

High Integrity GPS-Based Precision Landing Using Integrity Beacon Pseudolites

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ABSTRACT

The Integrity Beacon Landing System (IBLS), developed and tested at Stanford University, is a GPS-based Category III precision landing system. IBLS is a Kinematic GPS system which uses Integrity Beacon pseudolites placed under the approach path. The large geometry change overflight ensures observability for direct cycle ambiguity resolution. Once cycle position fixes accurate to the centimeter-level are possible. The real-time accuracy has been extensively demonstrated through flight tests in a Piper Dakota, Beech King Air, and Embraer

Although high navigation accuracy is certainly necessary for Category III precision landing, an extremely high level of navigation system integrity, with high continuity of function and rapid response, three basic methods of integrity monitoring have been suggested for GPS: airborne ground-based monitoring of received spacecraft ranging signals and reference station monitoring of airborne sensors for the detection of failures in airborne components, and receiver integrity monitoring (RAIM). The first two methods have a well established history within the context of Instrument Landing System (ILS) architecture, and they will almost certainly also be present in any likely GPS-based architecture. The transition from the familiar (ILS) to the new (GPS) will require a cautious and comprehensive verification. Highly effective RAIM will be of paramount importance in this respect and will be a key segment of the navigation system.

The great precision of carrier phase provides the leverage for an unprecedented level of integrity. Tight detection thresholds may be set without incurring high false alarm rates (provided that sufficient redundant measurements collected during Integrity Beacon overflight ensure the availability of cycle ambiguity resolution). In addition, initial analysis indicates that the availability of cycle ambiguity resolution is approximately 97% for an unaugmented GPS constellation and approaches 100% with a minimal number of geostationary or ground-based ranging sources. Preliminary results indicate that Navigation Performance (RNP) specifications for Category III accuracy, integrity, and continuity can be met by IBLS.

INTRODUCTION

Although both differential code and kinematic carrier phase technology have been proposed to meet various challenges involved in precision approach and landing, the extreme precision of the GPS carrier phase provides the ultimate GPS navigation performance. The most difficult airborne navigation challenge, however, is that of Category III precision landing. The extreme specifications for accuracy, integrity, and continuity demand a new level of GPS navigation system performance. While specific requirements for carrier phase positioning can not be unanimously agreed upon yet, it is likely that a system which can provide the accuracy and flight control accuracy necessary for precision landing, in the order of a few meters must be maintained, continuously, throughout the approach. Whether code-based positioning can provide the necessary performance depends much upon the specific accuracy requirements assumed.

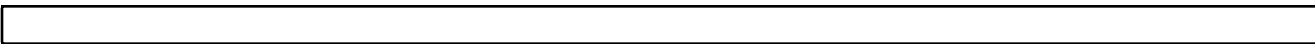
The great benefit of GPS to aviation is its potential to provide seamless navigation from takeoff to landing. The most difficult airborne navigation challenge, however, is that of Category III precision landing. The extreme specifications for accuracy, integrity, and continuity demand a new level of GPS navigation system performance. While specific requirements for carrier phase positioning can not be unanimously agreed upon yet, it is likely that a system which can provide the accuracy and flight control accuracy necessary for precision landing, in the order of a few meters must be maintained, continuously, throughout the approach. Whether code-based positioning can provide the necessary performance depends much upon the specific accuracy requirements assumed.

2. For carrier phase, Navigation System Error (NSE) is nearly a negligible contribution to Total System Error (TSE). This allows maximum margin in Flight Technical Error (FTE) and, therefore, maximum flexibility in flight control system design.
3. The high precision of carrier phase empowers an unprecedented level of Receiver Autonomous Integrity Monitoring (RAIM) performance.

1. Carrier phase measurements leverage RAIM in the sense that extremely tight detection thresholds may be set without incurring unacceptably high false alarm rates, thereby insuring both high integrity and high continuity.
2. The redundant ranging measurements obtained from ground-based pseudolites ensure the availability of high performance RAIM within the IBLB bubble.

