GLOBAL POSITIONING SYSTEM
BASED RUNWAY INSTRUMENTATION SYSTEM

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<tr>
<td>3D</td>
<td>Three-dimensional</td>
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<tr>
<td>A/D</td>
<td>Analog-To-Digital</td>
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<tr>
<td>ADS-B</td>
<td>Automatic Dependent Surveillance-Broadcast</td>
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<td>AEC</td>
<td>Avionics Engineering Center</td>
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<td>AGL</td>
<td>Above Ground Level</td>
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<td>ATC</td>
<td>Air Traffic Control</td>
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<tr>
<td>bps</td>
<td>Bits per second</td>
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<tr>
<td>C/A</td>
<td>Coarse/acquisition</td>
</tr>
<tr>
<td>CDMA</td>
<td>Code Division Multiple Access</td>
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<tr>
<td>CDU</td>
<td>Control Display Unit</td>
</tr>
<tr>
<td>cm</td>
<td>Centimeter</td>
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<tr>
<td>cm/s</td>
<td>Centimeter per second</td>
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<tr>
<td>CTS</td>
<td>Clear-To-Send</td>
</tr>
<tr>
<td>dB</td>
<td>Decibel</td>
</tr>
<tr>
<td>dBm</td>
<td>dB referenced to one milliWatt</td>
</tr>
<tr>
<td>DBEN</td>
<td>Binary message format used by Ashtech Z-12 receiver</td>
</tr>
<tr>
<td>DD</td>
<td>Double Difference</td>
</tr>
<tr>
<td>DGPS</td>
<td>Differential Global Positioning System</td>
</tr>
<tr>
<td>DOS</td>
<td>Disk operating system</td>
</tr>
<tr>
<td>DSP</td>
<td>Digital Signal Processor</td>
</tr>
<tr>
<td>ECEF</td>
<td>Earth-Centered Earth-Fixed</td>
</tr>
<tr>
<td>FAA</td>
<td>Federal Aviation Administration</td>
</tr>
<tr>
<td>ft</td>
<td>Foot</td>
</tr>
<tr>
<td>GDOP</td>
<td>Geometric Dilution of Precision</td>
</tr>
<tr>
<td>GLONASS</td>
<td>Global Navigation Satellite System</td>
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<tr>
<td>GPS</td>
<td>Global Positioning System</td>
</tr>
<tr>
<td>GRIS</td>
<td>GPS based Runway Instrumentation System</td>
</tr>
<tr>
<td>HDOP</td>
<td>Horizontal Dilution of Precision</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Full Form</td>
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<td>--------------</td>
<td>-----------</td>
</tr>
<tr>
<td>HP</td>
<td>Hewlett Packard</td>
</tr>
<tr>
<td>IF</td>
<td>Intermediate Frequency</td>
</tr>
<tr>
<td>I/O</td>
<td>Input/Output</td>
</tr>
<tr>
<td>kB</td>
<td>Kilobytes</td>
</tr>
<tr>
<td>KUNI</td>
<td>Ohio University Airport in Albany, Ohio</td>
</tr>
<tr>
<td>LLH</td>
<td>Latitude, Longitude, Height</td>
</tr>
<tr>
<td>m</td>
<td>Meter</td>
</tr>
<tr>
<td>m/s</td>
<td>Meter per second</td>
</tr>
<tr>
<td>MHz</td>
<td>Megahertz</td>
</tr>
<tr>
<td>ms</td>
<td>Millisecond</td>
</tr>
<tr>
<td>NASA</td>
<td>National Aeronautics and Space Administration</td>
</tr>
<tr>
<td>nmi</td>
<td>Nautical Mile</td>
</tr>
<tr>
<td>OS</td>
<td>Operating System</td>
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<tr>
<td>PC</td>
<td>Personal Computer</td>
</tr>
<tr>
<td>P(Y)-code</td>
<td>Precise Code</td>
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<tr>
<td>PDOP</td>
<td>Position Dilution of Precision</td>
</tr>
<tr>
<td>PP</td>
<td>Post-processing</td>
</tr>
<tr>
<td>PR</td>
<td>Pseudorange</td>
</tr>
<tr>
<td>PRN</td>
<td>Pseudorandom Noise</td>
</tr>
<tr>
<td>RF</td>
<td>Radio Frequency</td>
</tr>
<tr>
<td>RHCP</td>
<td>Right-Hand Circularly Polarized</td>
</tr>
<tr>
<td>RMS</td>
<td>Root-Mean-Squared</td>
</tr>
<tr>
<td>RTCM</td>
<td>Radio-Technical Commission for Maritime Services</td>
</tr>
<tr>
<td>RTK</td>
<td>Real Time Kinematics</td>
</tr>
<tr>
<td>RTPNAV</td>
<td>Real-Time Precise Navigation</td>
</tr>
<tr>
<td>RTS</td>
<td>Ready-To-Send</td>
</tr>
<tr>
<td>SD</td>
<td>Single Difference</td>
</tr>
<tr>
<td>S/N</td>
<td>Signal-To-Noise</td>
</tr>
<tr>
<td>SV</td>
<td>Space Vehicle</td>
</tr>
<tr>
<td>TDOP</td>
<td>Time Dilution of Precision</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Definition</td>
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<tr>
<td>-------------</td>
<td>------------------------------------------------</td>
</tr>
<tr>
<td>TOA</td>
<td>Time-Of-Arrival</td>
</tr>
<tr>
<td>TDMA</td>
<td>Time Division Multiple Access</td>
</tr>
<tr>
<td>UERE</td>
<td>User-Equivalent Range Error</td>
</tr>
<tr>
<td>UPS</td>
<td>Uninterruptible Power Supply</td>
</tr>
<tr>
<td>URE</td>
<td>User Receiving Equipment</td>
</tr>
<tr>
<td>U.S.</td>
<td>United States</td>
</tr>
<tr>
<td>UTC</td>
<td>Coordinated Universal Time</td>
</tr>
<tr>
<td>VDL</td>
<td>VHF Digital Link</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>
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<tr>
<td>WGS-84</td>
<td>World Geodetic System 1984</td>
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</table>
1 INTRODUCTION

A runway instrumentation system is used at aircraft test ranges to precisely track aircraft, and provide surveillance data to the Range Control Center (RCS) and to the Range User. Current systems used to perform multiple aircraft sensing and tracking can be divided into (1) Radar sensing systems, and (2) Laser sensing systems. The disadvantages of the radar system are its high cost, large structure, and its performance is limited by factors such as mobile-user size and range, as well as signal distortion caused by diffraction from objects. Laser systems have fairly good accuracy (approximately 1 foot (ft) up to 5 nautical miles (nmi)) [1], but are limited in range by weather conditions, such as cloudiness and humidity. Both radar and laser systems are based on the emission of a signal and its reflection from the mobile-user. In principle, this allows for tracking of non-cooperative targets. In practice, however, the mobile-user aircraft are still equipped with some type of reflector to increase the accuracy through better knowledge of the point at which the signal reflects off the aircraft.

