A REAL-TIME BI-DIRECTIONAL DIFFERENTIAL GLOBAL POSITIONING SYSTEM

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Ranjeet S. Shetty

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This thesis entitled
A REAL-TIME BI-DIRECTIONAL DIFFERENTIAL
GLOBAL POSITIONING SYSTEM

BY
RANJEET S. SHETTY

has been approved for
the School of Electrical Engineering and Computer Science
and the Russ College of Engineering and Technology by

Chris G. Bartone
Assistant Professor of Electrical Engineering and Computer Science

R. Dennis Irwin
Dean, Russ College of Engineering and Technology
Traditionally, Differential Global Positioning System (DGPS) provides corrections to enable high accuracy position solution to mobile users. The Local Area Augmentation System (LAAS) employs DGPS to obtain precise positioning of aircraft for various levels of landing categories in the airport vicinity. Unrelated to LAAS, some remote-positioning systems transmit measurements from a mobile user to another location to determine the state of the mobile user remotely. The Bi-directional DGPS proposed here would enable both of these features simultaneously within the same architecture.

The purpose of this research was to demonstrate a Bi-directional DGPS, within a prototype LAAS, that integrates both DGPS and remote-positioning capabilities. The Bi-directional DGPS was successfully demonstrated at the Ohio University Airport using both a van and an aircraft as a mobile user with a fixed supporting ground-based station. This thesis presents the architecture, results and conclusions of these demonstrations.

Approved: Chris Bartone

Assistant Professor of Electrical Engineering and Computer Science
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<thead>
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<th>Description</th>
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<tbody>
<tr>
<td>ADS-B</td>
<td>Automatic Dependent Surveillance – Broadcast</td>
</tr>
<tr>
<td>AEC</td>
<td>Avionics Engineering Center</td>
</tr>
<tr>
<td>AH</td>
<td>Alert Height</td>
</tr>
<tr>
<td>ASMG</td>
<td>Airport Surface Movement Guidance</td>
</tr>
<tr>
<td>APL</td>
<td>Airport Pseudolite</td>
</tr>
<tr>
<td>ARNS</td>
<td>Aeronautical Radio Navigation Spectral</td>
</tr>
<tr>
<td>ATM</td>
<td>Air Traffic Management</td>
</tr>
<tr>
<td>bps</td>
<td>Bits per second</td>
</tr>
<tr>
<td>CRC</td>
<td>Cyclic Redundancy Code</td>
</tr>
<tr>
<td>DGPS</td>
<td>Differential Global Positioning System</td>
</tr>
<tr>
<td>DOP</td>
<td>Dilution of Precision</td>
</tr>
<tr>
<td>DSSS</td>
<td>Direct-Sequence Spread Spectrum</td>
</tr>
<tr>
<td>ECEF</td>
<td>Earth-Centered Earth-Fixed</td>
</tr>
<tr>
<td>ENU</td>
<td>East North Up</td>
</tr>
<tr>
<td>FAA</td>
<td>Federal Aviation Administration</td>
</tr>
<tr>
<td>GPS</td>
<td>Global Positioning System</td>
</tr>
<tr>
<td>HDOP</td>
<td>Horizontal Dilution of Precision</td>
</tr>
<tr>
<td>IFR</td>
<td>Instrument Flight Rules</td>
</tr>
<tr>
<td>IIP</td>
<td>Instantaneous Impact Point</td>
</tr>
<tr>
<td>JPO</td>
<td>Joint Program Office</td>
</tr>
</tbody>
</table>
L1  GPS L1 center frequency at 1575.42 MHz
L2  GPS L2 center frequency at 1227.6 MHz
LAAS Local Area Augmentation System
LGF LAAS Ground Facility
LLH Latitude Longitude Height
LV Launch Vehicle
m meters
NAS National Airspace System
nmi Nautical Miles
OS Operating System
PC Personal Computer
PPS Precise Positioning Service
PRC Pseudorange Corrections
PRN Pseudorandom Noise
PVT Position Velocity & Time
RNAV Random Navigation (or Area Navigation)
RF Radio Frequency
RR Reference Receiver
SPS Standard Positioning Service
STAR Standard Terminal Arrival Route
SV Satellite Vehicle
TOA Time of Arrival
TDMA Time Division Multiple Access
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>UAV</td>
<td>Unmanned Airborne Vehicle</td>
</tr>
<tr>
<td>UERE</td>
<td>User-Equivalent Range Error</td>
</tr>
<tr>
<td>UNI</td>
<td>Ohio University Airport</td>
</tr>
<tr>
<td>VDB</td>
<td>VHF Data Broadcast</td>
</tr>
<tr>
<td>VDOP</td>
<td>Vertical Dilution of Precision</td>
</tr>
<tr>
<td>VHF</td>
<td>Very High Frequency</td>
</tr>
<tr>
<td>VSWR</td>
<td>Voltage Standing Wave Ratio</td>
</tr>
<tr>
<td>WAAS</td>
<td>Wide Area Augmentation Network</td>
</tr>
</tbody>
</table>
1 INTRODUCTION

Satellite-based navigational aids are being researched to replace ground-based navigational aids in the National Airspace System (NAS) to modernize navigation and meet future requirements. These satellite-based navigational aids mainly comprise of the Global Positioning System (GPS), augmented by the Wide Area Augmentation System (WAAS) and the Local Area Augmentation System (LAAS).

The LAAS is being developed to support precision approaches and landings in and around the airport locality [1]. By employing multiple Differential GPS (DGPS) ground-based stations, LAAS is capable of providing a highly accurate position solution with high integrity, continuity, and availability required for precision approach.

This research proposes a Bi-directional DGPS which incorporates a remote positioning system within a prototype LAAS. The Bi-directional DGPS can provide a differentially corrected position solution at the mobile user itself and a differentially corrected remote position of the mobile user at the ground-based station, simultaneously. The system is therefore capable of providing accurate position information to the mobile user for precision landing or other applications. At the same time, the system can control, track, or monitor the mobile user with a high degree of precision of the mobile user’s Position, Velocity and Time (PVT) information. The mobile and ground user can use this PVT information from the Bi-directional DGPS to calculate its Instantaneous Impact Point.
Additionally, the mobile user transmits its pseudoranges and its differentially corrected position solution to the ground-based station. This enables the ground-based station to generate an integrity warning in case of a discrepancy. As a final note, the availability of precise PVT information on a mobile user allows the ground-based station to calculate an IIP of the user vehicle that could be used for range/airport safety. This capability helps increase the situational awareness in and around the airport.

The scope of the research was to implement a prototype Bi-directional DGPS based on a prototype LAAS that would work in real-time. The prototype mini-LAAS software, both air and ground, were modified such that the existing system functions were not affected. The prototype architecture of the system was setup at the Ohio University Airport (UNI). A van test, using an Ohio University van, and a flight test, using the Ohio University DC-3 Aircraft, were performed on July 9, 2002 and September 4, 2002, respectively, to demonstrate the real-time performance of the system.

The truth data was obtained using two Ashtech Z12 GPS receivers and post-processed for a kinematic carrier phase truth solution of the mobile user (van or aircraft). This truth data was then compared to the data collected and was post-processed using Matlab simulations.

This document is organized as follows: Chapter 2 discusses background material to gain a better understanding of the research presented. Chapter 3 presents a conceptual overview of the Bi-directional DGPS. Chapter 4 describes the prototype architecture of
the Bi-directional DGPS. Chapter 5 describes the analysis of the data collected and presents the results obtained. Chapter 6 summarizes the conclusions of this research. Chapter 7 provides recommendations for future work.
2 BACKGROUND

2.1 Global Positioning System

The GPS is a satellite-based navigational aid that enables accurate, continuous, and worldwide three-dimensional PVT determination of users with the appropriate receiving equipment [2]. The GPS Space Segment consists of 24 satellites (i.e., Satellite Vehicles (SVs)) arranged in 6 orbital planes with 4 satellites in each plane. The satellites are at an attitude of approximately 11,000 nautical miles (nmi) and have an approximate orbital period of 12 hours. GPS provides two services, the Standard Positioning Service (SPS) for the civil community and the Precise Position Service (PPS) for authorized users (e.g., military users).