The high performance of carrier phase can only be achieved, however, if the integer cycle ambiguities can be accurately resolved for each space vehicle. The Integrity Beacon Landing System (IBLS) concept, conceived and developed at Stanford University is a high integrity solution to real time cycle ambiguity resolution for Category III precision approach (Figures 1a,b). Two (or more) ground-based GPS Integrity Beacon pseudolites provide the basis for explicit estimation of cycle ambiguities during the approach. Integrity Beacons are simple, low power transmitters that broadcast L1 carriers modulated with unused PRN codes. The large geometry change that occurs during pseudolite overflight ensures the observability needed for cycle ambiguity estimation. Once cycle ambiguities have been initialized, real-time centimeter level position fixes are possible. The high accuracy (low NSE) of IBLS has been successfully demonstrated through several hundred navigation test approaches in a Piper Dakota [2,3,4], forty-nine auto-

The aim of the present work is to clarify the various elements of integrity monitoring based on the system and the role of RAIM, availability of kinematic (carrier phase) bubble. The fully three-dimensional nature of GPS along with the availability of velocity output a great potential impact on future navigation/flight control architectures. The foreseeable future, the implementation of precision approach and landing will likely be an Instrument Landing System (ILS)-GPS sensor will function simply to replace the glideslope and localizer) formerly the ILS. In the transition to GPS, the elements of ILS integrity monitoring will



approaches on a Beechcraft King Air [5], and more recently 110 successful automatic landings of a United Airlines Boeing 737 [6]. In previous studies performed at Stanford fundamental observations were made regarding navigation integrity with IBLS:

and used as well. Integrity monitoring is separated into ground monitoring, for the ground segment (glideslope and localizer) failures, and redundant airborne sensor detection of failures in the airborne segment. In replacing ILS with GPS, how entirely new navigation system fault tree considered [9]. In particular, the tradi-

Figure 1a. IBLS Concept (Top View)

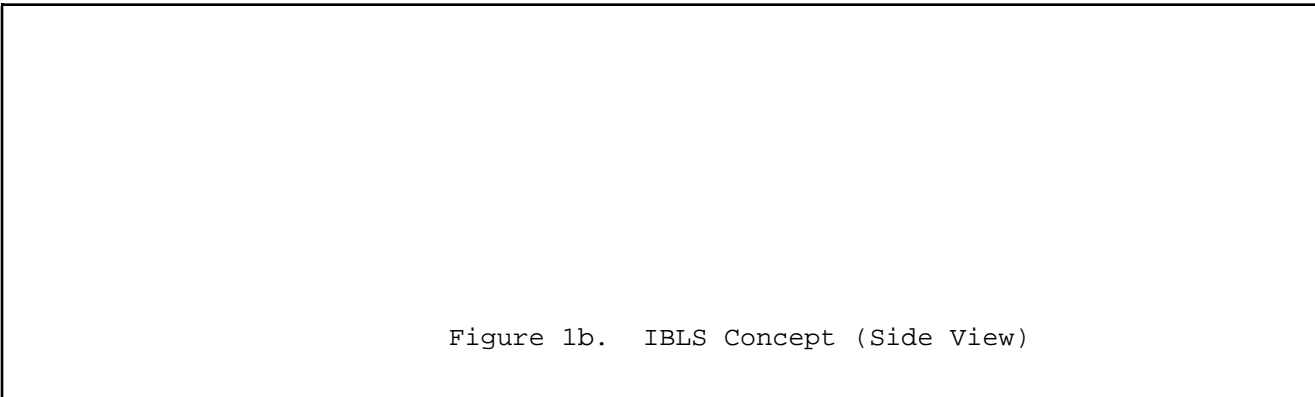
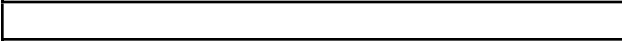


Figure 1b. IBLS Concept (Side View)



layer of protection against airborne segment failures.

system ground and air segments are now Kinematic RAIM, as a final layer of complemented by a space segment. Ground protection against failures in all monitoring and redundant airborne sensors can again be segments. used as the bases for detection of ground and airborne hardware failures, respectively. The effects of ranging errors originating at the spacecraft are usually eliminated due to the very nature of differential positioning. A majority of other space failures can be detected by ground monitoring. In general, the integrity monitoring concepts for ILS are also well suited for, and present in, any GPS-based precision architecture.