The research presented in this Thesis is aimed at the development of a high precision, real-time GPS-based runway instrumentation system (GRIS). The proposed system is designed to produce real-time position and velocity data on a single mobile-user aircraft, but its concept could be applied to tracking multiple targets as well.
2 SYSTEM OVERVIEW

2.1. System background

The concept of using GPS technology incorporated with a data link for the purposes of aircraft tracking and Air Traffic Control (ATC) management is still relatively new and under research. The runway instrumentation function is similar to a concept known as automatic dependent surveillance-broadcast (ADS-B) [2]. ADS-B enables the transmission of aircraft location to other aircraft and/or ATC in an operating area and plotting of its location without the use of expensive radar equipment. A GRIS can augment or replace ground-based tracking radars and can be used as part of a collision avoidance system on the ground or in the aircraft.

2.2. GRIS Description

The GRIS is based on an inverse Differential Global Positioning System (DGPS) concept. In regular DGPS, a ground-based, fixed reference station calculates corrections for GPS satellites based at the surveyed location of the reference station GPS antenna. These corrections are broadcast to mobile users, who can improve their navigational accuracies by applying the broadcast corrections to their own GPS measurements. With inverse DGPS, the mobile user broadcasts its measurements, which are received by the reference station where all the processing is performed. By combining the received measurements from the mobile user with the reference station GPS measurements, high precision position and velocity data of the mobile user can be calculated. The system operates in a real-time mode and the end-result data can be represented in either absolute coordinates, or relative coordinates with respect to the reference station. Absolute coordinates would be expressed in the World Geodetic System from 1984 (WGS-84), since GPS satellite positions are referenced to WGS-84.

The GRIS system, used to track a single mobile-user, consists of the airborne and ground station sub-systems. Basic components of both sub-systems are dual-frequency GPS
receivers and Very High Frequency (VHF) radio transmitter/receiver equipment. The airborne sub-system broadcasts aircraft GPS receiver raw data to the ground station. In the ground station, the ground and airborne GPS data are combined and high-accuracy vehicle positions and velocities are calculated. This information is then fed to display and processing systems through a high-speed data link. For the multiple vehicle capability, a Time Division Multiple Access (TDMA) or a Code Division Multiple Access (CDMA) data link would replace the current, single vehicle data link. Although the current system can be extended to multiple targets, this is outside the scope of this Thesis.

The proposed GRIS system can be used as a replacement for the existing radar and laser tracking systems, but it can also be used as a truth-reference or flight-reference system for the evaluation of other airborne navigation and landing systems.

2.3. GRIS Requirements

Performance objectives for the GRIS include position accuracy, velocity accuracy, timing, operating range of the system, data output, and the number of simultaneously tracked targets.

The specific GRIS requirements are summarized below.

- 3-Dimensional position accuracy better than 0.1 m (Root-Mean-Squared or RMS);
- 3-Dimensional velocity accuracy better than 10 cm/s (RMS);
- Typical operating range between 10-20 nmi in a high-accuracy mode, and extended range between 100-200 nmi in a reduced accuracy mode;
- Real-time position and velocity data output at 10 samples per second per vehicle, utilizing Ethernet data link. The update rate requirement will be dependent on the
GPS receiver used for implementation, and may change during the design stage of the project. Synchronization to Coordinated Universal Time (UTC) to within 1 ms, with latency less than 0.2 seconds;

- Simultaneous tracking of a minimum of four airborne vehicles.

In addition to the above performance requirements, airborne sub-system design considerations should include minimization of its size, adaptability to a variety of aircraft platforms, and maximization of the use of automated operation.
3 GPS OVERVIEW

Satellite navigation is usually implemented as a radio-navigation system. Radio-navigation systems that were developed in the late 1920's utilize low operating frequencies and thus do not require line-of-sight, but they are less accurate than more recently developed systems that use relatively short wavelengths. Newer systems are generally highly accurate but require a line-of-sight between the transmitter and the receiver stations. One major advantage of satellite-based navigation systems is they provide an all-weather, worldwide navigation capability. The major disadvantages of satellite-based navigation systems are their susceptibility to intentional or unintentional interference, and temporary unavailability of the transmitted signal due to an obstacle blocking or lack of satellite visibility coverage [3].

The first two satellite-based radio-navigation systems are the United States Navy's Transit System, also known as the Navy Navigation Satellite System (NNSS), and its Russian counterpart - Tsikada. The two systems provided a two-dimensional, high-accuracy positioning service, but had limited applications due to long periods of time required for one position fix (0.5 – 2 hours). They are suitable for slow moving objects, but not for aircraft with high-dynamic motion. This shortcoming led to the development of both the U.S. Global Positioning System and the Russian Global Navigation Satellite System (GLONASS). Both systems are passive ranging systems, and provide both range and range-rate measurements. Both GPS and GLONASS provide global coverage, continuous/all weather operation, ability to serve high-dynamic platforms, and high accuracy [2]. Once GPS was fully operational, the U.S. Navy ceased operation of Transit on December 31, 1996 [3].
3.1. Some GPS Applications

Both GPS and GLONASS originated as solely military systems, but in the last decade or two their uses in civilian applications have extensively developed. Some of the GPS applications are summarized as follows [2]:

- The Aviation industry incorporates a global navigation satellite system (GNSS) and its augmentations into the systems that provide aircraft guidance through all stages of flight, and monitoring for collision avoidance as part of ATC.

- Spacecraft Guidance for NASA Space Shuttle flights nowadays utilizes GPS technology for providing guidance in all phases of the shuttle’s operation, i.e., ground launch, orbiting, reentry, and landing.

- Maritime usage relates to navigation and guidance of small and large ships. Some systems incorporate also local area differential GPS networks to increase system accuracy during harbor approach and river navigation.

- Land Surveying, Mapping and Guidance utilizes GPS technology in different industries. The surveying community takes advantage of highly accurate differential methods to obtain results within the millimeter range. Railroad companies use similar techniques in determining train location with respect to adjacent tracks. The automotive industry employs GPS for route guidance, tracking and emergency messaging. The positioning data from GPS can be combined with a street database and digital moving map displays to help drivers with navigation directions as well as the most efficient routing.

Many more applications exist for both GPS and GLONASS. For example, this Thesis investigates the use of inverse DGPS for runway instrumentation applications.
3.2. GPS Segments

The Global Positioning System consists of three segments: satellite constellation, ground control/monitoring network, and user receiving equipment. A simple diagram, shown in Figure 1, illustrates the interaction and dependencies of these segments.

3.2.1. Space Segment / Satellite Constellation

The space segment of GPS consists of a 24-satellite constellation. The GPS satellites, also known as space vehicles (SV), have an orbital period of one-half of a sidereal day or 11 hours 58 minutes. The satellite orbit planes have an inclination angle of 55 degrees relative to the equatorial plane [2]. Each satellite transmits on two carrier frequencies denoted as L1 and L2. The L1 carrier frequency is 1575.42 MHz, and is modulated by
two pseudorandom noise (PRN) codes: (1) the coarse/acquisition code (C/A) code, and (2) the precise (encrypted) code (P(Y)-code), as well as navigation message data. The L2 carrier frequency is 1227.60 MHz, and is currently only modulated by the P(Y) code and the navigation message data. The C/A code has a period of 1 ms and is generated at a chipping rate of 1.023 mega chips per second (Mcps). The P(Y) code for each satellite has a period of one week and is transmitted at 10.23 Mcps. The navigation data is transmitted at 50 bits per second (bps). A typical power spectrum of C/A code and P(Y)-code at the L1 carrier frequency is shown in Figure 2.

