Precision Landing Tests with Improved Integrity Beacon Pseudolites

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ABSTRACT

Stanford's Integrity Beacon Landing System uses ground-based pseudo-satellite transmitters known as Integrity Beacons to resolve carrier phase ambiguities on final approach, giving IBLS both high integrity and centimeter-level accuracy. This paper discusses two improved Integrity Beacon designs and the results of flight tests with these new beacons.

The original Integrity Beacons were not synchronized to GPS time. The IBLS reference station was required to measure the beacon carrier phase reference information using a direct cable connection to each Integrity Beacon, which proved inconvenient in practice. We therefore constructed a pair of *Autonomous Integrity Beacons*, pseudolites whose transmitted signals are synchronized to GPS satellite signals using the *Omni-Marker* principle invented at Stanford. Flight tests using these beacons showed that IBLS performance was maintained with the reference station in a convenient location some six kilometers from the beacons.

The original Integrity Beacons produced a short-range "bubble" of usable signals. While this was sufficient to demonstrate the IBLS concept, a longer-range beacon would have additional applications. To this end, we constructed an Autonomous Integrity Beacon with a range of greater than four kilometers, using a pulsing scheme similar to that recommended by RTCM-104 to alleviate the near/far problem. Flight tests showed that this long-range beacon provided useful information to IBLS everywhere within its expanded bubble, without blocking satellite reception by IBLS or conventional GPS receivers.

INTRODUCTION

The *Integrity Beacon Landing System* (IBLS) developed at Stanford University exceeds the navigation requirements for Category III "blind" landings [6–8]. The capabilities of this system have been demonstrated in several flight test campaigns [1–4] culminating in 110 successful automatic landings of a Boeing 737 [5].

IBLS uses differential carrier-phase GPS navigation to achieve the high levels of accuracy and integrity required for Category III landings. The IBLS receiver on board the landing aircraft forms differential GPS measurements by comparing the code and carrier signals it receives against an equivalent set of signals received by the IBLS reference station on the ground.

The carrier phase integer ambiguities are resolved as the landing aircraft flies over a set of *Integrity Beacons* placed underneath the approach path. These beacons are