In the succession of a new navigation aircraft precision landing, a careful and

Figure 2. Comparison of Kinematic and Code-Based RAIM

approach toward integrity monitoring is highly effective RAIM will be of importance in this respect. RAIM, like airborne sensors, enables the final integrity decision to be made at the aircraft. However, unlike airborne sensors, RAIM has the potential failures originating in all three navigation segments (Table 1). One crucial example found in the recent SV 19 phenomenon, ranging error originating at the spacecraft not have been detectable by ground monitoring depending on the specific receiver architecture involved. This type of failure is, however, with kinematic RAIM. In a more general sense, need for kinematic RAIM arises as a final integrity monitoring against unknown types resulting from the transition from Furthermore, the comprehensive fault capability of kinematic RAIM can be used, architectures, to relax the requirements on monitoring and redundant airborne sensors.

A highly effective integrity monitoring consistent with the expected ILS-implementation would include:

1. A ground monitor station, as a first layer of protection against ground and space segment failures.
2. Redundant airborne sensors, as a first

Table 1. Methods of Integrity Monitoring

INTEGRITY MONITOR	DETECTS FAILURES IN
Ground Monitor	Ground and Space Segments
Redundant Airborne Sensors	Airborne Segment
Kinematic RAIM	Ground, Airborne, and Space Segments

This result is indicated conceptually in Figure 2 by the fact that no part of the normal condition carrier phase ellipse exceeds the solid threshold and no part of the failure carrier phase ellipse lies to the left of the same threshold. (2)

The performance of absolute kinematic RAIM inside the IBL bubble, has been established in previous work [7,8,9]. The designation absolute is appropriate in the sense that it is the integrity of the cycle ambiguity resolution process (to which the subsequent relative kinematic trajectory will be tied) that is being monitored. The availability of absolute kinematic RAIM is ensured by the presence of the Integrity Beacon pseudolites and the resulting large number of redundant measurements collected during bubble passage. The preliminary studies cited above have established through Monte Carlo simulation and flight test, that sub-meter positioning accuracies are protectable with extremely high integrity (low probability of missed detection) and continuity. Given a residual threshold, R, the false probability of false alarm) using absolute kinematic RAIM. (3)

The state estimate, estimate error, and resulting weighted-least-squares solution respectively (4)

An appropriate (5)

above (6)

under normal error conditions (NC) is defined (7)

kinematic RAIM. (8)

After successful cycle ambiguity resolution, relative kinematic RAIM is performed. The modifier relative refers to the integrity monitoring of a kinematic trajectory given a set of resolved cycle ambiguities. Note that the high precision of carrier phase is still available after the bubble exit, although the availability of RAIM may be somewhat degraded if more augmentation, in the form of additional ranging sources, is present. Availability considerations will be discussed in more detail below. The mathematical development of relative kinematic RAIM is presented. (9)

where δx is defined by the relation (10)

At an arbitrary epoch after bubble exit, the observation equation is given by (1)

An assessment of the availability of RAIM performed by Monte Carlo simulation. representative international cities with Ca approaches were selected for the simulation. Francisco, Chicago, New York, London, Amst Frankfurt, and Tokyo. In the simulations, ephemeris was used to propagate the position of 24 Block II GPS space vehicles (SVs). In a pseudolite overflight. The vector represents SV hard failure model [12] was used to simulate the effect of scheduled (stationkeeping maneuver) and unscheduled (hard failures) spacecraft down elevation mask of 7.5 deg was assumed.