![Power spectrum of C/A code and P(Y)-code at L1](image)

Figure 2, Power spectrum of C/A code and P(Y)-code at L1

3.2.2. Ground Control / Monitoring Network

The ground control segment maintains the satellites' proper functionality. Major tasks include monitoring of the satellites' correct orbital position and clock data, satellite subsystem health and status, satellite solar arrays, battery power levels, and replacement of bad satellites or activation of the spares [2]. As satellites pass over the monitoring
stations, the pseudorange and delta range measurements, received navigation message data, and local weather condition information are all collected by the monitoring stations and then transmitted to the master control station. The information for individual satellites is processed, and the corrected clock information, ephemeris, almanac and other data are uploaded via the ground uplink antennas.

3.2.3. User Receiving Equipment

The user receiving equipment (URE), or typically referred to as just a GPS receiver, consists of five principal components: antenna, receiver, processor, input/output (I/O) device (i.e., control display unit or CDU), and a power supply [2]. A block diagram of generic GPS receiving equipment is illustrated in Figure 3.

![Figure 3, Generic GPS receiver architecture](image-url)
Initially, satellite signals are received by the right-hand circularly polarized (RHCP) antenna, which provides almost hemispherical coverage. After the received radio frequency (RF) CDMA signals have been filtered through a bandpass filter and passed through a pre-amplifier, they are then downconverted to an intermediate frequency (IF). In modern GPS receivers, the IF signals are sampled and digitized by an analog-to-digital (A/D) converter. The sampled data are then transmitted to the digital signal processor (DSP). The DSP consists of N parallel channels that simultaneously track the codes and carriers from up to N different satellites. Individual channels include code and carrier tracking loops that perform code and carrier-phase measurements, and also demodulate navigation message data. Two different satellite-to-user measurement types may be produced through the tracking channels: pseudoranges and integrated Doppler frequency shifts. Depending of the application of the receiver, a particular measurement type is chosen and forwarded together with demodulated navigation message data to the navigation/receiver processor. The task of this processor is control of the receiver through its operational sequence, which includes signal acquisition, signal tracking and data collection. In addition, the processor may also compute the position, velocity, and time (PVT) solution from the measurements. In the final process of the user receiving equipment operation, obtained PVT solution data are transmitted to the I/O device. A final component of the URE is a power supply that can either be integral, external or a combination of the two.

3.3. Performance of Standalone GPS

GPS implements the concept of one-way time-of-arrival (TOA) ranging to determine user position [2]. The concept involves measuring the time it takes for a signal transmitted by an emitter source (i.e., satellite), at a known location in a defined coordinate system, to reach a user receiver. The signal propagation time is multiplied by the speed of the signal (i.e., speed of light) to obtain the emitter-to-receiver distance. If propagation-time measurements are obtained from multiple-emitter sources at known locations, the position of the user receiver can be calculated.
It is intuitive to presume that if a 3-D user position is desirable, TOA ranging measurements from a minimum of three independent emitter sources are required. It turns out, in fact, that the minimum number of GPS transmitting satellites needed for accurate 3-D user position computation is four, since the clocks of GPS and user receivers are not synchronized. Even though satellites are equipped with highly accurate atomic clocks, they have a clock offset from the UTC system, as does the less accurate user receiver clock. The two offsets are generally not the same, but in determining accurate TOA measurements only the relative difference between the GPS and receiver clock is required. Therefore, one additional TOA measurement is needed for computation of a receiver clock offset from GPS time.

TOA ranging measurements are performed on either or both C/A PRN ranging code and P(Y) PRN code. Correlating the incoming PRN code with the receiver's locally generated PRN code, the range that contains the geometric satellite-to-user range and an offset attributed to the difference between the satellite and receivers clocks can be obtained. This measurement is denoted as pseudorange, and can be mathematically represented as follows:

\[ \rho = r + c \cdot (t_u \cdot \delta t) \]  
(1)

and

\[ r = c \cdot (T_u - T_s) = c \cdot \Delta t \]  
(2)

Where: \( \rho \) is a pseudorange; 
\( r \) is the true geometric range between the satellite and the receiver antenna; 
\( c \) is the GPS speed of light (299792458 m/s); 
\( t_u \) is the offset of the receiver clock from GPS system time; 
\( \delta t \) is the offset of the satellite clock from GPS system time;
$T_u$ is the user time at which the signal reached the user receiver; $T_s$ is the satellite time at which the signal left the satellite.

The timing relationships between the true geometrical range and the measured pseudorange are shown in Figure 4.

![Diagram showing the timing relationships between true geometrical range and measured pseudorange](image)

Figure 4, Range measurement timing relationship

The above diagram shows that the difference between the true geometric range and the measured pseudorange is only due to the unsynchronized satellite and receiver clocks. In real-life applications, there are additional error sources that also contribute to differences between the true geometric range and the pseudorange. These errors are referred to as pseudorange errors, or also known as the user-equivalent range errors (UERE).

The user position error also depends on the geometry of the satellites relative to the user. The dilution of the accuracy of the position errors due to satellite geometry is called the Geometric Dilution of Precision (GDOP).

3.3.1. Pseudorange Errors

The pseudorange errors, as previously mentioned, are contributed by different error sources, including satellite clock stability, estimation of the ephemerides to be uplinked to
the satellites, relativistic effects, propagation of the signal through different atmospheric media (i.e., ionosphere, troposphere), noise and resolution of the receiver tracking loops, and arrival of the signal at the receiver via multiple paths due to reflections from the Earth and nearby objects generally referred to as multipath [2]. A summary of the major pseudorange error sources and the error budget is provided in Table 1 [2].

Table 1, GPS C/A code pseudorange error budget (from [2])

<table>
<thead>
<tr>
<th>Segment Source</th>
<th>Error Source</th>
<th>GPS 1σ Error (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Space</td>
<td>Satellite clock stability</td>
<td>3.0</td>
</tr>
<tr>
<td></td>
<td>Predictability of satellite perturbations</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>Other (thermal radiation, etc.)</td>
<td>0.5</td>
</tr>
<tr>
<td>Control</td>
<td>Ephemeris prediction error</td>
<td>4.2</td>
</tr>
<tr>
<td></td>
<td>Other (thruster performance, etc.)</td>
<td>0.9</td>
</tr>
<tr>
<td>User</td>
<td>Ionospheric delay</td>
<td>5.0</td>
</tr>
<tr>
<td></td>
<td>Tropospheric delay</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>Receiver noise and resolution</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>Multipath</td>
<td>2.5</td>
</tr>
<tr>
<td></td>
<td>Other (interchannel bias, etc.)</td>
<td>0.5</td>
</tr>
<tr>
<td>System UERE</td>
<td>Total (RSS)</td>
<td>8.0</td>
</tr>
</tbody>
</table>

3.3.2. Geometric Dilution of Precision

It was mentioned in Section 3.3 that a minimum of four satellites is needed to compute the user position. This statement assumes good satellite geometry relative to the user receiver antenna. At certain instances of time, line-of-sight vectors from the user's receiving antenna to the visible satellites do not provide an adequate geometry, and more than four satellites are needed to produce an accurate position. This degradation of accuracy is known as geometric dilution of precision or GDOP [3]. GDOP is a multiplier that converts range errors into the 4-D solution space. Several other DOP parameters can be defined, including the position dilution of precision (PDOP), time
dilution of precision (TDOP), horizontal dilution of precision (HDOP) and vertical dilution of precision (VDOP).

Due to several error sources that limit the performance of the stand-alone GPS receiver, a differential GPS (DGPS) technique was established for applications where sub-meter accuracy is desired, as is the case for the GRIS project.

