FINAL REPORT

Local Area Augmentation System Research and Development

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December 2009

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Prepared under:
Federal Aviation Administration Research Cooperative Agreement 98-G-002
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EXECUTIVE SUMMARY

In support of satellite-based navigation technology for aircraft precision approach and landing, research was performed in several technology areas to establish or increase safety. These areas include multipath-limiting antenna design for high-accuracy and high-integrity, antenna group and phase delay estimation, multipath modeling, algorithms for precise velocity estimation and fault detection, GPS/inertial integration techniques, pseudolite transmitter and receiver designs, satellite anomaly monitoring equipment design, transform-domain algorithms for identification of satellite anomalies, interference detection and advanced receiver processing techniques, characterization of tropospheric propagation delays due to nominal conditions and hydrometeors, monitor designs for detection of excessive satellite signal acceleration and satellite cross-correlation errors. Flight data collection was used to verify theoretical results for most of the above research areas.
1.0 INTRODUCTION

In support of satellite-based navigation technology for aircraft precision approach and landing, research was performed in multiple technology areas to establish or increase safety to benefit the flying public. These technology areas are listed below along with the reference numbers for 94 publications that resulted from the research.

1) Differential Global Positioning System Architectures [1-9]
2) Carrier phase processing techniques [10-13]
3) Integrity monitoring algorithms [14]
4) Multipath and obstruction modeling [15-26]
5) GPS/inertial integration [27-47]
6) GPS batch and sequential processing techniques [48-61]
7) Pseudolite architectures [62-63]
8) Interference detection and processing algorithms [64-66]
9) Antenna design [67-75]
10) Tropospheric and ionospheric propagation delays [76-81]
11) Cross-correlation error characterization [82-84]
12) Instrumentation receiver design for anomaly monitoring [85-94]

Each of these research areas are summarized in the following sections.
2.0 DIFFERENTIAL GLOBAL POSITIONING SYSTEM ARCHITECTURES

Investigations were conducted into different architectures that could be used for aircraft precision approach and landing operations. One of the options is the differential carrier-smoothed Course/Acquisition (C/A) code architecture that was flight tested in 1995-1996 and reported in [2]. Figure 2-1 shows the ground station block diagram for this architecture, which forms the basis for some of the investigations documented in this report. A prototype version of the ground station was also maintained at the Ohio University airport in support of local flight tests and numerous anomaly investigations [8]. The architecture consists of three or four reference receiver/antenna combinations that are compared for consistency in the differential corrections processor.

![Figure 2-1. Differential GPS Ground Station Block Diagram [from 2]](image)

The corrections processor is also responsible for the integrity of the corrections that are broadcast to aircraft users. The corrections are transmitted to the user using a very high frequency (VHF) data broadcast transmitter/antenna system. The system, as flight tested, achieved aircraft vertical position accuracies of 0.7 m (95%) and lateral position accuracies of 0.34 m (95%) measured over 45 approaches. Integrity of the broadcast corrections was accomplished by comparing the corrections from the three reference receiver/antenna combinations. The noise on the pseudorange corrections was found to be on the order of 0.15 m (standard deviation). This low level of noise is accomplished by using multipath-limiting antennas for each of the ground antenna systems (see Section 10). It was recognized that the remaining noise is not normally-distributed, which led to several investigations into the propagation of errors as documented in [4-6], where noise and bias type errors are considered separately.
Several areas of further research were identified as a result of the flight tests: monitor design in the presence of errors (see Section 4.0), multipath and obstruction modeling (see Section 5.0), receiver processing techniques (see Section 7.0), interference detection and processing (see Section 8.0), tropospheric and ionospheric propagation effects (see Section 11.0), low transmitted signal power as it relates to cross-correlation errors between satellites (see Section 12.0), and detailed understanding of possible signal anomalies (see sections 9.0 and 13.0). In addition, three architectural components were studied in detail; increased use of carrier phase as described below and in Section 3.0, pseudolite augmentations (see Section 8.0) and integration with inertial measurements to increased robustness (see Section 6.0).

Increased reliance on carrier phase measurements was investigated in [1, 3, 7, 9]. Architectures were designed and tested using only carrier phase measurements in a batch processor. These techniques were found to be very effective, but do require an increased number of satellites for integrity purposes. Figure 2-2 shows an example of the parity vectors used for error detection for seven satellites.

![Parity Vectors for Seven Satellites in a Three-Dimensional Space](from 9)

Decimeter-level accuracies were obtained when at least seven GPS satellites were available to a batch processor. Convergence times were generally on the order of tens of minutes. Faster convergence times were obtained when a combined GPS/Galileo constellation was simulated – typical convergence times were on the order of a few minutes.
Three areas were investigated in support of carrier phase processing techniques. First, phase wrap-up caused by rotating a GPS antenna is documented in [10]; second, detection and correction of cycle slips are documented in [12]; and third, the development of precise GPS velocity algorithms are documented in [11, 13].