The satellite broadcasts ranging codes and navigation data using Code Division Multiple Access (CDMA) technology, which is a form of Direct-Sequence Spread Spectrum (DSSS). The GPS signals are transmitted at two center frequencies L1 (1575.42 MHz) and L2 (1227.6 MHz). The L1 signal has two carrier components, a precise (P) pseudorandom noise (PRN) code and a coarse/acquisition (C/A) PRN code. The L2 signal consists of the encrypted P-code also known as the Y-code. The Y-code is available only to PPS users through cryptography.
2.1.1 GPS Principle

The GPS employs the concept of Time-of-Arrival (TOA) ranging to determine the user position [2]. The timing information is embedded in the satellites that are transmitting ranging signals. This enables the user receiver to calculate the precise time when the signal left the satellite. The receiver also notes the time when the signal was received thereby permitting the satellite-to-user propagation time calculation. This propagation time is multiplied by the propagation constant, which is the speed of light, to obtain a measurement of the satellite-to-user range.

2.1.2 GPS System Configuration

The GPS comprises of three main system segments as shown in Figure 2.1 [3].

- The GPS Space Segment, which consists of all the GPS SVs.

- The GPS Ground Control Segment, which consists of the ground-based infrastructure to monitor, predict, and control parameters of the GPS SVs.

- The GPS User Segment, which consists of the end user equipment located about the earth.
2.1.3 Pseudorange Calculations

Using the concept of TOA, satellite-to-user range is calculated [2]. Satellite-to-user range from three satellites is sufficient to determine the user position if the time of transmission and the time of reception are known exactly. Figure 2.2 illustrates the position determination using satellite-to-user ranges from three satellites with perfect knowledge of time. It is observed that R1, R2, and R3 are the three satellite-to-user ranges. This is true only if the user receiver clock (i.e., receiver time) is synchronized with the GPS system time (i.e., transmitter time). However, in reality, the receiver clock is not perfectly synchronized with GPS time. Thus three satellites are insufficient for precise position
determination. Figure 2.3 illustrates the effect of the receiver clock offset on the TOA measurements.
Let \( r \) represent the true satellite-to-user range and \( \tau t \) represent the signal propagation time from the satellite to the user. Then the true or geometric range can be expressed as:

\[
r = c(T_u - T_s) = c \tau t
\]  

(2.1)

where

- \( T_s \) = System time at which the signal left the satellite,
- \( T_u \) = System time at which the signal reached the user receiver,
- \( c \) = Speed of light.

Figure 2.3 Effect of the Receiver Clock Offset on the TOA Measurements

However, both the receiver clock and the satellite clock are typically offset from the system time. Thus the satellite-to-user range is called the pseudorange and is denoted by \( \tau \). The pseudorange contains the geometric satellite-to-user range (i.e., \( r \)), user clock
offset with respect to system time, and the satellite clock offset with respect to system time. Now the pseudorange can be represented as

\[ \gamma = c[(T_u + t_u) - (T_s + dt)] \]  

(2.2)

where

\[ dt = \text{Satellite clock offset with respect to system time (typically } t_{sv} \text{)}, \]
\[ t_u = \text{Receiver clock offset with respect to system time.} \]

Solving Equation 2.2 for the psuedorange, we get

\[ \gamma = r + c(t_u - dt). \]  

(2.3)

Since the GPS ground monitoring network determines the satellite clock offset and transmits these corrections to the satellites, \( dt \) is accounted for. Thus Equation 2.3 can be written as

\[ \gamma = r + ct_u. \]  

(2.4)

### 2.1.4 GPS Error Sources

Various error sources affect the satellite-to-user geometric range measurement [2]. The satellite signal experiences delays and distortions during propagation. The total time offset due to these delays and distortions can be represented as:

\[ \delta t_D = \delta t_{\text{atm}} + \delta t_{\text{noise}} + \delta t_{\text{mp}} + \delta t_{\text{hw}} \]  

(2.5)

where

\[ \delta t_{\text{atm}} = \text{delays due to atmosphere}, \]
\[ \delta_{\text{noise}} = \text{receiver noise}, \]
\[ \delta_{\text{mp}} = \text{multipath offset}, \]
\[ \delta_{\text{hw}} = \text{receiver hardware offsets}. \]

We can develop an error budget of the stand-alone GPS (i.e., non differential). Table 2.1 [2] presents the GPS Joint Program Office (JPO) User-Equivalent Range Error (UERE) budget for PPS and an estimate of the SPS receiver C/A-code UERE.

<table>
<thead>
<tr>
<th>Segment Source</th>
<th>Error Source</th>
<th>GPS 1s Error (m) for PPS</th>
<th>GPS 1s Error (m) for SPS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Space</td>
<td>Satellite clock stability</td>
<td>3.0</td>
<td>3.0</td>
</tr>
<tr>
<td></td>
<td>Predictability of satellite perturbations</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>Other (thermal radiation, etc.)</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Control</td>
<td>Ephemeris prediction error</td>
<td>4.2</td>
<td>4.2</td>
</tr>
<tr>
<td></td>
<td>Other (thruster performance, etc.)</td>
<td>0.9</td>
<td>0.9</td>
</tr>
<tr>
<td>User</td>
<td>Ionospheric delay</td>
<td>2.3</td>
<td>5.0</td>
</tr>
<tr>
<td></td>
<td>Tropospheric delay</td>
<td>2.0</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>Receiver noise resolution</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>Multipath</td>
<td>1.2</td>
<td>2.5</td>
</tr>
<tr>
<td></td>
<td>Other (inter-channel bias, etc.)</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>System UERE</td>
<td>Total root-sum-squared</td>
<td>6.6</td>
<td>8.0</td>
</tr>
</tbody>
</table>
The total system UERE is comprised of components from each system segment. It should be noted that the ionospheric delay for dual frequency PPS users will be smaller than the 2 – 3 m stated, and that most modern receivers will produce less receiver noise error than the stated 1.5 meters (m).

The following are the most common error sources in GPS:

1. **Satellite Clock Error:** Although satellites have atomic clocks, a deviation of up to 1 millisecond from the GPS time is possible [2]. This deviation could translate to a pseudorange error of 300 km. While the GPS SV clock error is predicted by the GPS ground control segment and encoded into the GPS broadcast message, not all of the absolute error is removed by the user because the actual transmitter clock in the SV drifts slightly from ephemeris update to ephemeris update. Net ranging errors induced by SV clock errors are in the order of 3.0 m (1s) as indicated in Table 2.1.

2. **Ephemeris Prediction Error:** Estimates of ephemerides of all the satellites are predicted by the GPS ground control segment and uplinked to the satellites for rebroadcast to the user [2]. These estimates contain a residual error known as the ephemeris error, which stem from the accuracy of the SV position prediction by the GPS ground control segment. The effective pseudorange error is in the order of 4.2 m (1s).
Atmospheric Effect: The atmosphere affects the GPS signals in both the ionospheric and the tropospheric region.

a. In the ionospheric region, free electrons are released due to the ionization of gas molecules by the sun’s ultraviolet rays. These free electrons influence the GPS SV radio frequency (RF) signal as it passes through the ionosphere. The ionospheric delay can be mitigated using a dual-frequency receiver as compared to a single-frequency receiver since the delay is frequency dependent and can be measured. For single frequency users, models such as Klobuchar model can remove, on average, about 50% of the ionospheric delay at midlatitudes based on almanac data contained in the GPS ranging message. This model is accurate to about 15 m (1σ) as compared to about 0.5 m (1σ) using dual-frequency receiver [4].

b. The refractive index of the troposphere delays the velocity associated with the GPS signal on both L1 and L2 with respect to free-space propagation. The refractive index is dependent on the local temperature, pressure, and relative humidity. Remondi models the tropospheric delay using the dry component (arises from dry air and gives rise to 90% of the tropospheric delay), the wet component (arises from water vapor) and the user height [2]. The estimated tropospheric delay error, after model corrections, is approximately 1.5 to 2.0 m as shown in Table 2.1.

Receiver Noise: This is produced by the movement of electrons in receiver components such as resistors and transistors that have operating temperatures above
absolute zero \[5\]. This accounts for an error of about 1.5 m \[2\] on the pseudorange measurement.

Multipath: Multipath is a signal that arrives at the receiver via multiple paths due to reflections from the Earth and/or nearby objects like buildings and vehicles \[2\]. Multipath distorts the resulting PRN codes and carrier phase of the received signal. If the path delay of the reflected signal increases with respect to the direct signal, the multipath error increases till it reaches the maximum and then decreases as a function of the receiver correlating spacing and direct signal-to-multipath signal power ratio \[2\].

