High Integrity GPS-Based Precision Landing Using I
Beacon Pseudolites

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ABSTRACT

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

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

The great precision of carrier phase provides the leverage for an unprecedented level tight detection thresholds may be set without incurring high false alarm rates (pr redundant measurements collected during Integrity Beacon overflight ensure the availab ambiguity resolution. In addition, initial analysis indicates that the availability resolution is approximately 97% for an unaugmented GPS constellation and approaches 1 a minimal number of geostationary or ground-based ranging sources. Preliminary result Navigation Performance (RNP) specifications for Category III accuracy, integrity, and IBLS.

INTRODUCTION

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 have not been unanimously agreed upon yet, it is likely that combined navigation and flight control accuracy on the order of a few meters must be maintained, continuity of function preserved for all but one in ten million (10^{-7}) approaches, and loss of integrity limited to one in a billion (10^{-9}) approaches [1].

Although both differential code and kinema phase technology have been proposed to m various challenges involved in precision a landing, the extreme precision of the GPS c provides the ultimate GPS navigation perf Kinematic carrier phase offers three distin over code-based positioning:

1. Carrier phase positioning can unquestionably provide the accuracy necessary for precision landing. Whether code-based positioning can provide the necessary performance depends much upon the specific accuracy requirements assumed.

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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.

The high performance of carrier phase can only be achieved, however, if the integer cycle ambiguities can be accurately resolved for each space vehicle (SV). The Integrity Beacon Landing System (IBLS) 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 autocoupled approaches on a Beechcraft King Air [5], and most recently 110 successful automatic landings on a United Airlines Boeing 737 [6].

In previous studies performed at Stanford [7,8,9], two fundamental observations were made regarding navigation integrity with IBLS:

1. Carrier phase measurements leverage RAIM in the sense that extremely tigh detection thresholds may be set witho incurring unacceptably high false ala rates, thereby insuring both hig integrity and high continuity.
2. The redundant ranging measurements obtained from ground-based pseudolite ensure the availability of high performance RAIM within the IBLS bubble.

The aim of the present work is to clarify t various elements of integrity monitoring based landing system and the role of RAIM, availability of kinematic (carrier phase) bubble exit.

INTEGRITY MONITORING

The fully three-dimensional nature of GPS p along with the availability of velocity out a great potential impact on future navigation/flight control architectures. the foreseeable future, the implementation precision approach and landing will likel form of an Instrument Landing System (ILS)- architecture. In such an implementation, GPS sensor will function simply to repla inputs (glideslope and localizer) formerly the ILS. In the transition to GPS, the elements of ILS integrity monitoring will preserved as well. Integrity monitoring separated into ground monitoring, for the ground segment (glideslope and localizer t failures, and redundant airborne sensor detection of failures in the airborne segment. In replacing ILS with GPS, how entirely new navigation system fault tre considered [9]. In particular, the traditi

Figure 1a. IBLS Concept (Top View)

Figure 1b. IBLS Concept (Side View)

system ground and air segments are now complemented by a space segment. Ground monitoring and redundant airborne sensors can again be 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 segment failures can be detected by ground monitoring. In general, the integrity monitoring concepts established for ILS are also well suited for, and will likely be present in, any GPS-based precision landing architecture.

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

Figure 2. Comparison of Kinematic and Code-Based RAIM

A highly effective integrity monitoring architecture consistent with the expected ILS-lookalike 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 layer of protection against airborn segment failures.
3. Kinematic RAIM, as a final layer of protection against failures in al segments.