Detection of cycle slips and corrections for phase wrap-up are both required to enable the precise velocity algorithms that form the basis for today’s Relative Receiver Autonomous Integrity Monitoring (RRAIM) techniques that increase integrity and reduce time-to-alert requirements. These same velocity algorithms also enable the integration of GPS with inertial navigation where precise GPS velocity significantly improves the calibration of inertial dynamics and attitude (see Section 6.0). The precise GPS velocity algorithm is shown in Figure 3-1. Antenna motion between two measurements is obtained after correction for known geometry changes.

![Figure 3-1. Precise GPS Velocity Algorithm [from 13]](image)

The precise velocity algorithm was prototyped and flight-tested using Ohio University’s Douglas DC-3 and Piper Saratoga research aircraft. From [11, 13], in-flight differences between stand-alone and post-processed differential velocity solutions on the Piper Saratoga were found to be at the 2-4 mm/s level (standard deviation) for horizontal velocity components and 9.7 mm/s (standard deviation) for vertical velocity. Since these differences include noise contributions from three GPS receivers, stand-alone velocity errors are expected to be smaller than the results reported here. This is also indicated by the stand-alone velocity residual biases, which were found to be on the order of 0.1 mm/s or less, while residual standard deviations ranged from 0.8 to 3.2 mm/s for aircraft dynamics of up to 1 g (9.8 m/s²). Flight test dynamics were created by flying constant bank angle turns with varying bank angles up to 45 degrees.

In order to achieve the results provided above, all GPS error sources were evaluated in detail to ensure that the velocity performance can be guaranteed under a wide variety of
operational conditions. Table 3-1 provides a summary of the stand-alone GPS velocity error budget for an update rate of 1 second.

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<th>Velocity Error Source</th>
<th>Typical Velocity Error (for mm/s velocity accuracy)</th>
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<tr>
<td>Changes in orbit errors</td>
<td>bias: negligible; std negligible</td>
</tr>
<tr>
<td>Changes in tropospheric delays</td>
<td>bias: negligible; std negligible (both could be mm/s during unusual tropospheric activity)</td>
</tr>
<tr>
<td>Carrier noise</td>
<td>bias: negligible; std mm/s</td>
</tr>
<tr>
<td>Changes in multipath</td>
<td>bias: negligible; std mm/s</td>
</tr>
<tr>
<td>Stand-alone GPS position errors</td>
<td>position errors &lt; 10 m bias: negligible; std negligible. 10 m &lt; position errors &lt; 50 m: bias mm/s; std negligible</td>
</tr>
<tr>
<td>Changes in ionospheric delays</td>
<td>bias: mm/s (could be cm/s during ionospheric storm activity); std negligible (could be mm/s during ionospheric storm activity)</td>
</tr>
<tr>
<td>Changes in relativistic corrections</td>
<td>bias: mm/s; std mm/s (slowly varying)</td>
</tr>
<tr>
<td>Changes in satellite clock bias</td>
<td>bias: mm/s; std mm/s (slowly varying)</td>
</tr>
<tr>
<td>Uncorrected geometry changes</td>
<td>bias: cm/s - sub-m/s; std cm/s (slowly varying)</td>
</tr>
</tbody>
</table>

An example of stand-alone least mean squares (LMS) velocity residuals for the DC-3 is provided in Figure 3-2 for satellite 22.

Figure 3-2. Example of Stand-Alone RMS Velocity Residuals for Satellite 22 [from 13]

Figure 3-2 shows residuals with a bias of -0.33 mm/s and a standard deviation of 1.5 mm/s.
4.0 INTEGRITY MONITORING ALGORITHMS

Detailed analyses of several proposed integrity monitoring algorithms to be used for differential GPS were conducted. Mathematical models were documented for vertical and lateral protection levels, and analyzed under both fault-free and faulted conditions.

From [14], the performance of the baseline protection level algorithms defined in the "Minimum Aviation System Performance Standards for The Local Area Augmentation System" is verified by both theoretical analysis and computer simulation. It is shown that the underlying assumptions used in calculating the protection levels do not take into account the effect of the ground processing function. A modification to the baseline algorithms was presented. Procedures for verifying the algorithms along with other ground processing functions and/or with any number of reference receivers were demonstrated. Finally, improvements to the algorithms are discussed.

Based on accurate velocity performance (see Section 3.0), research was extended into Relative Receiver Autonomous Integrity Monitoring (RRAIM) techniques that are applicable to all differentially-corrected satellite systems. Figure 4-1 shows the RRAIM concept applied to the Wide Area Augmentation System (WAAS).

Figure 4-1. Relative Receiver Autonomous Integrity Monitoring

Additional integrity algorithm-related research was performed in several areas that are summarized in the following sections. Specifically, Section 5.0 covers multipath and obstruction monitoring; Section 9.0 addresses interference; Section 11.0 investigates tropospheric and ionospheric propagation anomalies; and Section 12.0 discusses cross-correlation errors. Each of these error sources need to be allocated to the fault-free and the faulted portions of the integrity monitoring algorithms.

Monitors were also designed for the detection of excessive satellite acceleration and low signal power errors that can invalidate integrity bounds for precision approach operations. The low signal power condition can increase errors caused by cross-
correlation amongst satellites, which is discussed in Section 12.0. Excessive acceleration can create differential errors due to latency of the correction. Figure 4-2 shows the aircraft range domain error growth due to acceleration present in the satellite signal.