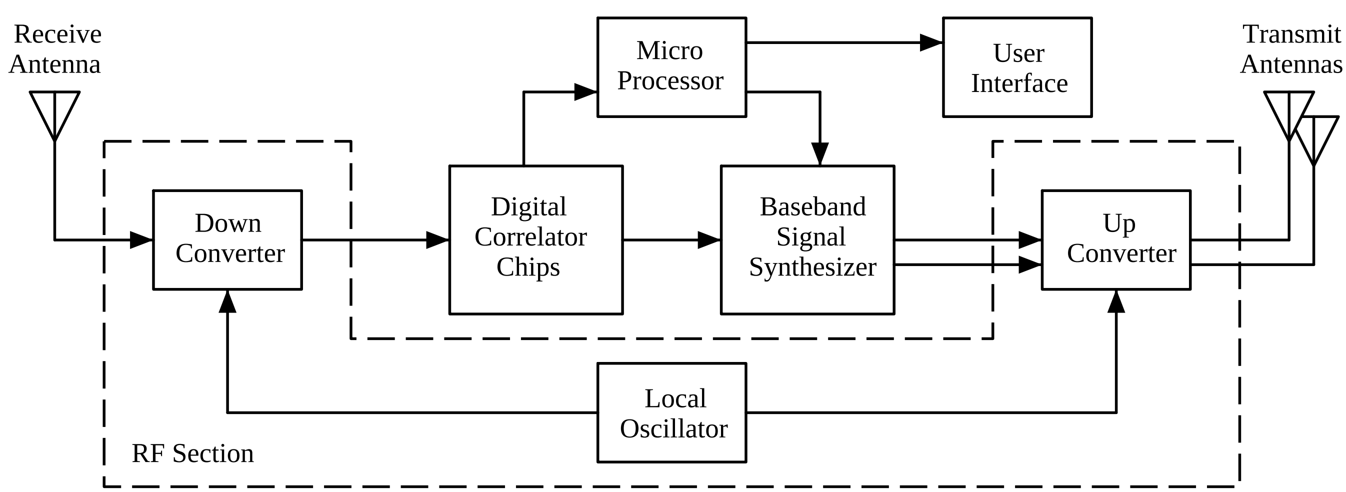

Figure 1: Block Diagram of Autonomous Integrity Beacon

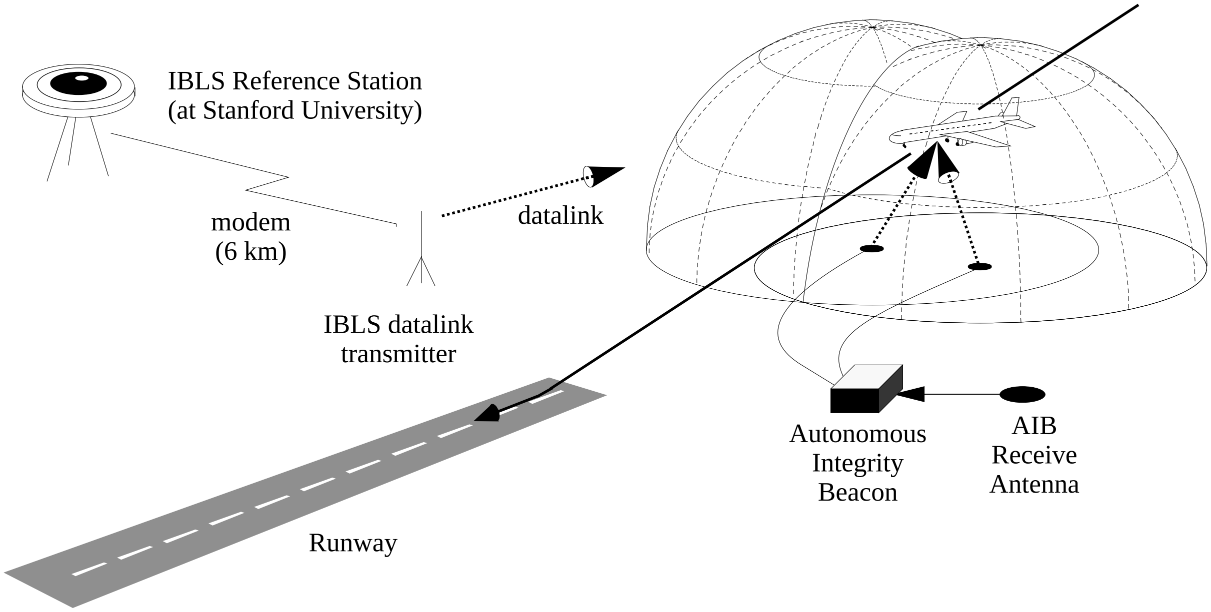

Figure 2: Integrity Beacon Landing System with Autonomous Integrity Beacon

ground-based pseudo-satellite or *pseudolite* transmitters which emit signals very similar to GPS satellite signals. As the aircraft flies over the beacons, its IBLS receiver collects carrier phase data from the satellites and the beacons. The IBLS system assembles this data into a matrix and performs a nonlinear least-squares batch algorithm to determine the integer ambiguities [3, 7].

GPS is a timing-based system which inherently requires precise clocks at each transmitter. However, the Integrity Beacons used in all previous flight tests contained comparatively poor clocks which were available and affordable. The original IBLS system calibrated these clocks by directly connecting the beacon signals to the IBLS reference receiver. The reference receiver measured the beacon signals and the satellite signals simultaneously, which effectively synchronized the beacon transmitters to precise GPS time.

While this approach worked in theory and in initial flight tests, it proved inconvenient as the test program expanded. The requirement for a direct connection forced us to locate the reference station near the beacons under the approach path, a kilometer or more from the runway. This distant location reduced the reliability of the datalink between the reference station and the aircraft. As a result, the datalink absorbed the largest fraction of our installation efforts at each new site.

To solve our datalink problems and move the reference station back near the runway, we needed another way to synchronize the Integrity Beacons to the GPS satellite signals. As necessity is the mother of invention, this necessity gave birth to the *Omni-Marker* concept [2, 9].

The Omni-Marker was invented by Dr. Clark Cohen at Stanford University. It can be thought of as an "electronic mirror" which reflects signals from selected GPS satellites. By comparing the direct and "reflected" satellite signals, a user receiver can compute an extremely precise differential range measurement.

In practice, the Omni-Marker consists of a GPS receiver closely linked to a pseudolite transmitter. The receiver controls the transmitter so that the transmitted signal has the same code phase and carrier phase as the signal received from a satellite. The PRN code of the transmitted signal differs from the satellite signal, so that the user receiver can tell the two signals apart.