2.2 Differential GPS

A DGPS implements a reference station to remove all the errors common to both the mobile user and the reference station for improved performance \[2\] \[3\]. Figure 2.1 is an illustration of DGPS.
In a ground-based absolute DGPS system, the ground-based reference station antenna is placed at a surveyed location. The reference station processes the GPS signals and measures the code carrier phase to produce measured pseudorange and integrated Doppler. Since its location is surveyed, the reference station can predict the true satellite-to-user range. The measured pseudorange and the predicted true range are compared to obtain the pseudorange corrections. These pseudorange corrections, and possibly associated data are then transmitted to the mobile user for use. The mobile user applies these corrections to its measurements. This cancels most of the common error sources thereby increasing an accuracy ranging from approximately 6-8 m (see Table 2.1) to sub-meter.
By using DGPS most of the common bias errors originating from outside the receiver can be eliminated. The following are the sources of common errors:

- Ionospheric delay
- Tropospheric delay
- Ephemeris error
- Satellite clock error

If the reference station and the mobile user distance become too great such that the error component measured at the reference station is different from the error component at the mobile user, the error terms becomes non-common or uncorrelated. This is caused by the spatial distance between the reference station and the mobile user. Thus we can call this occurrence spatial decorrelation of the error component. Common error terms that become uncorrelated due to spatial decorrelation will not be cancelled by DGPS.

The error parameters (ionospheric and tropospheric), modeled at the ground-based station, reach the mobile user after a delay. During the delay, error parameters change or decorrelate before they are applied to the mobile users. This time-based decorrelation is called the temporal decorrelation of the error component. Temporal decorrelation can become significant when the rate of change of the error component becomes larger than the data link rate, supporting the DGPS system. Both spatial decorrelation and temporal decorrelation occur most commonly in the ionosphere and the troposphere where the GPS SV signal passes through different paths of the atmosphere to reach the reference station and the mobile user respectively.
The following are the non-common errors not eliminated by DGPS:

- Receiver Noise
- Multipath
- Spatial decorrelation component
- Temporal decorrelation component

2.3 Local Area Augmentation System

The LAAS provides ground-based assets to augment the GPS for improved performance enabling precision approach and landing system application. RTCA identifies the [1] "operational goals of LAAS are as follows:

- To replace other Instrument Flight Rules\(^1\) (IFR) radio-navigation precise approach and landing systems.
- To support future terminal Area Navigation\(^2\) (RNAV) using augmented GPS.
- To support aircraft surface navigation.
- To provide high accuracy PVT information to support Automatic Dependent Surveillance – Broadcast\(^3\) (ADS-B) applications.

\(^{1}\)Crews following IFR must be capable of navigating and controlling the aircraft without clear visibility [3]. Air Traffic Management (ATM) authorities inform the crew of any other near by aircrafts.

\(^{2}\)RNAV is a method of navigation that permits aircraft operation on any desired flight path within the signal coverage of the station-referenced navigation aids or within the limits of the capability of self-contained aids or a combination of these [7].
• To provide high accuracy, high integrity positioning to support improved obstacle and terrain clearance."

LAAS is intended to provide radio-navigation vertical and lateral guidance for aviation IFR precision approaches and landings from about 20 nmi to runway threshold through touchdown and rollout. LAAS is being developed to be capable of providing this service to all the aircrafts in the area under all weather conditions. LAAS is planned for ‘precise RNAV’ in terminal area including curved approaches and departures and surface navigation on the airport [6].

Approaches and landings are categorized mainly on the basis on their decision height (DH), which is the height above the runway at which the landing must be aborted if the runway is not in sight. The LAAS is being designed to become the primary radio-navigation system to support *Category I*, *Category II*, *Category IIIa* and *Category IIIb* precision approach and landing capabilities [3]. An abort at decision height is based either on visibility (i.e., not able to see the runway) or an equipment failure. In case of an equipment failure, the landing may still continue at *Alert Height* (AH) if the avionics is fault tolerant or the crew takes over manually.

---

3 ADS-B is a surveillance technique in which the aircraft automatically provides data (via data link) derived from on-board navigation systems. Its purpose is to provide real-time surveillance information to ATM authorities and aircraft operator dispatch facilities [8].
4 A precision approach to the DH not lower than 200ft and the Runway Visual Range (RVR) not lower than 1800ft.
5 A precision approach to the DH not lower than 100ft and the RVR not lower than 1200ft.
6 A precision approach to the DH lower than 100ft and the RVR not lower than 700ft.
7 A precision approach to the DH lower than 50ft and the RVR not lower than 150ft.
8 The altitude below which landing may continue in case of equipment failure.
2.3.1 LAAS Performance

LAAS performance is classified in terms of defined levels of service called Performance Types [1] [9]. A particular Performance Type defines a required level of accuracy, integrity, continuity, and availability as observed at the output of an airborne subsystem. The three levels defined are Performance Types 1, 2, and 3. Performance Type 1 is the performance adequate to support Category I operations. Performance Type 2 is sufficient to support Category II and IIIa operations. Performance Type 3 is sufficient to support Category IIIb operations.

LAAS is being developed to provide PVT information for RNAV, Standard Terminal Arrival Routes (STAR) and future surveillance systems. LAAS would be capable of supporting low visibility take off operations and deviation guidance for departures. LAAS would enable flexibility in real-time air traffic management by sequencing arrivals efficiently. In addition, LAAS would provide course guidance with the desired level of performance appropriate for the category of operation, which enables the aircraft to be configured and stabilized prior to glide-path intercept. Curved and segmented path approach procedures would also be performed precisely using LAAS. LAAS, once deployed, would reduce the airspace protection zones surrounding the airport.
2.3.2 LAAS Subsystems

Figure 2.1 illustrates the basic components of LAAS [1][10].

The LAAS consists of three primary subsystems:

- The satellite subsystem provides space-based ranging signals. These ranging signals can be provided by GPS, WAAS, or GLONASS. In this research the ranging signals were provided by GPS.
• The ground subsystem is called the LAAS Ground Facility (LGF). The LGF consists of usually four Reference Receivers (RRs) and associated antenna systems. The ground estimates corrections and transmits them to the airborne subsystem using a Very High Frequency (VHF) Data Broadcast (VDB). For high availability, the LGF may also contain an Airport Pseudolite (APL) which transmits a GPS-like waveform for ranging. At the LGF, a site is defined to be an antenna system and associated RR(s). These sites are spatially separated in an attempt to decorrelate the ground multipath. These spatially separated sites are also used too obtain better accuracy, by averaging data, as well as, improved integrity, and continuity.

• The airborne subsystem applies the corrections to the airborne measurements, thereby computing a highly accurate position solution with high level of integrity, continuity and availability.

2.3.3 LAAS VHF Data Broadcast

The LAAS VDB is used to transmit GPS differential corrections and other integrity parameters from the LGF to the mobile users in the airport vicinity [11] [12]. The VHF Aeronautical Radio Navigation Spectral (ARNS) band from 108.000 MHz to 117.975 MHz is allocated for VDB. The modulation format employed for VDB is a Differentially encoded, 8-ary-Phase-Shift-Keying (D8PSK) scheme. The VDB uses an eight-time-slot-
per-half-second, fixed-frame, Time Division Multiple Access (TDMA) structure. The data rate for this link is 31,500 bits per second (bps). Excluding the header but including the Cyclic Redundancy Check (CRC), which is at the end of the application data, the effective data capacity of the VDB is 1776 bits (222 bytes) per frame.

The data frame (header + 222 bytes of application data + CRC) is time division multiplexed such that each of the 8 TDMA slots has a duration of 62.5 millisecond. The VDB data is transmitted in bursts. These transmission bursts can be variable in length, up to the maximum allowed within a time slot. The transmission of each burst begins 95.2 μs after the start of the time slot. A signal propagation guard time of 1261.9 μs at the end of each slot protects a one way propagation range of approximately 200 nmi [11].

2.3.4 Bias-Values

Bias-Values (B-values) are values that evaluate the signal’s integrity and quality [1] [13]. B-values are realized by comparing the differential corrections for a particular site to the average differential correction.