Most of the error is mitigated by the range rate correction, but an error remains that must be monitored by the differential GPS ground station.
5.0  MULTIPATH AND OBSTRUCTION MONITORING

Multipath and obstruction monitoring investigated under the cooperative agreement can be divided into several sub-areas:

1. Theoretical studies of earth-surface-based multipath reflections [15, 16]
2. The impact of tracking loop architectures on multipath error [17]
3. Effects of aircraft overflights of the ground reference antennas [18, 23]
4. Multipath errors caused by electronic components in receiver hardware [19]
5. Dynamic GPS multipath modeling taking into account the antenna environment, the antenna radiation pattern and the receiver tracking loops [20, 22]
6. Multipath mitigation techniques such as polarization steering [21] and spatial diversity [25]
7. The specific scenario where an aircraft in-flight observes multipath signals from the earth’s surface [24, 26]

In [15, 16], a multipath model was developed for a two-layered earth. Multipath parameters were modeled that include amplitude, phase-delay, time-delay, and phase-rate-of-change for a ground-reflected signal. Equipment was constructed to verify the theoretical predictions with actual field data. Figure 5-1 shows one of the measurement configurations for the measurement of both horizontal and vertical components of ground multipath.

![Figure 5-1. Measurement Equipment for Multipath Polarization Measurements [from 15]](image)

An example of how different polarizations are received by an antenna that is located above the reflecting surface is shown in Figure 5-2. The blue dots are from a vertically-polarized receiving antenna, the green dots are from a horizontally-polarized receiving antenna, and the yellow dots belong to a right-hand circularly-polarized (RHCP) receiving antenna. From this particular experiment, it was found that antennas that are
designed to reject left-hand circularly-polarized (LHCP) signals do not reject all of the LHCP multipath if it is accompanied by an RHCP signal that is coherent with the multipath signal. The most multipath rejection that can be expected is 3 dB for the case when the multipath signal is linearly polarized.

It was also found that tracking loop architectures experience different errors depending on the rate-of-change of the multipath error with respect to the direct signal. This became the topic of a detailed investigation into fading multipath errors [17]. An important result of this research was the development of a multipath error envelope for fading multipath as shown in Figure 5-3. The theoretical fading envelope was calculated and verified with bench test results.

During flight tests at Ohio University, loss-of-lock was observed at the reference sites during aircraft overflight of the ground antennas. The assumption was that the aircraft shields the reception of particular satellites when it flies over the antenna. The Ohio University Douglas DC-3 research aircraft was used to verify this effect in a controlled experiment. This aircraft was selected as it has a significant area that can obstruct the line-of-sight signal reception. The aircraft is shown in Figure 5-4.

The experiment was designed for overflights at multiple heights above the antenna, ranging from approx. 100 ft to 500 ft in 100-ft increments. Due to the brief nature of the overflight itself, predicted in the range of 20 to 200 ms, a sampling radio frequency (RF) front-end was used as described in Section 13.0. Data were post-processed to examine several signal parameters, including the acquisition margin and the Doppler frequency shift. The latter was found to be the best indicator of loss-of-lock during the overflight experiment. Strong correlation was found between the signal distortion and the surfaces of the aircraft that interrupted the GPS signal. It was also found that the duration of the
signal interruption is limited and can be managed by separation of the ground antenna locations to avoid loss of lock on more than one reference antenna.

![Figure 5-3. Fading Multipath Error Envelope [from 17]](image)

An example of an overflight scenario is shown in Figure 5-5. The left graph shows the Doppler frequency as a function of time and shows interruptions due to the starboard wing and the starboard aileron of the DC-3 during the overflight. The graph on the right
shows the satellite line-of-sight for satellite 10 calculated from the true aircraft position and the known satellite position. In the right graph, the aircraft is kept at the same location and the line-of-sight point that intersects with the plane of the aircraft goes from left to right. The circles indicate where a NovAtel GPS receiver returned measurements at a 1-Hz update rate. After the aircraft overflew the reference antenna, satellite 10 was declared lost by the GPS receiver.

![Figure 5-5. Example of Overflight Loss-of-Lock](image)

Another fundamental component of multipath consists of reflections caused by receiver hardware. Initially, it was thought that these reflections are common to all satellites, but depending on the path delays in the receiver, hardware-induced errors can be different for different satellites as documented in [19].

Based on the theoretical phenomena studied, electromagnetic models were developed that can be used for the siting and evaluation of multipath errors for aircraft precision approach operations [20, 22]. These models are needed for the overall safety proof of differential GPS architectures. The multipath model takes into account the antenna environment, the antenna radiation pattern and the receiver tracking loops. Throughout the research, the model was used to verify numerous observed phenomena, including unanticipated “ringing” in the pseudorange corrections due to poles and towers. The model was also verified using several field experiments. Examples of some of the objects that the multipath model is capable of handling are shown in Figure 5-6. On the left is a somewhat complex control tower structure located at Anoka County Airport. On the right is a hemi-cap cylinder that was used to verify the multipath signature created by such an object, which can be commonly found around an airport in the form of fuel tanks or aircraft fuselages. An example of detailed model verification is shown in Figure 5-7, which shows building 301 at the WJHTC. A dBsystems 200-MLA stacked dipole array antenna was located in front of the building. The modeled scenario is shown on the right side of Figure 5-7. The hangar building was modeled as a large...
rectangular block consisting of 6 faces, 12 right-angled edges, and 8 vertices. In total, 127 different multipath components are considered.

