminary studies on an integrated GRAS-Inertial navigation system for General Aviation users. A discussion of the advantages and limitations of the GRAS system was presented, and improvements proposed by way of integration with low-cost inertial sensors. A navigation architecture was proposed which is realisable at an affordable cost for GA users. Results were presented which analyse the issues associated with providing integrity for the final seconds of approach and landing at regional aerodromes.

It was shown that a typical scenario for the loss of GRAS would be on decent to a regional airport for an APV approach. For the aerodrome under consideration in this paper, it was shown that the GRAS signal was lost at an altitude of 1000 feet AGL, leaving approximately 120 seconds to run before making a landing.

A complimentary filter was proposed to calculate a high accuracy, high integrity navigation solution using the GRAS, MEMS inertial sensors and dead reckoning sensors. Results were presented which investigated the question of how the filter behaves following the loss of GRAS corrections, and what is the behaviour of the test statistic with varying quality inertial sensors. The results showed that it would be necessary to ensure that the stand alone GPS-Inertial solution (i.e. without GRAS) could meet an APV navigation standard.

The significance of these findings is that the integration of auxiliary sensors with a GRAS augmented GPS can have significant operational, economic and safety benefits to aviation users in regional areas. Further development of the ideas presented in this paper will be conducted for eventual implementation in a prototype system to be flown during GRAS operational trails in 2008.

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