AUTONOMOUS INTEGRITY BEACON

The Autonomous Integrity Beacon (AIB) uses the Omni-Marker Principle to synthesize two or more Integrity Beacon signals synchronized to a single GPS satellite. It consists of one receive antenna, two or more transmit antennas, an electronics package, and cables connecting these units (see Figure 1). With an AIB installed, the IBLS reference station can be relocated from the approach path to a more convenient site, chosen to optimize datalink coverage or satellite visibility.

To demonstrate the feasibility of this concept, we designed and constructed an AIB based on a six-channel Trimble TANS receiver. The baseband code and carrier signals we needed to synthesize the beacon signals were available as test outputs on the receiver's digital correlator chips, and the local oscillator signals we needed to drive the transmitter's upconverter were available on the RF circuit board. (This was pure serendipity; in more highly integrated receivers, these signals are generally unavailable.) The baseband carrier signal was taken from the output of a numerically controlled oscillator, which was not designed for this application and contained a great deal of jitter. Unfortunately, this jitter could not be eliminated from the transmitted signal.

We developed a custom circuit board to amplify, upconvert, and filter the transmitted signals. A set of fast RF switches were added to support the pulse tests described later. Bench tests of the breadboard AIB showed that it did indeed generate signals which our IBLS receivers could track. The breadboard AIB consumes approximately 5 watts from a 12-volt supply.

The carrier-phase noise level on the signals transmitted by our breadboard AIB appears to be 3 to 4 times higher that the equivalent noise level on the GPS satellites themselves. This result is undoubtedly due to the carrier jitter present in this breadboard AIB. A purpose-built AIB chipset would generate a much cleaner carrier signal. Nevertheless, this noise level is low enough to support IBLS testing.

AIB FLIGHT TESTS

Our goal for this series of tests was to confirm that IBLS could use signals from a standalone AIB to resolve the carrier phase integer ambiguities correctly, while the IBLS ground station was located some distance away. We installed the breadboard AIB under the approach path at Palo Alto airport, where many of our previous IBLS flight tests were conducted. The AIB reflected a high-elevation satellite (chosen according to the time of each flight test) to form two Integrity Beacon signal "bubbles" which overlapped the approach path. The AIB's transmit power was adjusted so that the signal bubbles were approximately the same size as in earlier IBLS tests.

For all the tests described in this paper, the IBLS reference station remained in our lab at Stanford, over six kilometers away. An IBLS datalink transmitter, placed near the runway, received data from the reference station through a telephone modem (see Figure 2). The IBLS user receiver on board the aircraft was essentially the same as in previous tests, with only small software changes required to accommodate the AIB.

We tested the breadboard AIB during a total of eleven landing approaches over two days. Each day of tests began with a static survey which determined the carrier-phase integers in the IBLS receiver for later comparison. During each approach, the aircraft flew through the AIB signal "bubbles" and then performed a touch-and-go landing. After each pass through the bubbles, the IBLS software processed the bubble data in a batch algorithm to resolve the carrier phase integer ambiguities.

AIB FLIGHT TEST RESULTS

Each bubble pass was successful in that the IBLS realtime integrity checks declared that the batch algorithm had successfully estimated the cycle ambiguity integers. The batch algorithm actually estimates each integer ambiguity as a floating point number. One measure of the quality of the Integrity Beacon data is the difference between each computed number and the known integers determined from the preflight static survey.

A histogram of these differences, for all the integers estimated during this test, is shown in Figure 3. Note that all differences are safely below the threshold of 0.5 which could cause an erroneous cycle ambiguity resolution. We believe that these differences would be even lower were it not for the carrier jitter present in our breadboard AIB. Although a purpose-built AIB would probably give even better results, the success of these tests does show that the Autonomous Integrity Beacon concept is feasible.

PULSED INTEGRITY BEACON

Every pseudolite transmits a "bubble" of usable signals. Outside the radius of that bubble (the *far* radius), the pseudolite's signal is too weak for a GPS receiver to detect. The Integrity Beacons used in IBLS tests until now generated a continuous signal, which meant they had a *near* radius as well. The near radius is the distance at which the pseudolite signal is so strong that it jams the receiver, preventing the receiver from detecting the signals from the GPS satellites. For such a pseudolite, the far radius is roughly ten times the near radius, regardless of the absolute size of either. This ratio is determined by the cross-correlation properties of the PRN codes used for the GPS C/A signals [9].