Figure 5-6. Examples of Objects that are Modeled in the Multipath Model

Figure 5-7. View of Building 301 at the FAA WJHTC (left) and Computer Model Representation (right) [from 22]

For this scenario, a setting pass of satellite 13 was selected to evaluate the multipath that would be caused by the hangar building. The model was used to predict the difference between the L1 frequency (1575.42 MHz) C/A code and integrated carrier phase observations. These same observables are also readily available from a NovAtel Millenium GPS receiver used for the model verification. An example of the unfiltered difference between the C/A code and integrated carrier phase (also referred to as code-minus-carrier or CMC) is shown in Figure 5-8, where the building was modeled as concrete with a dielectric ground plane. From Figure 5-8, a remarkable agreement is observed between the measured (red circles) and modeled (blue solid line) multipath error signatures. It is important to note that the envelope of the error trace is more important than the actual phasing for the purpose of safety evaluations. The reason for
this is that a minor change in geometry, on the order of a few cm, can result in a major change in the phasing of the multipath error. This is because of the GPS L1 wavelength of 19 cm, which can change the phase of the multipath error by 180 degrees for a geometry change of half a wavelength.

![Figure 5-8. Unfiltered CMC for large-object model validation scenario with concrete building, dielectric ground, and setting satellite (PRN 13) [from 22]](image)

Additional aspects of multipath that were addressed during the research were mitigation techniques in addition to siting and antenna design. Two techniques were investigated in detail: polarization steering [21, 25] and spatial diversity [25]. These methods are not currently in use, but show promise for future GPS antenna/receiver architectures.

In addition to ground multipath observed at a ground reference antenna, investigations were also completed into multipath observed at the aircraft antenna due to the earth’s surface. This research was initiated in an attempt to explain persistent bias-like errors observed during final approach portions of flight tests. Figure 5-9 shows the multipath scenario. Due to the aircraft’s downward vertical velocity, multipath fading is generated that could result in persistent biases (see Figure 5-3). Extensive modeling was performed to predict the biases as well as actual flight test experiments to verify the model results [24, 26]. One of the flight experiments was conducted at Middle Bass Island, Ohio using straight-in approaches to airport 3T7. Both ground and fresh water reflections were observed during the flight tests. Antennas were installed on the top of the DC-3 fuselage (RHCP) and the bottom of the DC-3 fuselage (LHCP). The bottom antenna was installed to measure the surface reflection directly for model verification. A detection algorithm was designed to provide estimates of multipath strength and fading frequency. Actual aircraft trajectory data were used to model the multipath errors using a high-fidelity model. Two receivers were simulated as examples: the first receiver is a wide band receiver with 0.1 chip correlator spacing, while the second receiver is narrow band with 1.0 chip correlator spacing. It was found that both receivers experience biases
in the carrier-smoothed pseudoranges of up to 0.3 m. The wide band receiver incurred peak errors at fading frequencies of 5 and 20 Hz, while the narrow band receiver’s maximum error occurred at a fading frequency of 30 Hz.

Figure 5-9. Multipath Scenario for Aircraft on Final Approach over Water

Figure 5-10. Aerial View of Middle Bass Island, Ohio

The narrow band receiver was implemented using a RF data collection system that sampled a 2-MHz bandwidth of the L1 signal at 5 megasamples per second.
GPS/Inertial integration algorithms were researched along five avenues:

- Increased GPS robustness through integration at the cm-level to enable coherent GPS signal integration up to several seconds [28, 31, 41-43, 47]
- Continuity during final approach after calibration of an inertial navigation system (INS) with a differential GPS aircraft position trajectory [44]
- Continuity during aircraft surface movement operations [32]
- Inertial error characterization for flight safety applications [29, 30, 33]
- Fundamental algorithm development to enhance GPS/Inertial integration [27, 34-40, 45, 46]

An integrated GPS/low-cost inertial system was developed and implemented to re-acquire and coherently track GPS signals at the 15 dB-Hz level. The system is capable of long integration up to approx. 1 second without knowledge of the GPS navigation data bits. Carrier phase noise remains at the cm-level for the 15 dB-Hz signal tracking. Flight tests were conducted to demonstrate the integrated system. A patent covering the technology was awarded in Great Britain in 2009, while applications in the United States and Canada are pending (GB patent 2435755B, US application 11/233,531). Figure 6-1 shows the high-level block diagram of the GPS/inertial integration mechanization.

The sampled GPS signals are compensated for aircraft dynamics using the inertial velocity solution. Once the GPS code and carrier phase measurements are obtained, they are used, in turn, to calibrate the drift in the inertial velocity solution. Although the concept is straightforward, implementation of this technique requires the introduction of...
multiple new technologies. First, the inertial velocities and the GPS measurements must agree at the cm-level to enable coherent tracking of the GPS signals. Next, lever arm corrections between the location of the gyroscope/accelerometer triad and the GPS antennas must be implemented with cm-level accuracy. Third, GPS navigation data must be processed in such a way that knowledge of the navigation data bits is not required. It is noted that traditional “wipe-off” techniques using known data bits are not always successful as there are data bits in the GPS message that can change without advance notice. If an integration technique would rely on known data bits, then the robustness of the solution would be questionable due to the unknown bit changes. Additional design considerations are documented in [28, 31, 41-43, 47].