3.4. Differential GPS

DGPS enhances stand-alone GPS accuracy through the removal of common errors from two or more receivers viewing the same satellites. In general, DGPS consists of a monitor or reference receiver, whose precise, surveyed position is known; and other receivers denoted as rovers or users that receive correction data from the reference station. Two different DGPS techniques can be used to correct for GPS errors: code-based and carrier-based [2].

3.4.1. Code-based DGPS technique

In the implementation of this method, the reference station makes code-based GPS pseudorange measurements like any other stand-alone receiver. Since the reference station knows its precise position, it can compute the biases in the received pseudorange measurements for each satellite in view. The biases in the ranging measurements are computed by differencing the pseudorange measurement from each satellite and the satellite-to-reference station true geometric range. Even though these biases do not accommodate all the error sources, they do include most of them (i.e., ionospheric and tropospheric delays, satellite clock offset, and satellite orbit error). After they are transmitted to the user receiver, the set of biases corresponding to the satellites in view is applied to the rover pseudorange measurements. The corresponding corrected 3-D rover position has accuracy on the order of several meters. In most of the current code-based DGPS methods, the code measurements are smoothed by the carrier-phase
measurements, which further improves the accuracy of the DGPS position solution to approximately 1 m.

3.4.2. Carrier-based DGPS technique – Double Difference

In order to provide centimeter-level accuracy, a DGPS technique that utilizes phase information of the GPS satellite signal carrier frequencies was developed [2]. This technique, commonly referred to as carrier-phase tracking, produces 3-D position accuracies of several centimeters in dynamic applications and millimeter-level for static applications [2]. The extremely high accuracy is achieved by processing the received satellite signal Doppler frequencies. Doppler frequency information is integrated to form very accurate measurements of the change in signal carrier phase between time epochs.

At the beginning of the process, the carrier-phase single difference (SD) is computed by differencing the measured integrated carrier phase at the reference station and the rover for the same satellite. This computation is repeated for all the satellites in view. The integrated carrier phases of the signal to both the reference station and the rover in terms of fractional and integer carrier cycles are shown in the following equations [2].

\[
\Phi_k^p(t) = \phi_k^p(t) - \phi^p(t) + N_k^p + S_k + f r_k + f r_k \cdot \beta_{spp} + \delta_{spp} \quad (3)
\]

\[
\Phi_m^p(t) = \phi_m^p(t) - \phi^p(t) + N_m^p + S_m + f r_m + f r_m \cdot \beta_{spp} + \delta_{spp} \quad (4)
\]

Where, \( k \) and \( m \) refer to two receivers' antenna phase centers;
\( p \) is the satellite signal source;
\( \phi^p(t) \) is the transmitted satellite signal phase as a function of time;
\( \phi_k^p(t) \) and \( \phi_m^p(t) \) are receiver measured satellite signal phases as a function of time;
\( N \) is the unknown integer number of carrier cycles from \( p \) to \( k \) or \( p \) to \( m \);
\( S \) is the phase noise due to all sources;
\( f \) is the carrier frequency;
\( \tau \) is the associated satellite or receiver clock bias;
\( \beta_{\text{iono}} \) is the advance of the carrier due to the ionosphere;
\( \delta_{\text{tropo}} \) is the delay of the carrier due to the troposphere.

The formulation of the single difference is as follows:

\[
SD_{km} = \phi_{km} + N_{km} + S_{km} + f\tau_{km}
\] (5)

Using two independent SDs, the interferometric double difference (DD) is formed as the difference between the two and has the following form:

\[
DD_{km} = \phi_{km} + N_{km} + S_{km}
\] (6)

Where, \( q \) refers to the second satellite and the receiver clock-bias terms are canceled.

The double difference equation can be rewritten in terms of the unknown baseline vector between the reference station and rover \((\delta)\), the difference of the unit vectors to satellites \( p \) and \( q \) \((\varepsilon^{pq})\), and signal wavelength \((\lambda)\), and is shown in the following equation:

\[
DD_{km} = (\overline{\delta} \cdot \varepsilon^{pq}) \lambda^{-1} = \phi_{km} + N_{km} + S_{km}
\] (7)

Of all the variables shown in the above equation, only the carrier-phase can be precisely measured by the receiver. In real-life applications, the combined carrier-phase measurements are used to produce the DDs and therefore, can be replaced by the term \( DD_{cp} \). In the absence of noise, the DD equations can be written in matrix notation and appear as follows:
\[
\begin{bmatrix}
DD_{cp1} \\
DD_{cp2} \\
DD_{cp3} \\
DD_{cp4}
\end{bmatrix} =
\begin{bmatrix}
e_{12x} & e_{12y} & e_{12z} \\
e_{13x} & e_{13y} & e_{13z} \\
e_{14x} & e_{14y} & e_{14z} \\
e_{15x} & e_{15y} & e_{15z}
\end{bmatrix}
\begin{bmatrix}
b_z \\
b_x \\
b_y \\
b_z
\end{bmatrix}
+ 
\begin{bmatrix}
N_1 \\
N_2 \\
N_3 \\
N_4
\end{bmatrix}
\lambda
\]  

Note that for four DDs, five satellites are needed, since two satellites are required to form each DD. There are two sets of unknowns in the above matrix equation that must be resolved: (1) three spatial components of the baseline vector, and (2) integer numbers of carrier-cycles associated with each DD.

The next step in DD processing is to form a similar set of DDs using the pseudoranges between each antenna and the same set of satellites. The details of this step will not be presented in this Thesis since the procedure is similar to the aforementioned carrier phase DD procedure. The pseudorange-based equivalent of the carrier phase DD matrix equation is similar to that of the carrier phase DDs, except that it is not ambiguous and therefore, it does not have the set of integer ambiguities \( N \). However, the noise on the pseudorange DDs is on the order of several meters, which is much larger than the noise on the carrier phase DDs.

At this point, the low noise (less than 1 cm) but ambiguous carrier phase measurements can be combined with unambiguous but noisier (1 to 2 m) pseudorange code measurements to form smoothed-code DDs [2]. This operation can be implemented using a complementary Kalman filter, which uses the average of the noisy code DD to center quieter carrier phase DDs. In other words, the Kalman filter propagates the smoothed-code DD to the current time epoch using the estimate of the smoothed-code DD from the previous epoch and the difference of the carrier phase DD across the current and past epochs [2]. The estimate, which is computed by averaging the DD pseudorange code difference, establishes the mean of the calculations; and the DD carrier phase
difference adds the most current low-noise information. The Kalman gain is also introduced to weigh the effect of the current code DD measurement. The smoothed-code DDs obtained in this manner, generally has an accuracy of ±1-2 meters or ±5-10λ, places a known limit on the size of the integer ambiguity, and is used in determining a floating solution of the unknown baseline [2]. The term “floating solution” is used to indicate that the ambiguities have not been fixed to their integer values.