Increasing the pseudolite's transmitted power increases the far distance at which its signals can be heard, at the cost of increasing the near distance within which all signals are jammed. This *near/far problem* is well-known to GPS researchers.

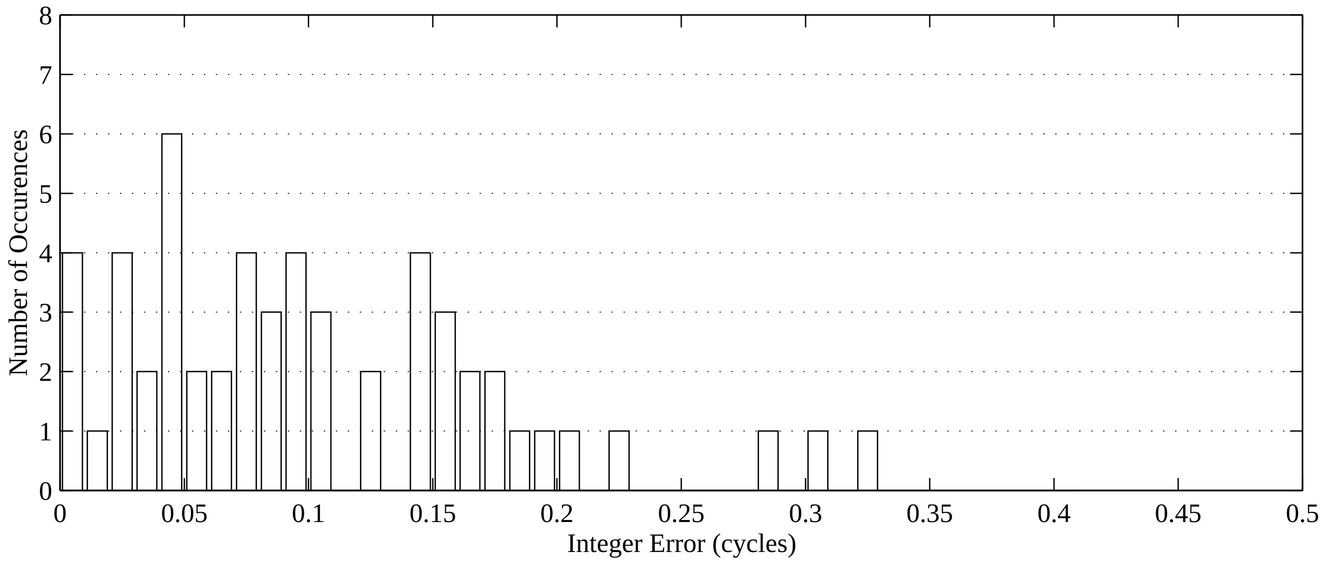

Figure 3: Histogram of Integer Differences during AIB Flight Tests

IBLS avoids the near/far problem by locating the Integrity Beacons below the aircraft's approach path. The beacons' power levels are set so that aircraft flies across the signal bubble, between the near and far radii. The near radius is close enough to the ground that the aircraft will not stray inside it by mistake.

Although the IBLS system design does not require it, there would be advantages to including longer-range pseudolites. An incoming aircraft could check that the Integrity Beacons and its own receivers were working before committing to a bad-weather approach. A long-range beacon could also be used as an additional ranging source to improve the geometry of a navigation solution or the availability of Receiver Autonomous Integrity Monitoring (RAIM).

Before increasing the power of the Integrity Beacons, one must find a way to mitigate the near/far problem. One way to do this is to transmit the beacon signal in short pulses, as suggested by the RTCM-104 committee a decade ago [10]. The user receiver will see only the pseudolite signal for the duration of the pulse; the rest of the time, it will see only the satellite signals. If the pulses are short, perhaps 100 microseconds out of every millisecond epoch, then the GPS satellite signals will be detected with only a slight decrease in signal-to-noise ratio. A sufficiently strong pseudolite signal can be received even if it only transmits ten percent of the time.

To experimentally verify this concept, we built a pulsing device into our Autonomous Integrity Beacon. We discovered in earlier experiments that the transmit pulses must be synchronized to the C/A code epochs; the AIB provided a convenient way to do this, as the epoch pulses were readily available.