Figure 6-2 shows an example of in-flight signal acquisition at low carrier-to-noise ratios of 15 and 17 dB-Hz. Most existing GPS receivers do not reliably track GPS signals that are below 32 dB-Hz.

![Examples of Acquisition Plots (1.2-s signal integration)](image)

In support of precision approach continuity, inertial coasting after loss-of-GPS guidance was considered for the scenario of Figure 6-3. To analyze the contribution of Local Area Augmentation System (LAAS) decorrelation errors, the scenario of Figure 6-3 was simulated considering a total loss of GPS guidance after the CAT I decision height through aircraft rollout completion. The inertial error model considered gyro drift (0.01 deg/hr), gyro noise (0.001 deg/square root hr), gyro misalignment (10 microradians), accelerometer bias (10 micro-g), gravity deflections (5 arcsec rms with a correlation distance of 20 nmi) and gravity anomalies (25 milli-g with a correlation distance of 20 nmi). A dynamic-state Kalman filter was implemented to calibrate the INS velocity solution. The position state was initialized with the last valid LAAS solution. It was found that the inertial azimuth alignment serves as the dominant inertial error source for this particular scenario.
In order to understand inertial measurement unit (IMU) sensor errors as they affect flight safety, detailed analyses were conducted to characterize inertial errors, especially for non-navigation-grade inertial sensors [29, 30, 33]. A four-degrees-of-freedom calibration platform was constructed to separate IMU error sources. The platform is depicted in Figure 6-4. Pitch and roll angles can be controlled between -45 and +45 degrees, while the heading angle has no limitations. Up and down motion of several inches can also be implemented simultaneously with the angle variations.

The benefit of the continuous heading angle motion is that multiple errors can be made observable over time. An example of this is shown in Figure 6-5, where a Systron...
Donner MotionPack™ was analyzed. After removal of the gyro bias contribution, the next largest error contributor is the scale-factor, followed by misalignment error. For the accelerometers, the bias error dominates, closely followed by the scale-factor error.

![Figure 6-5. Separation of Inertial Measurement Unit Error Sources](image)

The results obtained using the motion platform are crucial for the understanding of integrity aspects and specifications required for IMUs when applied to aviation applications.

In addition to the above inertial integration studies, ten publications were generated on fundamental algorithm development to enhance GPS/Inertial integration [27, 34-40, 45, 46]. Key results include the implementation of inertial algorithms in the frequency domain to enhance the observability of inertial errors, batch processing techniques to improve the robustness of GPS/inertial integration, separation of position and dynamic models in the Kalman filter to dramatically improve short-term GPS/inertial integration. The separation or segmentation approach is illustrated in Figure 6-6. GPS C/A code and carrier phase measurements are processed separately to avoid introduction of the code noise into the dynamics estimation. Once a GPS receiver is designed to achieve state-of-the-art carrier phase tracking performance, the carrier phase measurements are used directly to estimate the dynamics. The C/A code pseudorange measurements are not used in the dynamics estimator as these would introduce noise that is well in excess of that available from the carrier phase. For example, typical C/A code noise is on the order of 1 m (for a 1-second update rate), while the carrier phase noise is on the order of mm (for a 1-second update rate). The benefit of using the carrier phase translates into more precise attitude and heading determination. In fact, test results demonstrated pitch and roll angle performance at the 0.3 milliradian (rms) level, which is consistent with that of navigation-grade inertial systems [35].
Figure 6-6. Segmented GPS/Inertial Integration
Both traditional GPS sequential as well as batch processing techniques were analyzed in terms of performance and observability of anomalous behavior. Many of the processing techniques developed were applied to GPS anomalous event monitoring (see Section 13.0). Figure 7-1 shows the block diagram of one of the final joint time/frequency domain processing techniques developed for robust and accurate navigation [56]. A batch processing acquisition is implemented using Fast Fourier Transforms (FFT) in the frequency domain. Based on the course results from the FTT, a sequential processor is directed to obtain high-resolution code phase measurements. It is noted that the carrier phase measurements from the batch processor are already highly accurate and don’t need to be refined using sequential processing. The benefit of the course FFT processing is that the entire signal space can be searched and monitored to ensure acquisition and tracking of the desired signals.

Batch processing is implemented as an open-loop processing technique, and in more recent publications, the batch processor is referred to as an open-loop batch processing approach [61]. Open-loop batch processing was found to have three distinct advantages compared to closed-loop processing: 1) Improved signal observability; 2) Parallel computation, especially for multi-bit processing implementations; and 3) Improved tracking robustness.

Batch processing techniques are investigated in detail in [48, 49, 52, 53, 57, 58, 60]. The implementation of batch processing in Field-Programmable Gate Array (FPGA) hardware is discussed in [50, 51]. A carrier-to-noise ratio (CNR) estimator for batch processing is developed in [55]. A novel acquisition technique based on the repeatability of successive code phase measurements is provided in [59].
technique is especially useful for robust signal acquisition, as the probability of detection does not rely on the noise distribution or the CNR of the received signals. If the distribution of the noise is known, then this method also provides an estimate of the CNR.