where ϕ is the $n \times 1$ vector of single-difference phase measurements (aircraft minus reference) adjusted by the appropriate cycle ambiguity estimates obtained from pseudolite overflight. The vector represents the sum of single-difference phase error and cycle ambiguity resolution error. The i th row of the observation matrix, H ($n \times 4$, $n > 4$), where

e_i is the line-of-sight vector to satellite i . The four-dimensional state vector u consists of simply the raw availability of having at least three elements of the user vector displacement in view. The raw availability results of reference station, x , and a clock bias, τ . Given a set of cycle ambiguity estimates with error covariance matrix, P_{amb} and carrier phase measurement standard deviation For an unaugmented GPS constellation, the time of more satellites are in view is of σ_0 , the effective measurement error is distributed as

To assess potential improvement in the raw availability illustrated in Figure 3, the availability of RAIM, several augmentation schemes were function of the accuracy specification (δ) tested. First, the ranging signals threshold (R), and an integrity buffer geosynchronous Inmarsat WAAS transponders relationship can be roughly expressed as (longitudes 15.5W, 55W, and 179E deg) were considered. A representative hard failure model was applied to these spacecraft as well [12]. As expected, (11) the results show much improved raw availability (99.98%). Second, augmentation from ground-based pseudolites outside the bubble were considered. These RAIM-augmentation pseudolites were assumed for the application of relative kinematic a hard failure probability of 10^{-5} per approach. For the application of relative kinematic Pseudolite azimuths were randomly selected uniformly vertical protection limit for between 0 and 360 deg, while elevations threshold (R) set for $\text{Prob}(\text{FA}) = 10^{-7}$, δ b uniformly between -5 deg and +5 deg. The results requirement of $\text{Prob}(\text{MD}) = 10^{-10}$, again show much improved raw availability carrier positioning error of , and a

Figure 3. Relevant RAIM Parameters

Figure 4. Histogram of Worst Case Mode S (Inmarsat Augmentation, Elev. Mask 7.5 d

Extrapolating the results in Table 2 suggests that raw availability can reach any desired level as the number of space-based or ground-based ranging sources is increased.

system failure probability of 10^{-5} , the availability slope is approximately 10.

Once the raw availability of RAIM is projected, the quality of RAIM geometries must be evaluated. In this respect, the complete spectrum of conceivable fault scenarios must eventually be considered. Although this is a challenging endeavor, such an effort is already underway for the assessment of absolute kinematic RAIM. Preliminary results already published [9] indicate excellent fault detection performance for a number of widely diverse failure modes. In the context of relative kinematic RAIM, the associated fault modes to protect against will likely be somewhat lesser in variety and less frequent in occurrence than those for absolute kinematic RAIM, simply due to the fact that the latter integrity check is performed first. A preliminary determination of geometry quality for relative kinematic RAIM can, however, be made using the traditional assumption of single-channel failures only. With this approximation, RAIM availability is limited on the basis of the worst-case failure mode slope for a given geometry [13]. Specifically, an availability limit can be set such that for a given geometry, if the worst-case slope exceeds the limit, RAIM is declared to be unavailable.

CONCLUSIONS

Table 2. Summary of Relative Kinematic RAIM Availability

AUGMENTATION	RAW AVAILABILITY (%)	TOTAL AVAILABILITY (%)
None	99.4	97
Inmarsat	99.98	99.9
One Pseudolite	99.97	99.9
Two Pseudolites	99.998	99.99

A summary of the key points discussed in this paper is given:

1. Carrier phase measurements are well-suited for the application of precision landing in that the needed NSE can definitely be achieved, the ultimate level of flexibility in the design of future flight control systems is allowed, and an unprecedented level of RAIM performance is possible.
2. Kinematic RAIM will play a crucial role in navigation integrity monitoring for precision landing. It complements existing forms of integrity monitoring and provides a comprehensive final layer of fault detection capability for (ground, air, and space) segments.
3. The availability of absolute kinematic RAIM is ensured by the existence of Integrity Beacon pseudolites and the large number of redundant measurements collected during pseudolite overpass. The availability of relative kinematic RAIM is essentially limited only by the raw availability of having five or more satellites in view. The relative RAIM availability of an unaugmented system is approximately 97%.

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Figure 1a. IBLIS Concept (Top View)



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