The RTCM-104 standard recommends a complex pulse pattern which is comparatively difficult to generate. For our experiments, we chose instead to generate a simple pulse at a fixed time delay from the epoch pulse. To ensure that the unmodified IBLS receiver could track the pulsed signal accurately without cycle slips, we increased the transmit pulse length to 125 microseconds. (A receiver designed to track pulsed signals would function well with pulses 100 microseconds or shorter.)

The pulses were produced by a set of fast PIN-diode switches in the path of the transmitted signal. RTCM-104 recommends that the pulse generator provide at least 100 dB of isolation when the pulse turns off. We used two 60 dB switches in series to provide a theoretical isolation of 120 dB when off.

The AIB output signal level is roughly –30 dBm, and the cables to the transmit antennas attenuate these signals by about 20 dB. We used a 45 dB low-noise amplifier at each transmit antenna to boost the output signals to roughly –5 dBm for the short-range pulsed bubble tests. For the long-range tests, however, we needed +15 dBm or more. However, we did not have enough amplifiers to drive both transmitted signals at this level, so the long-range tests used only a single bubble. (The power levels cited are approximate, as we could not measure them accurately in the field.)

PULSED FLIGHT TESTS

We performed three sets of tests with the pulsed AIB. The first test was intended simply to demonstrate that the concept worked. We placed the pulsed AIB atop a parking structure near our lab on the Stanford campus, with the IBLS reference station and datalink transmitter nearby. Our flight test aircraft maneuvered over the AIB at about 500 meters altitude to measure the characteristics of the pulsed bubble. We plotted in Figure 4 a top view of the points where a valid AIB signal was received. The plot shows that the AIB signal was usable out to about three kilometers.

During these maneuvers, the IBLS software attempted to resolve the carrier phase ambiguities using the AIB, even though the geometry of each solution attempt was quite poor. These solution attempts each converged to an answer, but the answers generally were not precise enough to uniquely identify the integers because of the poor geometry. Each attempt did correctly update the position covariances, however, and after several attempts the solution converged on the correct integers. This process was repeated several times, and post-processing confirmed that the integers were always identified correctly. This result shows the robustness of the IBLS technique.

The second test placed the AIB in the usual IBLS approach and landing configuration with both bubbles pulsed at the highest available power level, about –5 dBm. We performed seven approaches in this configuration. IBLS successfully identified the integers each time, as confirmed by post-processing comparison with a preflight static survey. This result demonstrates that IBLS accuracy was not degraded by the pulsed beacon signals.

For the final test, we left the AIB in the same location but reconfigured the amplifiers to provide the maximum possible output power (about +22 dBm) to a single transmit antenna. Our flight test aircraft flew around the airport traffic pattern to measure the coverage area of the pulsed AIB signal. Figure 5 is a top view of the airport area showing the points where a valid AIB signal was received. Also shown, for reference, are the runway and a circle representing the size of the original, non-pulsed AIB signal bubbles.

The figure shows that the AIB signal was lost in the crosswind turns and, to a lesser extent, in the base turns. During these turns, the beacon receive antenna on the bottom of the aircraft was pointed away from the AIB transmit antenna. We believe the signal was lost in these turns because the fuselage blocked the beacon signal.

The maximum range achieved in this test was approximately 4.5 kilometers. At that point, the aircraft was low on the horizon as seen from the AIB. Both the transmit and receive antennas are patch antennas whose gain patterns fall off sharply at low elevation angles. We believe signals were lost at this point because the antenna patterns provided insufficient gain. We are exploring ways to improve the AIB and aircraft antenna patterns and to mitigate the blockage effect.