Batch processing techniques are still in the early stages of acceptance, mostly because of demanding processing requirements. However, open-loop batch processing techniques have significant advantages over closed-loop sequential processing techniques and are expected to become common place now that a significant portion of the basic research underlying batch processing has been completed. For current research applications, open-loop batch processing is necessary for anomaly monitoring (see Section 13.0), robust GPS/inertial integration (see Section 6.0) and interference processing (see Section 9.0).
8.0 PSEUDOLITE ARCHITECTURES

Pseudolite (ground-based satellite) architectures were investigated to increase the availability of GNSS to mitigate potential lack of availability for aircraft precision approach and landing operations. A prototype airport pseudolite (APL) was designed and implemented to operate in conjunction with a differential GPS ground station [62, 63]. The block diagram of the ground system for the APL is shown in Figure 8-1 [63]. The APL transmit antenna is similar to the LAAS Ground Facility (LGF) reception antenna in terms of multipath-limiting design. Also, the APL signals are transmitted into the LGF reception antennas such that the signals can be synchronized to the LGF corrections to within approximately 0.1 m.

![Figure 8-1. Block Diagram of APL Ground System [from 63]](image)

The aircraft component uses different antenna configurations, including antennas mounted on top of the DC-3 fuselage and also in the nose cone, as shown in Figure 8-2, to analyze signal propagation effects around the DC-3 fuselage.

![Figure 8-2. Pseudolite Reception Antenna Mounted in DC-3 Nose Cone](image)
A detailed block diagram of one particular aircraft configuration is shown in Figure 8-3 [63].

Key challenges consisted of multipath, near-far problems, and synchronization to GPS. Multipath was addressed by using multipath-limiting dipole-array antennas (see Section 10.0) in combination with a wide-band signal structure. Synchronization to GPS was addressed by reception of the APL signals in the ground reference station that also receives the GPS satellite signals. Finally, the near-far problems were addressed through power management at the aircraft. Figure 8-3 shows the APL pseudorange errors before (left graph) and after power management (right graph). As can be observed from this figure, the unfiltered APL ranging errors reduced from 3 m to approximately 0.5 m after power management was implemented.

The pseudolite architecture was flight-tested and found to be feasible to enhance availability of reduced constellation geometries.
9.0 INTERFERENCE DETECTION AND PROCESSING ALGORITHMS

The effects of continuous wave interference were investigated in [64], while advanced detection techniques were researched in [65, 66]. Test statistics were developed for interference detection in the time and frequency domains. A significant benefit was obtained by using software-defined radio techniques to monitor for interference. The techniques were evaluated using Ohio University’s shielded anechoic chamber where broadcast GPS signals were radiated inside the chamber along with interference signals. The equipment configuration is shown in Figure 9-1.

A GPS antenna was mounted on a tripod outside the building and the signal was amplified and routed to the shielded anechoic chamber where it was transmitted toward the receiving antenna. At the same time, a controlled interference signal was also transmitted in the chamber. A spectrum analyzer was used to monitor the signal strength and a RF data collection system was used to store the RF samples for later analysis using a variety of processing techniques.

One of the most promising algorithms that was implemented consisted of a large sample T-test in combination with a Berry-Esseen overbound to ensure that desired probabilities of false alarm and missed detection could be quantified. Figure 9-2 shows an example of interference detection of a Continuous Wave (CW) signal that is well below the noise floor. Shown is a time sequence in ms (0 to 10,000), where the CW signal is turned-on in the middle of the data collection interval. An example of broadband interference
detection is shown in Figure 9-3. The level of interference was set at -76 dBm, which is 23.5 dB below the level at which GPS receivers must operate properly.

Figure 9-2. Example of Continuous Wave Detection in the Frequency Domain

Figure 9-3. Example of Broadband Interference Detection in the Time Domain
10.0 ANTENNA DESIGNS

Multipath-limiting GPS antennas were designed and tested for high-accuracy, high-integrity aviation applications and Very-High Frequency (VHF) antennas were designed and tested for broadcast of differential GPS data. This research led to GPS and VHF antennas that were subsequently built by industry for the Local Area Augmentation System (LAAS).

One example of a high-performance reception antenna is the Integrated Multipath-Limiting Antenna (IMLA) shown in Figure 10-1.

![Figure 10-1. Integrated Multipath-Limiting Antenna](image)

This antenna was designed using multiple design iterations and tested using a variety of test methods. One test method is shown in Figure 10-2, where the dipole array antenna was measured precisely in Ohio State University’s Compact Antenna Range, operated by the Electro-Science Laboratory. This antenna range enables highly-precise phase measurements with noise levels at the 0.01 degree level, which enables accurate verification of the antenna with respect to the design parameters. Another series of tests consisted of environmental experiments to verify that the antenna characteristics did not change as a function of temperature and humidity. These tests are illustrated in Figure 10-3. The dipole array antenna was heated at different humidity levels over periods of time of several days to ensure that the measurements repeat over a wide range of conditions.