To obtain a fixed baseline solution, an ambiguous set of actual integer number of carrier-cycles must be resolved. This is possible by iterating each smoothed-code DD through the limited range of carrier wavelengths, recalculating the least squares baseline solution for each iteration, and then examining the residuals [2]. Those residuals that are within a small threshold value are identified, and the respective sets of integer number of carrier wavelengths are stored as a possible ambiguity solution. If this is done on epoch-by-epoch basis, all stored ambiguity sets will diverge over time (go above the threshold value), except for the right set of integer number of carrier wavelengths that will stay within the formed limits. The baseline solution derived from this method has centimeter-level accuracy in dynamic systems, and millimeter-level accuracy is observed in static systems. The efficacy of this approach is somewhat challenged by the fact that ambiguity resolution may require a long time to perform, and in highly dynamic systems, it is sometimes almost impossible within the time/scope of the operation. This problem can be diminished by combining the two carrier frequencies (L1 and L2) to produce a wide-lane wavelength of approximately 86 cm (λw). This is almost five times the wavelength of the L1 carrier signal, which will significantly speed up the search process since search limits are now only ±3λw [2].

3.5. Processing Techniques for DGPS

The discussion so far focused on the principles used to compute the rover differentially-corrected absolute position, or the baseline between the rover and the reference station, and assumed that the measurement information from the rover is available to the
reference station, or vice versa. In real-life applications, this information needs to somehow be forwarded from one station to another. Two different approaches were developed to accommodate the processing: (1) real-time kinematic (RTK) processing and (2) post-processing.

3.5.1. Real-Time Kinematic Processing

For applications where the user is moving (i.e., kinematic environment) with respect to the fixed reference station, and a real-time navigation solution is required, the desired information from one station is transmitted to another using a data link. Several protocols for this information exchange have been developed throughout the industry, but the one defined by the Radio-Technical Commission for Maritime Services (RTCM) Study Committee 104 has been accepted by the international community as a common standard [2]. The RTCM message format contains header information, frame ID that identifies one of sixty-four possible message types, reference station ID, time reference for the message, parity check bits, etc. A summary of possible RTCM message types is shown in Table 2 [2].

3.5.2. Post-Processing

In applications where real-time navigation computations are not an issue, post-processing of the collected data is performed to compute the baseline vector between two stations. For research purposes, off-line processing is the desired method, since the data can be processed multiple times, both in the forward and backward directions. The latter increases the robustness of the kinematic solution, since all measurements can be used to determine the integer ambiguities. Because of this property, post-processing techniques are usually applied to obtain the reference truth trajectory [4].
Table 2, Summary of RTCM SC-104 Message Types

<table>
<thead>
<tr>
<th>Message Type</th>
<th>Status</th>
<th>Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Fixed</td>
<td>C/A code pseudorange (PR) corrections</td>
</tr>
<tr>
<td>2</td>
<td>Fixed</td>
<td>PR correction difference data used with old parameters</td>
</tr>
<tr>
<td>3</td>
<td>Fixed</td>
<td>Reference station coordinates</td>
</tr>
<tr>
<td>4</td>
<td>Retired</td>
<td>No longer in use; replaced by Type 18 to 21</td>
</tr>
<tr>
<td>5</td>
<td>Fixed</td>
<td>Satellite constellation health information</td>
</tr>
<tr>
<td>6</td>
<td>Fixed</td>
<td>Filler message</td>
</tr>
<tr>
<td>7</td>
<td>Fixed</td>
<td>Radio beacon network description</td>
</tr>
<tr>
<td>8</td>
<td>Tentative</td>
<td>Pseudolite almanac information</td>
</tr>
<tr>
<td>9</td>
<td>Fixed</td>
<td>C/A code PR corrections for subsets of SVs</td>
</tr>
<tr>
<td>10</td>
<td>Reserved</td>
<td>P-code differential corrections</td>
</tr>
<tr>
<td>11</td>
<td>Reserved</td>
<td>C/A code L2 corrections</td>
</tr>
<tr>
<td>12</td>
<td>Reserved</td>
<td>Pseudolite station parameters</td>
</tr>
<tr>
<td>13</td>
<td>Tentative</td>
<td>Ground transmitter parameters</td>
</tr>
<tr>
<td>14</td>
<td>Reserved</td>
<td>Auxiliary message for surveying</td>
</tr>
<tr>
<td>15</td>
<td>Reserved</td>
<td>Ionosphere and troposphere corrections</td>
</tr>
<tr>
<td>16</td>
<td>Fixed</td>
<td>ASCII coded message for display</td>
</tr>
<tr>
<td>17</td>
<td>Tentative</td>
<td>Ephemeris almanac</td>
</tr>
<tr>
<td>18</td>
<td>Tentative</td>
<td>Uncorrelated carrier phase measurements</td>
</tr>
<tr>
<td>19</td>
<td>Tentative</td>
<td>Uncorrelated PR measurements</td>
</tr>
<tr>
<td>20</td>
<td>Tentative</td>
<td>Corrections to the carrier phase measurements</td>
</tr>
<tr>
<td>21</td>
<td>Tentative</td>
<td>Corrections to the PR measurements</td>
</tr>
<tr>
<td>22 to 58</td>
<td>Reserved</td>
<td>Multipurpose messages</td>
</tr>
<tr>
<td>59</td>
<td>Tentative</td>
<td>Proprietary message</td>
</tr>
<tr>
<td>60 to 63</td>
<td>Reserved</td>
<td>Multipurpose messages</td>
</tr>
</tbody>
</table>
4 SYSTEM DESIGN

GRIS implements the differential GPS principle, more specifically inverse DGPS. It is designed to operate as a real-time system, providing an updated navigation solution every second. GRIS consists of two sub-systems: (1) airborne and (2) ground station.

4.1. Airborne Sub-system

The function of this system is to receive the GPS signals, obtain aircraft's raw pseudorange and integrated carrier phase measurements, and transmit them to the ground station utilizing a VHF data link. This system consists of four components mounted in a metal enclosure, and two external antennas. The components internal to the enclosure are: Ashtech Z-12 GPS receiver, Z-world LP3130 micro-controller, Motorola RNet 9600 VHF radio transmitter, and switching power supply. A block diagram of the airborne sub-system is depicted in Figure 5.

---

Figure 5, Block diagram of GRIS airborne sub-system
Data transfers within the airborne enclosure are accomplished using the RS-232 serial communication protocol. Each of the four airborne sub-system components is documented in the next four sections.

4.1.1. Ashtech GPS Receiver / Antenna

The GPS signal is received with a Sensor Systems dual-band L1/L2 GPS antenna. The signals are then passed through a dual-band pre-amplifier before entering the GPS receiver unit. The pre-amplifier is connected to the receiver through N-type pin connectors and a Belden 8219 (RG-58/U-type) cable provided by Ashtech [5]. Electrical specifications for the antenna cable are listed in Table 3.

Table 3, Antenna cable electrical specifications

<table>
<thead>
<tr>
<th>Insertion Loss</th>
<th>Characteristic Impedance</th>
<th>VSWR (input/output)</th>
<th>DC Resistance</th>
</tr>
</thead>
<tbody>
<tr>
<td>17 dB max (at 1.5 GHz)</td>
<td>50 ohm (nominal)</td>
<td>1.1:1 max (at 1.5 GHz)</td>
<td>0.5 ohm</td>
</tr>
</tbody>
</table>

The Ashtech 2-12 GPS dual-frequency receiver incorporates twelve independent channels that offer true all-in-view automatic tracking of GPS SVs [5]. For its proper operation in the GRIS application, certain parameters of the Z-12 receiver need to be configured. These parameters include identification of the receiver (ID), site name, data-recording interval, minimum number of SVs needed, elevation mask angle, and setting up serial port communications and the DBEN message.