KINEMATIC RAIM

The exceptional fault detection perforn
kinematic RAIM is illustrated by compari
traditional code-based RAIM in Figure 2.
conceptual plot of position error versus m
residual. The probability "ellipses" near
represent the case of normal condition err
multipath and receiver thermal noise. F
failure mode, the ellipses will slide up th
axis (as indicated in the figure) a distanc
to the magnitude of the failure. A horiz
drawn to represent the navigation system
requirement. Two hypothetical (vertical)
thresholds set on the measurement residua
shown. The fundamental concept behind RAI
detection is the use of the residual (ar
quantity) as an indicator of excessive po
[10]. Specifically, if the residual e
threshold, a navigation failure is declared

Although there is complete freedom in the s
detection thresholds, false alarms will in
threshold approaches the origin. A thre
however, always be chosen to produce a spec
alarm rate under normal error conditions
Figure 2, thresholds resulting in equivaler
rates are shown for carrier phase ar
measurements as solid and dotted lines, re
Using code measurements with the dotted t
will produce the desired (small) false al
will have a rather high rate of undetecte
position error (i.e., missed detection), as
the darkly shaded portion of the failure co
ellipse. Note that using the solid (ca
threshold with code measurements would decr
number of missed detections but would also
high probability of false alarm, as indic
darkly shaded portion of the normal condi
ellipse. The figure conceptually illustra
severe tradeoff that exists between missed
false alarm when code measurements are usec
accuracy applications. In contrast, wh
measurements are used, this tradeoff is rat
that very low rates of missed detection can
simultaneously with very low rates of fa

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.

The performance of absolute kinematic RAIM, inside the IBLS 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 (low probability of false alarm) using absolute kinematic RAIM.

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 no 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.

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

(1)

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 $(n \times 1)$ vector represents the sum of single-difference phase error and cycle ambiguity resolution error. The ith row of the observation matrix, H ($n \times 4$, $n>4$), is , where e_i is the line-of-sight vector to satellite i. The four-dimensional state vector u consists of the three elements of the user vector displacement from the 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 of σ_ϕ, the effective measurement error is distributed as

(2)

where

(3)

The state estimate, estimate error, and re
resulting weighted-least-squares solution
respectively

(4)

(5)

(6)

where

(7)

Given a residual threshold, R, the false
under normal error conditions (NC) is defin

(8)

For a navigation system accuracy specifica
missed detection event is given by

(9)

where δx is defined by the relation

. (10)

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

The most fundamental measure of RAIM availa
simply the raw availability of having at l
in view. The raw availability results ob
simulation are given in the first column
for an unaugmented GPS constellation, the f
time five of more satellites are in view is

To assess potential improvement in the raw availability of RAIM, several augmentation schemes were also tested. First, the ranging signals from three geosynchronous Inmarsat WAAS transponders (longitudes 15.5W, 55W, and 179E deg) were considered. A representative hard failure model was applied to these spacecraft as well [12]. As expected, 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 to have a hard failure probability of 10^{-5} per approach. Pseudolite azimuths were randomly selected uniformly between 0 and 360 deg, while elevations varied uniformly between -5 deg and +5 deg. The results again show much improved raw availability.

Figure 3. Relevant RAIM Parameters

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.

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.

As illustrated in Figure 3, the availabil
function of the accuracy specification (a
threshold(R), and an integrity buffer
relationship can be roughly expressed as

(11)

For the application of relative kinematic
availability limit is nearly vertical. Spe
a one-meter vertical protection limit for
threshold (R) set for Prob(FA) = 10^{-7}, δ b
integrity requirement of Prob(MD) = 10^{-10},
carrier positioning error of , and a

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

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

A histogram of maximum failure mode slop
vertical position error, obtained from M
simulation, is shown in Figure 4 for th
Inmarsat augmentation. The figure clearly
the large majority of geometries will be a
relative kinematic RAIM. Figure 5 is a p
estimated total RAIM availability as a fun
specified limit slope. For a limit slop
availability is 99.9%. The results for the
constellation and pseudolite augmentation a
the second column of Table 2. Note that e
unaugmented constellation, the total avai
relative kinematic RAIM is roughly 97%.

Figure 5. Availability vs. Limit Slo
(Inmarsat Augmentation, Elev. Mask 7.5 d

noteworthy that, due to the high precisio
phase, the total availability is rather cl
by the raw availability of having five sate

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 is 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 all (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. IBLS Concept (Top View)

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