The dipole array antennas were designed to function as either reception or transmission antennas. The transmission feature was used for the pseudolite research described in Section 8.0. Key features of the dipole array antenna are its sharp roll-off in gain at the horizon to mitigate ground multipath, in combination with a high-gain starting at 3 degrees above the horizon to track low-elevation satellites and to broadcast signals to aircraft on a 3-degree approach glidepath.
In addition to the actual antenna design, much effort was dedicated to the understanding of antenna phase and group delay characteristics which turned out to be a dominant error source for differential GPS systems [67, 72, 75]. These investigations started with observed antenna biases on the DC-3 research aircraft when the reception antenna close to the VHF “V-antenna” was used. This configuration is shown in Figure 10-4. Large angle-of-arrival-dependent group delay errors were observed on the order of 1 m. Similar errors can also be generated by the antenna itself and caused numerous design iterations to mitigate this error category to below 0.1 m.
VHF antenna designs started with a single-bay elliptically-polarized design shown on the right of Figure 10-5, followed by a three-bay design to increase signal coverage at low altitude, including during aircraft rollout. The three-bay VHF antenna is shown on the left in Figure 10-5. Additional details on the VHF design considerations can be found in [68-70, 73].
11.0 TROPOSPHERIC AND IONOSPHERIC PROPAGATION DELAYS

For single-frequency GPS users, the troposphere is the second-largest error source, while it dominates for dual-frequency GPS users who can correct for most of the ionospheric delay error. In addition, tropospheric errors are different in different locations; an example of tropospheric error decorrelation over a 9 nmi baseline is shown in Figure 11-1. During a weather event, range errors between the two sites can be different by up to 0.32 meters.

![Figure 11-1. Example of Tropospheric Decorrelation Errors](image)

Tropospheric decorrelation errors were studied extensively as documented in [76-80]. As part of the study, a dedicated 5-km baseline data collection system was developed to verify the theoretical models. This system is shown in Figure 11-2 and does not only collect dual-frequency GPS data at both locations, but also pressure, humidity, temperature an rainfall parameters at both sites. In addition, tropospheric decorrelation was characterized over different baseline lengths and in different geographical areas using data from existing reference stations throughout the US.

The results from this research have been applied to the integrity design of the LAAS and are currently also considered for future Wide Area Augmentation System (WAAS) architectures. Results from this research are applicable to all GPS users.

Ionospheric studies focused on the determination of the size and magnitude of higher-order ionospheric delays.
A dual-frequency correction removes the second-order ionospheric delay error, but higher-order terms that are a function of frequency-tripled and frequency-quadrupled are not removed. To study these higher-order contributions, radar data from the Arecibo observatory in Puerto Rico were used to measure these effects as illustrated in Figure 11-3 [81].
12.0 CROSS-CORRELATION ERROR CHARACTERIZATION

Cross-correlation errors are generally small, but under the right circumstances, these errors can be quite large as illustrated in Figure 12-1. For this figure, two satellites were generated by a radio frequency GPS simulator. The relative received power difference between the two satellites was set at 6 dB, while the carrier smoothing was limited to 1 second. For a correlator spacing of 0.5 chip, the expected error can reach 19.2 m. Due to slightly changing Dopplers between the two satellites, the actual error reached approximately 12 m. These type of cross-correlation errors were analyzed in detail and documented in [82-84].

![Figure 12-1. Cross Correlation Errors on C/A Code Measurements](image)

Although cross correlation affects both the reference and airborne receivers, the two receivers do not share the same code phase and carrier frequency offsets between interfering satellites. As a result, the differential correction does not correct for cross correlation and the level of cross correlation errors must be monitored by the reference receiver. Worst case cross correlation errors were calculated as a function of relative received signal strength, relative Doppler frequency and relative Doppler rate of change frequency. For example, Figure 12-2 shows the relationships between Doppler frequency offset and relative signal strength difference for a maximum cross correlation error of 0.2 m. For Doppler frequency offset below 1 Hz, the maximum signal strength difference is 7 dB to limit the error on the weaker satellite to a maximum of 0.2 m. At higher Doppler frequency offset, the signal strength difference can be much larger as the cross correlation error is modulated by the difference in the received Doppler frequencies. The theoretical results in Figure 12-2 were verified with hardware simulations. Although the occurrence of the maximum error is not generally realized, the probability of this error is sufficiently large that it cannot be ignored. Factors that are simulated to model the cross-correlation error include relative received signal strength, relative Doppler frequency shift (i.e. fading frequency), relative change in Doppler frequency shift, relative code phase shift, relative rate of change of code phase shift, navigation data bits on the two satellites, relative delay between the navigation data bits from the two satellites, smoothing time constant and receiver correlator type.
Figure 12-2. Relationship between Relative Signal Strength and Doppler Offset to Limit Cross Correlation Error to 0.2 m after Smoothing [from 84]

The results from this research were used to develop requirements for low signal power monitoring in the LAAS and to develop error budgets for GPS-based architectures.
13.0 INSTRUMENTATION RECEIVER DESIGN FOR ANOMALY MONITORING

The development of the GPS Anomalous Event Monitor (GAEM) took place over approximately a ten-year time period [85-94]. The later hardware development is also referred to as the Transform-Domain Instrumentation GPS Receiver (TRIGR) that has been used to identify GPS anomalies, interference detection and processing techniques as well as GPS receiver architecture designs. In addition, two monitoring systems are now installed at the William J. Hughes Technical Center (WJHTC) and Ohio University to continuously monitor the integrity of the GPS signals. These systems are crucial to characterize GPS anomalies as they affect high-integrity aviation systems. Recent anomalies have included ionospheric scintillation, aircraft overflights, local interference, non-standard satellite code transmissions, and satellite phase discontinuities.