Receiver identification and site name are encoded in the DBEN message to make its transmitted data recognizable at the ground station.
To set up receiver identification the following steps are used:

- Press "4" on the receiver to go to screen 4;
- Enter SUBCOMMANDS menu;
- At the prompt for CODE OF COMMAND type 432 to enter RECEIVER IDENTIFICATION screen;
- Type RV at RECEIVER IS prompt, and ?? at REMOTE IS prompt.

The site name information is set up on screen "9" of the GPS receiver. At the prompt SITE located at the upper-left corner of the screen, ROVR is entered. Name ROVR and identification RV are logically chosen to denote rover usage of the Z-12 receiver. Other names can be used as long as they are consistent with the setup of the ground station processing software.

Data-recording interval, minimum number of SVs needed and elevation mask angle are all receiver properties that can be set on screen "4" of the Z-12. Data-recording interval is set to one second (faster data update rates were not explored in this Thesis). Minimum number of satellites is set to three, end elevation mask angle is set to ten degrees. These are common values often used for different applications of the Z-12 receiver.

Configuring serial port and DBEN message is also accomplished through screen "4" of the Z-12 receiver [6]. PORT A is arbitrarily chosen as a mean of serial communication. After selecting PORT A and entering PORT A PARAMETER SELECTION screen, all options except REAL TIME are set to OFF, and BAUD RATE is set to 57600 bps. This baud rate is selected to be higher than the capacity of the data link, since it was determined that the data stream from the receiver is not continuous. The data are buffered in the micro-controller, which is discussed in Section 4.1.2. After setting REAL TIME option to ON, MEASUREMENTS OUTPUT ON PORT A screen can be
entered by selecting the same option. At this screen, BINARY format is chosen and only DBEN is set to ON. To enter DBEN DATA FORMAT SELECTION screen, DBEN is selected. DBEN data format needs to be configured as UNPACKED, UNSMOOTHED and FULL P CODE.

An RS-232 cable provided by Ashtech is used to connect to the micro-controller. One end of this cable has a socket 16-pin circular connector, and the other end has a DB-9 pin connector. Power to the Ashtech Z-12 is provided by a 22-gauge wire cable with a three-pin circular connector that plugs into the Z-12.

4.1.2. Z-World LP3130 Low-Power C-Programmable Controller

The Z-world LP3130 is a low-power micro-controller designed for use in low-power and battery-powered embedded applications [7]. Its application in the GRIS system is to provide a modified RTS/CTS communication protocol between the Z-12 GPS receiver and the Motorola RNet 9600 radio transmitter.

During the design of the airborne sub-system, three unexpected interface issues became apparent. First, the RNet radio transmitter uses the RTS (Request To Send) pin on its serial interface to enable the transmitter. For proper operation, the RTS must be given approximately 20 ms before the actual data is sent to the transmitter. At the same time, it was observed that the Z-12 receiver is designed to transmit data via its serial ports only when the RTS and CTS pins are connected. Second, the Z-12 receiver does not output one data message continuously. As a result, empty periods of time between the data bytes could be interpreted as real data by the transmitter/receiver. Third, it was found that the RNet transmitter is not capable of hundred-percent duty-cycle operations for more than 5-10 minutes. These three problems prevented the use of a properly-wired cable between the Z-12 and the RNet transmitter. Instead, a micro-controller was implemented that receives data on serial port one, which has the RTS and CTS pins connected, and transmits processed data on serial port two, which utilizes a modified
RTS/CTS handshaking protocol. Furthermore, the micro-controller eliminates the spacing between the data bytes from the Z-12 to avoid misinterpretation of the "missing" bytes and to optimize the duty cycle of the transmitter.

The modified RTS/CTS protocol is implemented as follows: (1) a number of data bytes are received from the Z-12 receiver at a rate of 57600 bits per second, (2) the microcontroller sends RTS to the RNet 9600, (3) delay is encountered while waiting for RNet 9600 to send CTS back, (4) more data bytes are coming and are temporarily buffered with "missing" bytes left out, (5) RNet 9600 sends CTS back to micro-controller, and (6) temporarily buffered data bytes are transmitted to the RNet 9600 at a rate of 9600 bits per second. The data flow and modified RTS/CTS handshaking are controlled through an embedded C-program which block diagram is illustrated in Appendix B: Software block diagram for LP3130. This method provides for approximately a thirty-percent duty cycle.

A few hardware modifications to the off-the-shelf micro-controller are also required for its proper operation in this application. These modifications are reflected in the addition/modification of two DB-9 connectors (one pin and one socket), addition of a MAX232 chip used for conversion from RS-232 to digital TTL signal levels, and vice versa, and addition of a voltage regulator used to lower the power supply voltage level of 12 Volts to 8.5 Volts needed by the micro-controller. It is noted that the original power supply was selected without complete knowledge of the RNet interface complications. The schematic of the hardware changes made to the development board of the micro-controller is represented in Figure 6.
4.1.3. Motorola RNet 9600 VHF Radio Transmitter / Antenna

To transmit raw measurement data received from the Z-world micro-controller, a Motorola RNet9600 one channel radio modem is used [8]. Compact in size, the RNet9600 modem transmits 4 Watts of RF power, and operates at a frequency range between 138-143 MHz. Using an HP spectrum analyzer, the actual peak power was measured to be slightly above 4 Watts at 141.6 MHz. A BNC 50-ohm RF connector is used to supply the transmitted power to a COMAT bent whip antenna. The Voltage Standing Wave Ratio (VSWR) of this VHF antenna were established using an HP network analyzer, and are shown in Figure 7.
Figure 7, Airborne VHF antenna Voltage Standing Wave Ratio

Data communication is provided via a DB-9 socket interface connector. A modified RTS/CTS protocol is used to transmit data from the micro-controller unit, at a data rate of 9600 bps. The Motorola RNet 9600 radios have multiple asynchronous data rate capabilities, but the default and fastest rate is 9600 bps. Configuring this rate at its default value provided the fastest possible communication with the ground station as well as the lowest duty cycle, and did not seem to have an adverse effect on the performance of the system. The default value for the data word length is set to eight bits, and the default for number of stop bits is set to one bit. These values remain unchanged.

The radio is designed with a built in sixty-second time-out timer that prevents overheating of the system if a hundred percent duty cycle is encountered. Since the duty cycle is controlled by the Z-world micro-controller, this timer was disabled internally by placing dip-switch 3 of the SW1 into the OFF position [8]. Power to the radio unit is
provided through a two-wire cable with a positive voltage supplied on pin 4 of the DB-9 connector.

4.1.4. Power Supply and Consumption

The airborne GRIS sub-system has power supplied externally by the aircraft. This is accomplished using 115 VAC that is internally converted to 12 VDC by a switching power supply. This power supply is manufactured by Switching Power, Inc. and has the following characteristics:

- Model: OFSX-100D-UF
- Input voltage: 115-240 VAC at 50/60Hz
- Input current: 4 Amps
- Outputs: 31 Amps at 5 VDC, or 3 Amps at 12 VDC

The maximum power consumption figures are illustrated in Table 4.