Figure 2.2 illustrates a LAAS subsystem with multiple RRs where N is the total number of GPS satellites and M is the number of RRs in the LAAS ground system, assuming one RR per site within an LGF.
Consider a particular RR say “RR m” and a particular SV say “SV n”. Now the pseudorange measurement would be represented as $\rho_m^n$. The predicted true pseudorange can be calculated from the ephemeris of the SV and the known position coordinates of the RR. Therefore the pseudorange corrections (PRCs) can be calculated from the difference of the measured pseudorange and the true pseudorange as:

$$PRC_m^n(t_m) = \rho_m^n - R_m^n = \{t^n + \text{iono}^n + \text{tropo}^n + \varepsilon^n\} + \{n_m^n\} + t_m$$  \hspace{1cm} (2.6)$$

where:

$$PRC_m^n = \text{Pseudorange correction for SV n from RR m}.$$
\[ R_m^n = \text{True Pseudorange from RR m to SV n}, \]

\[ t^n = \text{Clock Error of SV n}, \]

\[ iono^n = \text{Ionospheric Delay for SV n}, \]

\[ tropo^n = \text{Tropospheric Delay for SV n}, \]

\[ \varepsilon^n = \text{Ephemeris Error from SV n}, \]

\[ n_m^n = \text{Noise Component (receiver noise and multipath) with RR m for SV n} \]

\[ t_m = \text{User Receiver Clock bias of RR m}. \]

In equation 2.6, the terms in the first set of brackets represent errors in the pseudorange which are common to the ground-based reference station and the mobile user. These errors will cancel each other in the DGPS solution. The term in the second bracket should be considered in the B-value calculations. The last term which is the clock bias must also be removed to allow for a comparison between different RRs. An estimate of the clock bias is obtained by averaging the PRCs for all SVs that are common to all M RRs. The estimate is expressed as:

\[ \hat{t}_m = \frac{1}{N} \sum_{i=1}^{N} PRC_m^i(t_m) = t_m - \Delta t_m \]  \hspace{1cm} (2.7)

where \( \Delta t_m \) is the difference between the true clock bias and the estimated clock bias.

This clock bias estimate is subtracted from the PRC:

\[ PRC_m^n = PRC_m^n(t_m) - \hat{t}_m = \{t^n + iono^n + tropo^n + \varepsilon^n\} + \{n_m^n\} + \Delta t_m \]  \hspace{1cm} (2.8)

Once the estimated clock bias is removed from each of the RRs, an average pseudorange correction is computed across all M RRs:
The B-values, signifying error in the PRC for a particular RR m, can be calculated by taking the difference between $PRC^n_m$ with that particular RR m removed, and the $PRC^n_m$:

$$B^n_m = PRC^n - \frac{1}{M-1} \sum_{j \neq m}^{M} PRC^n_j$$  \hspace{1cm} (2.10)

A threshold can be set for the maximum B-value to be 0.4 m. If the B-value for a particular SV is too big, the corresponding pseudorange measurement is not used for the position solution. These B-values are also transmitted to the mobile user. The mobile user decides whether or not to use the pseudorange measurements depending on the B-values.

2.4 Remote Positioning

Figure 2.4 is an illustration of a remote-positioning system for a mobile user and ground-based station that is based on GPS.
The mobile user’s measurements and position are computed using GPS. The computed parameters are then transmitted to the remote positioning ground-based station by means of a data link. Using this information the ground-based station can monitor, track, and/or control the remote user. Key applications of remote positioning systems are as follows.

- Remote positioning can be used for applications such as ADS-B and Airport Surface Movement Guidance\(^9\) (ASMG).

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\(^9\) A surface movement guidance for aircrafts in all weather conditions [6]
Remote positioning information can also be used for controlling or maneuvering Unmanned Airborne Vehicles (UAV) or remote pilot applications.

Remote Positioning can be used for launch vehicle (LV) or missile monitoring, controlling, and/or maneuvering application. The high precision PVT information, a DGPS based remote positioning system enables, could be used for IIP calculations of the LV, missile, UAV, and aircraft. Although IIP methodology has historically been applied to range safety applications [14] [15] [16] for LVs, with the increased use of UAVs, and the terror event of September 11, 2001, a high precision DGPS remote positioning system would enable IIP calculation of LV, missiles, UAV, and aircraft throughout the NAS. These IIP calculations could be done in the background, and only brought to the airspace operator’s attention if a hazardous situation arose.
3 BI-DIRECTIONAL DGPS

3.1 An Overview

It is known that transmitting differential pseudorange corrections via the VDB uplink would provide differentially corrected positions at the mobile user; this system would benefit the mobile users in precision landings, auto-pilot, precise positioning etc. It is also known that transmitting measurement and position via a VDB downlink would provide remote positions and/or measurements of the mobile user at the ground-based station; this DGPS system enables the ground-based station to track or control mobile users within a given range.

The Bi-directional DGPS presented here, is fundamentally a LAAS DGPS integrated with a remote positioning system. This system enables us to obtain high accuracy differential position solution at the mobile user, while at the same time, the ground-based station can acquire a highly accurate PVT solution of the mobile user. Figure 3.1 is an illustration of a Bi-directional DGPS system.
Both the remote positioning DGPS ground-based station and the mobile user receive GPS navigation signals from the GPS satellites. The ground-based station calculates the differential PRCs (and associated B-values) and transmits these to the mobile user via the data link. The mobile user subsequently applies these corrections to its pseudorange measurements, thus obtaining a high accuracy position solution. The mobile user then transmits the measured pseudoranges and position solution to the ground. The ground-based station calculates a differentially corrected position solution of the mobile user from the transmitted pseudoranges; this remotely calculated position solution is then compared to the user transmitted position solution to enable a closed loop integrity check for the Bi-directional DGPS System.
3.2 Bi-directional DGPS Ground Reference Station

The ground reference station is very similar to the LGF. Figure 3.2 is a functional block diagram of the Bi-directional DGPS ground reference station.

![Bi-directional DGPS Ground-Based Station Functional Block Diagram](image)

The GPS receiver decodes the GPS navigation signals. The communication port of the receiver is connected to a Personal Computer (PC) with a real-time operating system (OS) (e.g., QNX OS). The SV positions are calculated from the receiver time and ephemeris data. The measured pseudoranges are then smoothed by a smoothing filter.
using the integrated Doppler measurements [1]. The smoothed pseudorange is compared
to the predicted true range, and the SV clock corrections and the clock bias estimations
are subsequently added to this difference thereby generating PRCs. These corrections are
transmitted to the mobile user using a VDB. The rest of the modules (shaded in grey) in
the block diagram will be discussed in Section 3.4.

3.3 Bi-directional DGPS Mobile User

The mobile user can be an aircraft, UAV, LV, or missile. Figure 3.3 is a functional block
diagram of the Bi-directional DGPS mobile user.

Figure 3.3 Bi-directional DGPS Mobile User Functional Block Diagram
The mobile user also receives the GPS navigation signals, which are decoded with the GPS receiver. Here the LAAS air software processes the decoded GPS data. Similar to the ground-based station, the measured pseudoranges are smoothed by the smoothing filter using the measured integrated Doppler measurements. The tropospheric correction is modeled (differential model) and applied to the output of the smoothing filter. The PRCs received at the mobile user are also applied to the output of the smoothing filter. The SV clock correction is then applied to the result. This results in a highly accurate position solution at the mobile user that can be used by the mobile user.

The differentially corrected PVT solution, measured pseudoranges, and measured integrated Doppler are then transmitted to the ground-based station for high integrity and precision remote PVT determination of the mobile user.

3.4 Remote Positioning in Bi-directional DGPS Ground-based Station

Figure 3.4 is Figure 3.2 with the remote positioning system indicated by darkened blocks.
Figure 3.4 A Complete Bi-directional DGPS Ground-based Station Functional Block Diagram

The ground-based station receives the differentially corrected position solution, measured pseudoranges and measured integrated Doppler from the mobile user. The measured pseudoranges are smoothed with a smoothing filter using the integrated Doppler measurements. The tropospheric corrections (calculated from a differential model, but at the ground-based station), pseudorange corrections (calculated at the ground-based station), and the SV clock corrections are applied to the output of the smoothing filter to obtain a high accuracy position solution of the mobile user at the ground-based station. The calculated position solution is compared to the transmitted position solution for
integrity purposes thus ensuring accurate remote position of the mobile user at the ground-based station.
4 PROTOTYPE ARCHITECTURE/EXPERIMENTAL SETUP

The experimental setup consists of a ground-based station, a mobile user station, and a truth reference system.