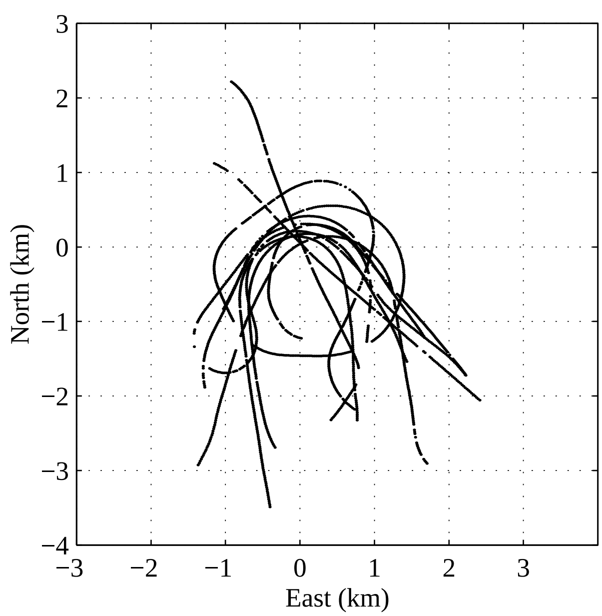

Figure 4: First Pulsed AIB Range Test

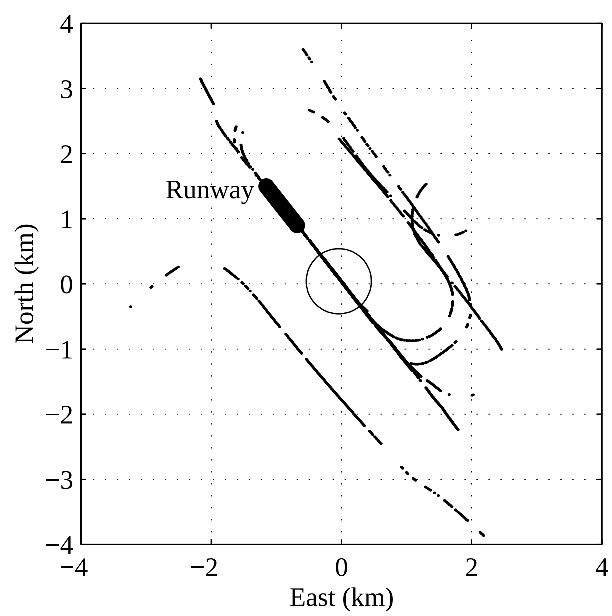

Figure 5: Pulsed AIB Range Test at Airport

INTERFERENCE TESTS

During both flight tests with the high-power pulsed signals, we attempted to measure the "near" radius within which the AIB transmissions jammed the satellite signals in non-cooperating receivers. On the theory that the least expensive receivers would be the least tolerant of interference, we acquired two low-cost handheld receivers from different manufacturers. We set each receiver to display the relative signal strengths for the satellites it was tracking and examined the trends in those displays under different conditions. The results for the two receivers were virtually identical.

As expected, each receiver showed a noticeable but negligible drop in signal strength on each satellite when we turned on the pulsed AIB transmitters. No additional signal degradation was noted until the receivers were brought within about ten meters of one transmit antenna. From a radius of ten meters down to about one meter, the signal strengths slowly declined. At a distance of one meter from the antenna, both receivers were still doing position fixes, although the displayed signal strengths were very low. When the receivers were brought still closer to the antenna, the satellite signals disappeared entirely and both receivers complained of poor satellite visibility.

Theoretically, a pulsed pseudolite transmitter should not jam the satellite constellation at any distance. We believe that the close-in jamming we saw can be attributed to signal leakage through the pulse switches or to thermal noise being amplified when the switches were off. Careful system design could probably reduce the size of this "near" radius, if necessary. If not, locating the beacon transmitters within a ten-meter clear zone should not present operational difficulties.

While a single pulsed pseudolite can be installed so as not to interfere with the GPS satellite signals, it may be more difficult to install multiple pulsed pseudolites in the same vicinity without mutual interference. Two pseudolites which share the same pulse time slot will be subject to the near/far problem with each other. Unless the distances and signal strengths are carefully controlled, as in the placement of IBLS Integrity Beacons, one will be heard and the other will be jammed. One possible solution is to use separate pulse time slots, but the combined duty cycle of all the pulses together cannot exceed 20 or 25 percent without unacceptably degrading the signals from the GPS constellation. Clearly, more research is needed in this area before multiple pulsed pseudolites see widespread use.

CONCLUSION

Our flight test results with a breadboard Autonomous Integrity Beacon show that the AIB concept is feasible. It is no longer necessary to locate the IBLS ground reference station within a cable's length of the Integrity Beacons themselves.

Our flight test results with a pulsed AIB show that a long-range pseudolite is also feasible. Signals from a long-range pseudolite can improve the availability of GPS navigation and Receiver Autonomous Integrity Monitoring, help resolve carrier-phase ambiguities, and carry digital data as well.

Both of these developments remove previous constraints on designs for GPS precision landing systems. However, more research is necessary before multiple long-range pseudolites can be used at the same airport.

ACKNOWLEDGMENTS

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