<table>
<thead>
<tr>
<th></th>
<th>Voltage</th>
<th>Current</th>
<th>Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z-12 receiver</td>
<td>12 Volts</td>
<td>1.7 Amps</td>
<td>20.4 Watts</td>
</tr>
<tr>
<td>μ-controller</td>
<td>12 Volts</td>
<td>25 mA</td>
<td>300 mW</td>
</tr>
<tr>
<td>RNet 9600</td>
<td>12 Volts</td>
<td>1.3 Amps</td>
<td>15.6 Watts</td>
</tr>
<tr>
<td>Total</td>
<td>N/A</td>
<td>~ 3 Amps</td>
<td>~ 36 Watts</td>
</tr>
</tbody>
</table>

4.2. Ground Station Sub-system

The ground station is responsible for receiving data transmitted from the aircraft, combining these data in differential processing with data received from a local GPS receiver, and finally transmitting processed aircraft navigation solutions over an Ethernet data link to the main computer-control system. Two crucial components of the ground
station sub-system are the Ashtech Z-12 GPS receiver and the Motorola RNet 9600 VHF radio receiver, accompanied with the respective receiving antennas. In addition to these essentials, the ground station is equipped with two processing computers used for navigation data processing and data conversion/formatting, respectively. A block diagram of the ground station sub-system is depicted in Figure 8.

![Block Diagram](image)

**Figure 8, Block diagram for GRIS ground station sub-system**

4.2.1. Ashtech GPS Receiver / Antenna

The GPS antenna/receiver combination is of the same type as the one used in the airborne system. Necessary cables used for the interface between the antenna and the receiver, as well as for further interface with the navigation processing computer, are also identical to those used in the airborne system. The characteristics and properties of these cables are fully described in Section 4.1.1. Specific parameters must be configured for the
proper operation of this system, but the procedure followed in setting these is identical to the one described in Section 4.1.1 and therefore, will not be repeated here.

The exact values of the configured parameters are as follows:

- Receiver identification is BA (referring to base station) and remote ID is ??;
- The site name is AIRP (referring to the airport);
- Data recording interval is set to one second;
- Minimum number of satellites in view is set to three;
- Elevation mask angle is set to ten degrees;
- **PORT A PARAMETER SELECTION:**
  - Real-time is ON;
  - Baud rate is 57600 bps;
  - Binary format of data transfer is chosen;
  - DBEN message and SNAV (ephemeris data) are set to ON – different from airborne unit;
  - DBEN message is set up as UNPACKED, UNSMoothED and FULL P CODE.

The GPS signal received through the active dual-band GPS antenna is passed through the pre-amplifier and received by the Z-12 receiver. At the receiver stage, the signal is down-converted to IF, passed through an A/D converter, twelve channels and navigation processor, and finally, utilizing serial communication protocol, is transmitted to the real-time, differential-processing computer. There is no direct physical connection between the Z-12 receiver and the Motorola radio receiver, instead, both are connected to the differential-processing computer.
4.2.2. Motorola RNet 9600 VHF Radio Receiver / Antenna

The Motorola RNet radio receiver is configured exactly the same as the unit included in the airborne sub-system. The information received by the ground station radio receiver is being transmitted employing a serial communication protocol to the real-time, differential-processing computer. For the detailed explanation on how to set up the RNet 9600 radio modem, refer to Section 4.1.3.

The radio antenna used for the base station unit is a circularly-polarized, custom made wide-band VHF antenna. The VSWR of this antenna was measured and is shown in Figure 9.

![Figure 9, Reference station VHF antenna Voltage Standing Wave Ratio](image)

VSWR: 2.0 and better
Frequency band: 114.5 MHz – 155.5 MHz
VSWR: 5.0 and better
Frequency band: 106.0 MHz – 169.5 MHz
VSWR (min): 1.05 at frequency of 146.00 MHz
4.2.3. RTPNAV Processing System

The information received by the Z-12 GPS receiver and the RNet 9600 VHF radio receiver is combined to produce the real-time differential navigation solution of the aircraft being tracked. Typically, DGPS processing refers to a situation where a ground station transmits differential corrections to an aircraft. After an aircraft has received the information from the ground station, it processes these data combined with its raw measurements to obtain a highly accurate, differential solution.

In the GRIS application, an aircraft transmits its raw measurements to the ground station where differential processing is performed. This technique, commonly referred to as inverse DGPS processing, presently does not have wide-spread usage in runway instrumentation applications, but is undergoing extensive research. An investigation was performed in order to obtain information about current producers of real-time inverse RTK processing software. Products manufactured by two different companies were found: Inverse RTK by Waypoint Consulting Inc [9], and RTPNAV by Ashtech Inc [6]. RTPNAV was already available at the Avionics Engineering Center. The product by Waypoint consulting incorporates appealing features (e.g. simultaneous tracking of up to twenty remote targets, moving base station, etc.), which could be examined in future stages of the GRIS project. The primary disadvantage of this product is that the real-time processing option only provides position accuracy of 1-5 meters. This performance does not satisfy the accuracy requirements for the GRIS. Therefore, at the time of this research, RTPNAV was determined to be the only viable product for GRIS implementation.

The Real-Time Precise Navigation software, version 3.3.30T finalized and released on November 11th, 1995, was evaluated for the GRIS application. Hardware requirements specify an Intel 80486 or better processor, a minimum of 610 kB of DOS memory, and a sentinel key plugged into the PC's parallel port. Additional hardware requirement for the PC, necessary for the proper operation of the overall ground station system, is a
minimum of two communication ports for the data exchange. A Pentium 90-MHz processor was used for the RTPNAV implementation.

To ensure proper functioning of the RTPNAV processing system, several parameters (i.e., communication, position, run-time and output) need to be configured prior to integration of this system in the GRIS structure. The list of these parameters, along with respective values different than the defaults, is presented in Table 5.

Table 5, RTPNAV settings changed from default values

<table>
<thead>
<tr>
<th>Location Menu</th>
<th>Parameter Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ashtech Precise Navigation (PNAV) Software</td>
<td>Working directory path</td>
<td>Create new directory</td>
</tr>
<tr>
<td></td>
<td>Type of processing</td>
<td>(B) Data Processing</td>
</tr>
<tr>
<td>Menu 3.0. Program Execution Mode and Rover Dynamics</td>
<td>Execution mode</td>
<td>Real-time</td>
</tr>
<tr>
<td></td>
<td>Processing mode</td>
<td>Navigation</td>
</tr>
<tr>
<td></td>
<td>Rover motion dynamics</td>
<td>Aircraft*</td>
</tr>
<tr>
<td>Setup Menu</td>
<td>Base Receiver Packet ID</td>
<td>BA</td>
</tr>
<tr>
<td></td>
<td>Base Receiver Dest ID</td>
<td>??</td>
</tr>
<tr>
<td></td>
<td>Base Receiver Comm Port</td>
<td>1 (Direct)</td>
</tr>
<tr>
<td></td>
<td>Base Receiver Type Reqst</td>
<td>RPC</td>
</tr>
<tr>
<td></td>
<td>Rover Receiver Packet ID</td>
<td>RV</td>
</tr>
<tr>
<td></td>
<td>Rover Receiver Dest ID</td>
<td>??</td>
</tr>
<tr>
<td></td>
<td>Rover Receiver Comm Port</td>
<td>2 (Remote)</td>
</tr>
<tr>
<td></td>
<td>Rover Receiver Type Reqst</td>
<td>RPC</td>
</tr>
<tr>
<td>Comm Menu (Communication Parameters)</td>
<td>COM 1 baud rate</td>
<td>57600</td>
</tr>
<tr>
<td></td>
<td>COM 2 baud rate</td>
<td>9600</td>
</tr>
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<td>Position Menu</td>
<td>Site name</td>
<td>AIRP</td>
</tr>
<tr>
<td></td>
<td>Site latitude</td>
<td>N 39 12 38.67009</td>
</tr>
<tr>
<td></td>
<td>Site Longitude</td>
<td>W 82 13 28.86137</td>
</tr>
<tr>
<td></td>
<td>Site ellipsoidal height</td>
<td>246.76</td>
</tr>
<tr>
<td>File Menu</td>
<td>Real-time data output</td>
<td>ASCII, CBEN, COM2</td>
</tr>
</tbody>
</table>