4.1 Hardware Configuration

4.1.1 Ground-Based Station

The ground-based station was setup in the AEC Hangar at UNI. Figure 4.1 shows the functional block diagram of the ground-based station hardware setup.
A NovAtel Pinwheel GPS Antenna and a 900 MHz FreeWave data link antenna were installed at the roof of the hanger, see Figure 4.2. Both the antennas were connected to RF cables running to the lab located on the 2nd floor (~ 60 m run) of the hangar. The Pinwheel Antenna is designed to operate at both GPS L1 and L2 frequencies [17]. The Pinwheel Antenna has a radiation pattern that is shaped to reduce signals arriving from low elevation satellites, which mitigate the errors associated with electromagnetic interference and multipath.
Figure 4.2 shows the data link antenna that was used for the van test. Different data link antennas were used for the 900 MHz FreeWave data link antenna during the van and flight test. The performance parameters of the antennas were studied using an HP8753 Network Analyzer.

Figure 4.3 is the measured *Voltage Standing Wave Ratio*\(^\text{10}\) (VSWR) plot of the data link antenna used for the van test.

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\(^{10}\) Voltage Standing Wave Ratio is a measure of impedance mismatch between the transmission line and its load [18]. Higher VSWR indicates greater mismatch. The minimum VSWR or perfect impedance match is unity. Unity VSWR ensures maximum power transfer to the load.
Figure 4.3 VSWR Plot of the Data Link Antenna used for the Van Test

The VSWR for the marked frequencies are shown in Table 4.1.
The range of the FreeWave data radio is 902 MHz – 928 MHz. Consider the mean of the range to be 915 MHz. To compute the VSWR at this frequency, an interpolation is performed using 900.000 MHz and 937.875 MHz as the two data points. The computed VSWR at 915 MHz is 2.8659. This VSWR is fairly high for this application. A VSWR of this magnitude would amount to a transmission loss of about 1.17 dB [19], so a better antenna was sought for the flight test.

Figure 4.4 shows the data link antenna that was used for the flight test.
The VSWR plot of this data link antenna is as shown in Figure 4.5. The VSWR, measured for the frequency of 915 MHz, is 1.5886. The performance of the antenna at this frequency was better than the data link antenna used for the van test. The transmission loss of the antenna at this frequency is only about 0.24 dB[19].
As shown in Figure 4.1, the GPS navigation signals are fed to the two RF ports of the NovAtel Beeline receiver using a power splitter. At least two reference receivers or ground-based stations are required to generate B-values. A NovAtel Beeline receiver was used for simplicity because it has two RF inputs that act like two separate receivers. It should be noted that normally at least two spatially separated site are used in an LGF installation to spatially decorrelate error terms; again only one simple antenna site was used to reduce complexity in the Bi-directional DGPS demonstration. The Pinwheel Antenna, which has a pre-amplifier in it, receives 5 Volts DC from one of the GPS
receiver RF port, while the other RF port has a DC block in its path. The receiver treats the RF inputs as though they were from two separate GPS antennas, but the ephemeris data is decoded only from the first RF input.

The FreeWave radio receives and transmits digital data for the data link [20]. This radio is a spread spectrum wireless transceiver which operates at a frequency range of 902 MHz - 928 MHz. Using the frequency hopping spread spectrum technology, FreeWave transceivers are capable of uncompressed data rates of 115.2 KBaud over distances of 20 statute miles or more. They are configured to work in the Full-Duplex Point-to-Point Mode at a baud rate of 38,400. The FreeWave radio transmits differential pseudorange corrections and B-values from the prototype LAAS ground-based station to the mobile user. At the same time, it receives the measured pseudoranges, integrated Doppler, and the differentially corrected position solution from the mobile user. These 900 MHz FreeWave Radios are a direct replacement for the nominal LAAS VDB radios. Only one minor software change is made in the mini-LAAS software to accommodate the FreeWave via the VDB radio architecture. The FreeWave radios were used in this demonstration for simplicity.

The LAAS ground-based station processor is an industrial grade PC from Cyber Research. The machine has a Pentium III processor with a speed of 500 MHz. The PC runs on QNX real-time OS and a prototype version of the mini-LAAS software.
Before the aircraft demonstration, the ground-based station Pinwheel antenna site was surveyed for a period of approximately two hours, using an Ashtech Z12 receiver.

The surveyed location in Latitude Longitude Height (LLH) was:

North 39° 12' 38.65540''
West  82° 13' 28.92817''
Orthometric height 245.316 m.

4.1.2 Mobile User Configuration

Figure 4.6 shows the functional block diagram of the mobile user hardware configuration.
In the case of a van test a GPS Pinwheel Antenna and a FreeWave Whip Antenna were used. Figure 4.7 is a photograph of the two antennas mounted on top of the van.

The Pinwheel Antenna is the same type as the one used at the ground-based station. The FreeWave Whip Antenna is a single-element antenna that can be attached directly to the wireless transceiver [20].

![Figure 4.7 Van mounted GPS Pinwheel Antenna and FreeWave Whip Antenna](image)

As shown in Figure 4.6 and 4.7, the RF cables run interior to the van through the “window bulkhead”. The GPS signal is split using a power splitter, where one output of the splitter is provided to the NovAtel GPS Beeline Receiver and the other is given to the Ashtech Z12 GPS Receiver (the Ashtech Z12 dual frequency surveying receiver system.
is used as a truth reference system). The Beeline Receiver powers the Pinwheel Antenna, so a DC block is connected at the Ashtech RF port. The GPS receiver and the FreeWave radio input data to the Prototype Bi-directional DGPS Airborne Processor via RS-232 data cables. The FreeWave transceiver receives the differential corrections from the ground-based station via the data link. These corrections are applied to the GPS position solution generated by the air LAAS processor. Thus a differentially corrected position solution is computed at the mobile user. The position solution, the measured pseudorange, and integrated Doppler are now transmitted to the ground-based station using the FreeWave radio. The equipment in the van is powered by a 115 V/60 Hz converter from the van’s 12 Volt DC battery.

A setup, similar to that shown in Figure 4.7, was used for the flight test. Figure 4.8 is a photograph of the system set-up in the DC-3 Aircraft.
Figure 4.8 Mobile User System Rack in the DC-3 Aircraft

Figure 4.9 is a photograph of the GPS patch antenna atop the DC-3 that was used for the flight demonstration. This antenna is a passive L1, L2 patch antenna (S-1575-14) from Sensor Systems Incorporated. Figure 4.10 is a photograph of the blade antenna mounted on the bottom of the DC-3 Aircraft used for the data link. It is an L-Band blade manufactured by Bendix, Incorporated.
Figure 4.9 GPS Antenna mounted on the Top of the DC-3

Figure 4.10 Data Link Antenna mounted at the Bottom of the DC-3
4.1.3 Truth Reference System

An Ashtech Z12 system is employed to acquire a reference truth trajectory. This system tracks the L1 an L2 GPS frequencies, which reduces ionospheric refraction effects [6]. The system accuracy is in the order of 0.1 m (95%) in post processing mode due to the use of carrier phase measurements at both L1 and L2 frequency.

The truth reference station was placed at the UNI South Tower located less than 0.5 nmi from the runway area. The L1/L2 antenna for the reference Z12 Receiver is mounted on a mast to reduce multipath susceptibility. Another Ashtech Z12 GPS Receiver is installed in the mobile user system. The data from the two Ashtech Z12 GPS Receivers were post processed to for a carrier phase ambiguity resolved truth position of the mobile user. These truth data files were used as true position for all data analysis.

The surveyed location of the South Tower reference site in LLH coordinates is:

North 39° 12' 33.14520"

West 82° 13' 25.93487"

Orthometric height 254.71 m.
4.2 Software Requirements

The software used for both the air and the ground-based station was a prototype version of the LAAS software, which used a QNX OS and a QNX Watcom C compiler. The following is a basic overview of the air and ground LAAS software, followed by a description of changes made to implement the Bi-directional DGPS functions.

4.2.1 Existing LAAS Code

In the mini-LAAS ground software, Ground.c is the main program. The function Process_serial_data in serial.c reads in the data from the serial ports. The ephemeris data acquired from the GPS receiver is decoded in Novatel.c. The SV positions are calculated in Svcalc.c. The surveyed reference position coordinates are entered in G_init.c. The ground position solution is then calculated in calpos.c and compared to its known surveyed location coordinates. The differential pseudorange corrections are computed in Intmon.c. These corrections are sent to a local function called Freewave_transmit in Serial.c of the LAAS air software. In real time all the parameters can be displayed on a screen which is controlled by Laasterm.c.