An overview of the GAEM is provided in Figure 13-1. A RF front-end is used in combination with a server to continuously record RF data in memory. If an event occurs as determined by one of several GPS receivers, the 30-s of RF data before and after the event is captured and send to internet clients for post-processing of the anomaly.

![Figure 13-1. Overview of the GPS Anomalous Event Monitor (GAEM)](image)

The processing is fully automated and includes the generation of quick-look reports to assess the severity of an anomalous event. An example of a more recent anomaly where unexpected phase discontinuities on satellite 21 were observed that caused receiver loss-of-lock is illustrated in Figure 13-2. The phase anomalies consisted of short-duration events lasting from 30 to 180 ms during which time the phase of the signal jumped by values of 90, -50, 60, and -60 degrees. After a phase jump, the satellite would not always jump back by the same value.
Figure 13-2. Example of Satellite Phase Anomalies Captured by the GAEM

The current GAEM systems collect RF data in a 2-MHz bandwidth, while the TRIGR hardware uses dual-frequency technology and collects data in a 24-MHz bandwidth for high-accuracy applications. The dual-frequency TRIGR hardware is shown in Figure 13-3. On the upper left is the RF front-end, upper middle shows the server computer with a Field-Programmable Gate Array (FPGA) card for dedicated interfacing and processing.

On the lower left of Figure 13-3 is the 4-bit data histogram, followed by a correlation function built from 112 correlators, followed by both L1 and L2 P(Y) code correlation functions. On the right of Figure 13-3 is the FPGA floor plan showing the correlators as well as the hardware interfaces.
The most recent version of the TRIGR has three frequencies; L1, L2 and L5 and preliminary data collections have demonstrated its potential for detailed ionospheric and anomaly investigations. Figure 13-4 shows example results of L5 WAAS satellite acquisition for both satellites 135 and 138.

Figure 13-4. Example of L5 WAAS Signal Processing
14.0 SUMMARY OF RESEARCH RESULTS

Major findings of the research are summarized below:

1. Multipath-limiting GPS antennas were designed and tested for high-accuracy, high-integrity aviation applications. Following the research, the GPS antennas were manufactured by industry for aviation applications.

2. Very-High Frequency (VHF) Data Broadcast (VDB) antennas were designed and tested. Following the research, the VHF antennas were built by industry for aviation applications.

3. A multipath model was developed for siting of GPS antennas. The model was used for the overall safety proof of differential GPS.

4. Precise GPS velocity algorithms based on carrier phase were developed. These algorithms form the basis for advanced integrity techniques such as Relative Receiver Autonomous Integrity Monitoring (RRAIM) for new aviation applications of GPS.

5. A Transform-Domain Instrumentation GPS Receiver (TRIGR) was designed and implemented. The TRIGR is used as a component of the GPS Anomalous Event Monitor (GAEM) that detects, stores and analyzes GPS anomalies. Two GAEM systems are installed at the William J. Hughes Technical Center and Ohio University for the purpose of GPS monitoring. During the past 5 years, the GAEM has captured several anomalous events, including ionospheric disturbances, aircraft overflights, non-standard satellite transmissions, local interference, and satellite phase discontinuities.

6. Tropospheric decorrelation errors were analyzed and a threat model was created based on theoretical models and data collected over multiple baseline lengths and in different geographical areas. The results from this research have been applied to the integrity design of the LAAS and are currently also considered for future Wide Area Augmentation System (WAAS) architectures. Results from this research are applicable to all GPS users.

7. Monitor designs were developed and tested for the detection of excessive satellite acceleration errors that can invalidate integrity bounds for precision approach operations. The results of this research are being applied to differential GPS systems.

8. GPS cross-correlation errors were characterized and the research results were used to develop requirements for low signal power monitoring for differential GPS applications.

9. Pseudolite architectures were designed and flight-tested, and found to be feasible to enhance availability of reduced constellation geometries.

10. Advanced GPS/Inertial integration algorithms were researched and resulted in the feasibility demonstration of robust GPS/inertial integrations at the cm-level for interference mitigation.

11. Interference detection algorithms were designed and tested for the detection of interference that is well below levels that affect GPS receivers. Sensitive interference detectors increase the range over which a detector is effective.
15.0 RESEARCH PUBLICATIONS


50. Gunawardena, S., “Feasibility Study for the Implementation of Global Positioning System Block Processing Techniques in Field Programmable Gate Arrays,” M.S.E.E., School of EECS, Ohio University, November 2000.


55. Sayre, M., “A Block Processing Carrier to Noise Ratio Estimator for the Global Positioning System,” Proceedings of the National Technical Meeting of The