In the LAAS air software, the main program is Ac.c. The Novatel.c, Svcalc.c and the function Process_serial_data in Serial.c are similar to those of the ground software. The
The air stand-alone position is computed in the Calculate_position function in Calpos.c. The pseudorange corrections are applied to the measured pseudoranges in Calculate_diff_position function of Serial.c. The differential tropospheric errors are modeled in Atmcor.c, and applied to the measured pseudoranges. The differentially corrected position is calculated in the Calculate_diff_position. The display is again controlled by Laasterm.c.

Both the air and the ground LAAS software version are compliant with the APL signals.

4.2.2 Modifications in the Ground LAAS software

In order to implement the Bi-directional DGPS within the existing system, the existing LAAS code was modified. The remote positioning data transmitted from the mobile user is read using serial.c via the FreeWave radio. In order to do so, new functions were written entitled; Process_Rem_data, Decode_Rem, and Decode_Rem_broadcast, which are very similar to Process_VDL_data, Decode_VDL, and Decode_broadcast that are contained in the LAAS airborne code. These functions read in the data from the serial port, verify the data transfer, and then assign them variable names. To keep this separate from the existing Serial.c, another program file called Serrem.c was created to perform these added functions. Since the position calculated here is of the mobile user, a differential tropospheric correction model was implemented by replicating the program file Atmcor.c from the air LAAS software.
Calrem.c was another program file created in the ground software. This file contains functions Calculate_diff_position, Snapshot_DGPS, Diff_ad_prop, dpos_iteration. These functions are similar to those in Calpos.c in the air software. Most of the variables were renamed to avoid disturbing the already existing variables in the ground software. The pseudorange correction and the tropospheric corrections are applied to the measured pseudoranges for each SV in the Snapshot_DGPS function. This permits a snapshot differential position solution of the mobile user in the ground software.

In the air software, the mobile user measured pseudoranges are smoothed using the measured integrated Doppler and the smoothed position solution is propagated to 5 Hz. Position smoothing and propagating was not implemented in the ground software, due to time constraints.

An additional display screen was added, see Figure 4.11. This display screen shows both the transmitted and the calculated remote position solution, and their differences, along with the GPS time.
4.2.3 Modifications in the Air LAAS Software

A list of all the parameters to be sent to the ground-based station was made. The parameters had to be tapped at the right places in the code so as to acquire new data for every GPS data epoch. The differential position solution was transmitted to enable remote positioning with integrity at the ground-based station. As an additional integrity check, the pseudoranges and the integrated Doppler for each SV were transmitted to the ground-based station. From these parameters the position solution can be recalculated at the ground-based station as the SV positions and SV clock corrections are available. The pseudorange corrections, also available at the ground-based station, make it possible to recreate the exact solution obtained at the air.
The remote positioning data of the mobile user that is transmitted to the ground-based station was not done more than once every second due to the slower data rate (1 Hz) in the ground.

An additional function called Rem_transmit was created in Serial.c in the air software. This new function is very similar to Freewave_transmit in the serial.c in the ground software, which is called in Ground.c. A binary file of the transmitted data, in the air, is also created, which allows data analysis in post-processing.

4.3 VHF Data Broadcast Rate Analysis

An 8-bit (1 byte) field is assigned to the message type allowing the LAAS to have up to 256 ($2^8 = 256$) message types [11]. Only eight message types have been assigned for LAAS so far. Message Type 1 is assigned for differential corrections broadcast. In this research, message block analogous to Message Type 1 was used for both differential corrections broadcast and remote positioning broadcast. At the end of each message block, a 32-bit CRC is present to ensure the message integrity. The spare bits, coded as zeros, are also transmitted in the message. These bits can be used for transmission of additional parameters in the future. CRC takes the spare bits into consideration while processing. The entire message is transmitted in one burst every second.
The message block header contains information on each LAAS transmission. Table 4.2 shows the parameters in the message header. In the prototype mini-LAAS ground-based station the Message Block Header shown in Table 5.2 is used.

Table 4.2 LAAS Message Block Header Parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Number of Bytes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Synchronization byte (1)</td>
<td>1</td>
</tr>
<tr>
<td>Synchronization byte (2)</td>
<td>1</td>
</tr>
<tr>
<td>Message ID</td>
<td>1</td>
</tr>
<tr>
<td>Sequence Number</td>
<td>1</td>
</tr>
<tr>
<td>Bytes to follow</td>
<td>1</td>
</tr>
<tr>
<td>VDB Checksum (End of the message)</td>
<td>1</td>
</tr>
<tr>
<td>Total</td>
<td>6</td>
</tr>
</tbody>
</table>

4.3.1 Data Uplink

The data to be uplinked to the mobile user is assigned in the function Freewave_transmit of Serial.c. The LAAS data parameters constitute 222 bytes. The header sums up to another 6 bytes. Table 4.3 shows the parameters, name, format, and size, transmitted from the ground-based station to the mobile user in the prototype mini-LAAS setup. This format, as shown in Table 4.3 is very similar to the LAAS Message Type 1 [11].
Table 4.3 Prototype LAAS Data Parameters Uplinked

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Format</th>
<th>Number of Bytes</th>
</tr>
</thead>
<tbody>
<tr>
<td>GPS Time</td>
<td>Double</td>
<td>8</td>
</tr>
<tr>
<td>$\sigma_{pr_{gnd}}$</td>
<td>Integer</td>
<td>1</td>
</tr>
<tr>
<td>Data Checksum</td>
<td>Integer</td>
<td>4</td>
</tr>
<tr>
<td>SV Number (for up to 13 satellites)</td>
<td>Integer</td>
<td>$1 \times 13$</td>
</tr>
<tr>
<td>Pseudorange Corrections (for up to 13 satellites)</td>
<td>Float</td>
<td>$4 \times 13$</td>
</tr>
<tr>
<td>Integrated Doppler (for up to 13 satellites)</td>
<td>Float</td>
<td>$4 \times 13$</td>
</tr>
<tr>
<td>B-Values from first RR (for up to 13 satellites)</td>
<td>Integer</td>
<td>$1 \times 13$</td>
</tr>
<tr>
<td>B-Values from second RR (for up to 13 satellites)</td>
<td>Integer</td>
<td>$1 \times 13$</td>
</tr>
<tr>
<td>B-Values from third RR (for up to 13 satellites)</td>
<td>Integer</td>
<td>$1 \times 13$</td>
</tr>
<tr>
<td>B-Values from fourth RR (for up to 13 satellites)</td>
<td>Integer</td>
<td>$1 \times 13$</td>
</tr>
<tr>
<td>Issue of Data or IOD (for up to 13 satellites)</td>
<td>Integer</td>
<td>$1 \times 13$</td>
</tr>
<tr>
<td>Padding</td>
<td>Integer</td>
<td>27</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>222</strong></td>
</tr>
</tbody>
</table>

4.3.2 Data Downlink

In the air, the Rem_transmit function of Serrem.c assigns the data parameters to be transmitted. The LAAS data parameters amount to 228 bytes. The header byte is again 6
bytes. Table 4.4 shows the parameters transmitted from the mobile user to the ground-based station and the format and size of each parameter.

Table 4.4 Prototype LAAS Data Parameters Downlinked

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Format</th>
<th>Number of Bytes</th>
</tr>
</thead>
<tbody>
<tr>
<td>GPS Time</td>
<td>Double</td>
<td>8</td>
</tr>
<tr>
<td>Data Checksum</td>
<td>Integer</td>
<td>4</td>
</tr>
<tr>
<td>Differentially corrected East Coordinate</td>
<td>Float</td>
<td>4</td>
</tr>
<tr>
<td>Differentially corrected North Coordinate</td>
<td>Float</td>
<td>4</td>
</tr>
<tr>
<td>Differentially corrected Up Coordinate</td>
<td>Float</td>
<td>4</td>
</tr>
<tr>
<td>Position Time</td>
<td>Double</td>
<td>8</td>
</tr>
<tr>
<td>SV Number (for up to 13 satellites)</td>
<td>Integer</td>
<td>$1 \times 13$</td>
</tr>
<tr>
<td>Pseudorange (for up to 13 satellites)</td>
<td>Double</td>
<td>$8 \times 13$</td>
</tr>
<tr>
<td>Integrated Doppler (for up to 13 satellites)</td>
<td>Float</td>
<td>$4 \times 13$</td>
</tr>
<tr>
<td>Padding</td>
<td>Integer</td>
<td>27</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>228</strong></td>
</tr>
</tbody>
</table>

Although the data is 228 bytes, it could be reduced to 222 bytes and fit into one, yet unidentified Message Type.
5 RESULTS AND DATA ANALYSIS

The data set from the van test was collected on July 9, 2002 from 254139 to 255205 seconds GPS Time, for a period of 1067 seconds. The data set from the flight test was collected on September 4, 2002 from 333549 to 338514 seconds GPS Time, for a period of 4966 seconds.

5.1 Results

5.1.1 Van Data Results

The van was driven on the runway centerline for eight loops of the runway and taxiway at UNI. The van was driven on the right and left of the runway, the third round. The mobile user positions (van), in East vs. the North coordinates, are plotted in Figure 5.1 to map the trajectory of the van.
Figure 5.1 Van Trajectory in East and North Coordinates

The point (0,0) is the ground-based station NovAtel GPS Pinwheel Antenna located on the AEC Hangar roof. The East coordinates of the remote van positions, as calculated by the mobile user (i.e., van), are plotted with respect to GPS time in Figure 5.2.
Figure 5.2 Calculated Remote Position East Coordinates of the Van

The East coordinates of the mobile user (i.e., van) DGPS positions are compared to that of the remote van positions calculated by the ground-based station, using the van pseudorange and integrated Doppler measurement. Their differences are plotted with respect to GPS time in Figure 5.3.
It is evident from Figure 5.3 that the difference between the user transmitted DGPS position and the remotely calculated DGPS position by the ground-based station, using the remote pseudorange and integrated Doppler measurement, is bound by 0.001 m. It can therefore be assumed that the calculated and transmitted positions are the same.

The East coordinates of the remote van positions are compared to the East coordinates of the truth data to generate absolute error plots. The errors in the East coordinates with respect to GPS time are plotted in Figure 5.4 using the Ashtech Z12 truth reference data.
It is observed from Figure 5.4 that the errors are within a meter. The mean error in the East coordinates is 0.051 m. The standard deviation of the error is 0.187 m.

The North coordinates of the remote van positions, as calculated by the van, are plotted with respect to GPS time in Figure 5.5.
The difference in the North coordinates of the mobile user (i.e., van) DGPS positions and the remote van positions, calculated by the ground-based station using the van’s measured pseudorange and integrated Doppler, with respect to GPS time are plotted in Figure 5.6.
As observed in Figure 5.6, the difference in the North coordinates is bound by ± 0.001 m. It can therefore be assumed that the calculated and transmitted positions are the same.

The errors in the North coordinates with respect to GPS time are plotted in Figure 5.7, using the Ashtech Z12 truth reference data.
Figure 5.7 Errors in North Coordinates of the Van

From Figure 5.7, it is observed that the error in the North coordinates is mostly within ± 1.0 m. The mean of the error is 0.135 m. The standard deviation of the error is 0.294 m.

The Up coordinates of the remote van position, as calculated at the mobile (i.e. van) user, are plotted with respect to GPS time in Figure 5.8.
Figure 5.8 Calculated Remote Position Up Coordinates of the Van

The difference in the Up coordinates of the mobile user’s DGPS positions and the remote van positions, calculated by the ground-based station, using the van’s measured pseudorange and integrated Doppler, with respect to GPS time is plotted in Figure 5.9.
From Figure 5.9, it is observed that the difference in the Up coordinates is bound by ± 0.002 m. It can therefore be assumed that the calculated and transmitted positions are the same.

The errors in the Up coordinates with respect to GPS time are plotted in Figure 5.10 using the Ashtech Z12 truth reference data.
From Figure 5.10, it is observed that errors ($\pm \sim 1.5$ m) are slightly higher than those in the East and the North coordinates. This may be due to the multipath since the van was driven close to the hangar and other buildings. The mean of the error in the Up coordinates is 0.097 m. The standard deviation of the error is 0.454 m.

Figure 5.11 is a plot of the magnitude of the error with respect to GPS time. As observed in Figure 5.11, the magnitude of the error in the East North Up (ENU) coordinates is within 2 m. The mean of the magnitude of the error is 0.526 m. The standard deviation of the magnitude of the error is 0.284 m. Overall, the error performance was very good based on the level of technology implemented for this system.
Figure 5.11 Magnitude of Error in ENU Coordinates of the Van

The sky plot of all the available satellites is plotted in Figure 5.12.
A maximum of seven satellites were present during the van test on July 9, 2002. At least six satellites were present at any given time. The mask angle was set to 5 degrees.

The Dilution of Precision (DOP) is a function of the satellite geometry. The various DOP parameters are calculated from the elements of \((H^TH)^{-1}\) matrix in the ordinary least-squares solution. The DOP parameters are defined as ratios of the standard deviations of components from the position covariance matrix in the numerator and the standard deviation of the pseudorange error in the denominator. The DOP parameters are geometry factors that statistically relate errors of the user state (position and time solution) to those of pseudorange errors. The Horizontal Dilution of Precision (HDOP) is
defined as the figure of merit type that measures the DOP of the horizontal (e.g., latitude/longitude) components of the positional portion of the navigation solution [21]. Figure 5.13 is the plot of the HDOP at the ground-based station with respect to GPS time during the van test.

![Figure 5.13](image.png)

**Figure 5.13 Horizontal Dilution of Precision During the Van Test**

As observed in Figure 5.13, the HDOP is very good and close to 1.1 for most of the van test.

The Vertical Dilution of Precision (VDOP) is defined as the DOP that measures the vertical (e.g., altitude) DOP components of the positional portion of the navigation
solution [21]. Figure 5.14 is the plot of the VDOP with respect to GPS time during the van test.

The sharp fall in both Figure 5.13 and Figure 5.14 signifies the arrival of a new satellite, SV 22, in the region. It should be noted that a VDOP of ~1.65 (average) is considered good. The low HDOP and VDOP (i.e., good SV geometry) help provide the good E,N,U position errors presented in Figure 5.4, 5.7, and 5.10 respectively.
5.1.2 Flight Test Results

The DC-3 Aircraft Flight profile performed on September 4, 2002, included a total of 6 low approaches. The first two low approaches were towards Runway 25 at UNI. The next three low approaches were towards Runway 7 at UNI. The last low approach was towards runway 25. The East vs. the North coordinates (i.e., ground track) of the remote aircraft positions are plotted in Figure 5.15.

Figure 5.15 DC-3 Trajectory in East and North Coordinates
The point (0,0) is the location of the Bi-directional DGPS ground-based station antenna located on the rooftop of the AEC Hanger.

The East coordinates of the remote aircraft positions, as calculated by the mobile user (i.e., van), are plotted with respect to GPS time in Figure 5.16.

![Figure 5.16 Calculated Remote Position East Coordinates of the DC-3 Aircraft](image)

The East coordinates of the mobile user (i.e., aircraft) DGPS positions are compared to that of the remote aircraft positions calculated by the ground-based station, using the
aircraft’s pseudorange and integrated Doppler measurement. Their difference is plotted with respect to GPS time in Figure 5.17.

As observed in Figure 5.17, there is a sudden increase in the difference. This is due to the ephemeris updates of all the SVs at GPS second 338431, as observed from the aircraft. Figure 5.18 shows the difference in the East coordinates of SV 22 due to the ephemeris update. These data were post-processed with the ephemeris data from the ground and air data set.

**Figure 5.17 Difference in East Coordinates of the DC-3 Aircraft**
The difference shown in Figure 5.11 is very small, on the order of ± 0.2 m. The ephemeris data set mismatch in the air and the ground can be remedied by transmitting an ephemeris CRC in the uplink [11]. This level of data checking was not done in this effort but could be implemented in future work.

There is a sudden increase in the difference as observed at the mobile user and the ground-based station.

\[\text{Figure 5.18 Difference in the East coordinates of SV 22 During the Flight Test}\]

The East coordinates of the remote aircraft positions are compared to the East coordinates of the truth data, using the Ashtech Z12 truth reference data. The errors in the East coordinates with respect to GPS time are plotted in Figure 5.19.
The error in the East coordinate is within ±2 m. The mean of the error in the East coordinates is 0.161 m. The standard deviation of the error in the East coordinates is 0.549 m.

The North coordinates of the remote aircraft positions are plotted with respect to GPS time in Figure 5.20.
The North coordinates of the mobile user (i.e., aircraft) DGPS positions are compared to that of the remote aircraft positions calculated by the ground-based station, using the aircraft’s pseudorange and integrated Doppler measurement. Their difference is plotted with respect to GPS time in Figure 5.21.
The slight increase in the difference is due to the almanac update in as observed from the aircraft; however, the difference is still low ($\pm 0.15$ m).

The North coordinates of the remote aircraft positions are compared to the North coordinates of the truth data using the Ashtech Z12 truth reference data. The errors in the North coordinates with respect to GPS time are plotted in Figure 5.22.
The mean of the error in the North coordinates is 0.026 m. The standard deviation of the error in the North coordinates is 0.548 m.

The Up coordinates of the remote aircraft positions are plotted with respect to GPS time in Figure 5.23.
Figure 5.23 Calculated Remote Position Up Coordinates of the DC-3 Aircraft

Figure 5.23 clearly shows the take-off, landing, and the six missed approaches.

The Up coordinates of the mobile user (i.e., aircraft) DGPS positions are compared to that of the remote aircraft positions calculated by the ground-based station, using the aircraft’s pseudorange and integrated Doppler measurement. Their difference is plotted with respect to GPS time in Figure 5.24.
Figure 5.24 Difference in Up Coordinates of the DC-3 Aircraft

The increase in the difference again is due to the almanac update in as observed from the aircraft. This difference was bounded by $\pm 0.23 \text{ m}$.

The Up coordinates of the remote aircraft positions are compared to the Up coordinates of the truth data using the Ashtech Z12 truth reference data. The errors in the Up coordinates with respect to GPS time are plotted in Figure 5.25.
The errors in the Up coordinates are within in $\pm 4$ m. The mean of the error in the Up coordinates is 0.328 m. The standard deviation of the error in the Up coordinates is 0.979 m.

The errors in the Up coordinates are relatively large for a DGPS system. The following factors could be responsible for this.

- Only one Pinwheel GPS Antenna, with moderate multipath mitigation technology was used.
The Pinwheel GPS Antenna was located on the hangar rooftop that has a corrugated metal roof thus located in a very non-ideal multipath environment.

The magnitude of the error component is plotted with respect to GPS in Figure 5.26.

Figure 5.26 Magnitude of Error in ENU Coordinates of the DC-3 Aircraft

The mean of the magnitude of the error component is 1.127 m. The standard deviation of the magnitude of the error component is 0.652 m.
Figure 5.27 is a plot of the azimuth vs. elevation angle of each of the SVs in the region.

Figure 5.27 Sky Plot of Satellites Available During the Flight Test

A total of 9 satellites were observed. The mask angle is set to 5 degrees.

Figure 5.28 is the plot of the HDOP with respect to GPS time during the aircraft test.
The HDOP is close to ‘1’, indicating very good satellite geometry in the horizontal orientation. The sudden rise in the HDOP indicates a satellite moving out of the region. The sudden fall in the HDOP indicates a satellite moving into the region.

Figure 5.29 is the plot of the VDOP with respect to GPS time.
Initially the VDOP is a little high indicating fair satellite geometry in the vertical (i.e., Up) orientation. This could add error in the vertical dimension.

B-values for each satellite were plotted and analyzed. As an example, Figure 5.30 shows a B-value plot of SV 22.
As observed from Figure 5.30, the B-values vary between ±0.3 m. This value of ±0.3 m is higher than a typical B-value, especially for the zero-baseline case illustrated here, and is likely due to non-stationary errors in the ground-based station. This could contribute to the error in the ENU coordinates.

The PRCs for each satellite were also plotted and analyzed. As an example, Figure 5.31 shows a PRC plot of all the SVs during the aircraft test.
As observed from Figure 5.31, the PRC plots of SV 25, SV 14, SV 13, and SV 6 follow a ramp-like function. This could contribute error to the ENU coordinates. These non-stationary PRCs of low frequency could be a result of multipath, tropospheric and ionospheric delays, and increased code jitter noise due to a decrease in carrier-to-noise ratio from low elevation satellites.

Comparing the flight test data to the van test data, we observe that the errors in aircraft position are larger than the errors in the van position. This is probably because of the
presence of more low elevation satellites during the flight test as compared to that of the van test (See Figure 5.12 and Figure 5.27).

During the van test and the flight test, including surface movement of the DC-3, the data link was never lost. The data transmitted was also accurate. This underscores the efficiency and continuity of the data link.
6 SUMMARY AND CONCLUSIONS

6.1 Summary

The LAAS is currently being designed to meet the high accuracy positioning requirements for precision approaches and landing in the airport locality. The LAAS could also provide position and velocity information for surface navigation and ADS-B. Prior to this research, a remote-positioning system was never integrated into the prototype LAAS. This is believed to be the first successful real-time demonstration of the Bi-directional DGPS based upon a prototype LAAS architecture. This thesis documents the incorporation of a remote-positioning system into the prototype LAAS for various applications such as aircraft, UAV, LV, or missile monitoring, tracking and/or control. In addition to providing highly accurate PVT information at the mobile user, this system provides highly accurate PVT information at the ground-based station, for the test conditions, to help increase situational awareness in and around the airport area.

A conceptual Bi-directional DGPS was proposed for the research. To implement the Bi-directional DGPS, the existing mini-LAAS ground and air software were modified. The VDB rate was analyzed to verify the number of bytes for the data transmission downlink. A preliminary experiment was conducted using an Ohio University van as the mobile user. The final experiment was conducted using the Ohio University DC-3 Aircraft as the mobile user. In both the experiments, the Bi-directional DGPS ground-based station was set up in the AEC Hangar at UNI.
An integrity check was also created for the remote position solutions transmitted to the ground-based station. From the transmitted pseudoranges and integrated Doppler measurements, the DGPS position solution of the mobile user was recalculated at the ground. This remotely calculated DGPS position solution and the mobile user transmitted DGPS position solutions were displayed in real-time. This enabled the comparison of the two DGPS position solutions.

In order to verify and demonstrate the results, the truth data was post-processed using Matlab simulations; position and error plots were generated.

6.2 Conclusions

The Bi-directional DGPS was successfully demonstrated in real-time at the Ohio University Airport.

The graphs of the difference between the transmitted and calculated snapshot position solutions as observed at the ground-based station, in post-process, shows that the two position solutions can be considered to have the same value in the case of a van test (average magnitude of distance is approximately 0.002 m). In the case of the flight test the average magnitude of distance is approximately 0.25 m. The two position solutions can be considered to have the same value until an ephemeris update occurs.
Comparing the results with the truth data, it is observed that the 1σ mean error in the position solution for the van test is approximately 0.526 m and the flight test is 1.127 m. Given that a single antenna was used at the ground-based station, these error values were fair.
7 RECOMMENDATIONS FOR FUTURE WORK

Although this Bi-directional DGPS system was successfully implemented in real-time based upon a prototype version of the LAAS, this research can be complimented and expanded in scope by the following recommendation.

- The system could be demonstrated using a more fully populated LAAS. This would entail the implementation of multiple ground-based station sites as well as a VDB.

- The integrity monitor could be improved by setting a threshold for the difference between the transmitted remote position and the calculated remote position. This would make it possible to indicate usable and unusable remote position readings. Additionally, a warning could be sent to the mobile user in case of a mismatch data set.

- The present mobile user system transmits the old remote position when the new remote positions are not available. One more byte could be added to the downlink indicating whether the remote position is new or old. In case of an old position, the stand-alone position could be transmitted, and an appropriate flag could be set to calculate what the position is based on (e.g. DGPS, stand-alone, WAAS, etc.).
• The mobile user transmits its position and measurement to the ground-based station only once per second. In addition, the data latency is about two seconds. To support remote pilot applications, the frequency of position and measurement transmission could be increased to 5 Hz. Also, the data latency could be in the order of milliseconds.

• An ephemeris CRC could be included in uplink to avoid the ephemeris mismatch. The ground-based station would then wait for at least two minutes but not more than three minutes before using the new ephemeris data once an ephemeris change is detected. This would enable both the ground-based station and the mobile user to use the same SV ephemeris set in the event of an ephemeris update.

• Velocity information, computed from the Bi-directional DGPS, could be downlinked to enable a system, independent of LAAS, to calculate the IIP with added integrity.
8 REFERENCES


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