* Note: Rover motion dynamics is set to Automobile during the van test
Most of the parameters described in Table 5 are self-explanatory and reflect changes and configurations already established in the Z-12 GPS receivers and RNet 9600 VHF radio receiver. However, the following parameters need additional clarification:

- **RPC base and rover receiver type requests refer to the **FULL P CODE** message type already established in the Z-12 receivers. This message type provides L1 C/A-code and carrier-phase, as well as L2 P-code and carrier-phase measurements.**

- **Direct** connection of the base receiver to communication port 1 means that the ground station Z-12 receiver is connected directly through a cable to the processing PC. **Remote** connection of the rover receiver to communication port 2 suggests that the airborne Z-12 receiver is located in a remote site, connection is established through a modem data link, and no messages are to be sent from the processing PC to the GPS receiver.

- **CBEN** real-time data output specifies the pre-defined data structure used in transmitting the differentially processed navigation solution to the QNX processing PC. Among others, CBEN data structure contains the following vital information: receiver GMT time, receiver site ID, number of satellites used in the position computation, PDOP, receiver's latitude, longitude and height, standard deviation of the respective components, receiver's velocity in East, North, and Up directions, and respective standard deviations.

In configuring RTPNAV for a specific application, there are additional sub-menus within the Setup menu that should be analyzed. Menus like **Attribute**, **Kalman**, **RunTune**, **WayPoint** have a great number of additional parameters whose values could change depending on the use of the processing software. In the GRIS application, these values should remain unchanged from their respective default values for the proper operation of the overall system.
4.2.4. QNX Processing System

Data processed differentially by the RTPNAV software is transmitted through a serial communication port (COM2) of the RTPNAV PC to a second processing unit. A custom made serial cable is implemented for this communication protocol. Information collected by the RNet 9600 radio receiver is transmitted to serial port COM2 of the RTPNAV PC, utilizing pin two of a DB-9 connector. At the same time, pin three of the same serial port COM2 is employed for transmission of the data processed by the RTPNAV software. The transmitted data are accepted by a serial port of the second PC, which runs the QNX4 version 4.22 real-time OS. A Pentium II processing platform is chosen for this operation primarily due to its availability at the time. The minimum hardware requirements for the proper operation of QNX4 OS can be obtained either from the user manual or the QNX official website [10].

The QNX PC platform is used to move data received from the RTPNAV PC into the Ethernet real-time data buffer acceptable by NASA's Iris graphics system. This data buffer implements the RTCS Gould/Encore buffer structure, and it is defined by 368 32-bit words or 1472 bytes [11]. The first 244 words of the buffer, referred to as the fixed area of the buffer, define commonly used offsets, and the last 124 words are considered the free space of the buffer, which is reserved for offsets specified externally by the user's setup. Since the Ethernet buffer is an integer buffer, data received from the RTPNAV PC is multiplied by the respective precision factors and truncated before being placed in the buffer. At the same time, the Iris graphics system uses the equivalent precision factors to divide data it receives from the Ethernet buffer. Table 6 illustrates currently defined precision factors.
Table 6, Precision factors used by NASA Iris graphics system

<table>
<thead>
<tr>
<th>Data Type</th>
<th>Time</th>
<th>Velocity</th>
<th>Linear</th>
<th>Angles [radians]</th>
<th>Angles [degrees]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Factor</td>
<td>$10^1$</td>
<td>$10^2$</td>
<td>$10^1$</td>
<td>$10^8$</td>
<td>$10^6$</td>
</tr>
</tbody>
</table>

In order to translate the data format received by the RTPNAV PC to the RTCS Gould/Encore data structure, a C-program was written to run on the QNX4 OS. This program defines data buffers, establishes communication protocol, decodes the RTPNAV message, converts this message into Ethernet data buffer format using precision factors, and writes the data out to the Iris graphics system. Appendix C: Software block diagram for QNX PC provides code logic used to implement the processing function of the QNX system.

4.2.5. Power Supply

Power required for the operation of the ground station sub-system is provided by two different sources: DC power supply and common wall outlets. Power for the Z-12 GPS receiver and RNet 9600 radio modem is supplied through a general 12-volt DC power supply. Two PCs utilized for software processing are connected to regular wall outlets. Since the ground station tracking system is stationary and “on the ground”, power management for this system was not a concern, and therefore was not considered in the implementation of the overall system.
5 SYSTEM TESTING

Prior to testing the GRIS system by means of flight-testing, a ground test was performed to ensure proper, general operation of the system. The van test is focused primarily on the availability and integrity of the communication data link, and it was employed through a van mobile platform acting as a mobile-user rover. Flight-testing is generally more complex, weather dependent, and more costly than a van test; the latter provides insights to possible problems with the system that might occur during the flight performance testing.

5.1. General Scenario

Both van and flight tests utilize two segments: ground tracking station and mobile rover platform. The ground station is assembled inside the Avionics Engineering Center (AEC) hangar facility at the Ohio University Airport (KUNI) in Albany, Ohio. The circularly-polarized VHF antenna (see Figure 10), is installed at the antenna bay located on the top of the AEC hangar.

Figure 10, Photograph of the ground station VHF antenna
In order to elevate this antenna as high as possible, the antenna is mounted on the top of an aluminum post. Several meters away from this antenna, located at the same antenna bay, the Sensor Systems dual-band GPS antenna and the Motorola RNet 9600 radio receiver are positioned. The GPS antenna location was surveyed in 1998, and its high-accuracy position was obtained using PRISM 2.0.00 post-processing software by Ashtech [12]. The GPS antenna coordinates in a geodetic (LLH) coordinate system are also used as the reference point for the ENU coordinate frame of the navigation processor, and are given by:

\[
\begin{align*}
\text{Latitude: North } & 39.012' \ 38.67009" \\
\text{Longitude: West } & 82.013' \ 28.86137" \\
\text{Ellipsoidal height: } & 246.76 \text{ meters.}
\end{align*}
\]

An antenna cable from the GPS antenna/pre-amplifier and a data link cable from the RNet 9600 radio modem are routed from the antenna bay to a laboratory below it, where the Z-12 dual-band GPS receiver, the RTPNAV processing system and the QNX processing system are located. The setup of these components is depicted in Figure 11.

Figure 11, Photograph of the ground station processing system
The ground station setup described above is preserved throughout both the van test and the flight test. The mobile rover platform, however, differs for the two test scenarios. During the van test, the "Bertz-mobile" was employed as a moving mobile-user system, and a Piper Saratoga (PA-32) aircraft was utilized during the flight test.

5.2. Van Test Setup

The "Bertz-mobile" is a full-size conversion van owned by Ohio University's AEC. The vehicle and its supplemental components are shown in Figure 12.

Figure 12, Photograph of the "Bertz-mobile" used during the van test
This vehicle has a dual-band GPS antenna installed on a wooden platform located in the center of the roof, and a VHF antenna located on the front part of the roof. The VHF antenna is a low-loss antenna with the ability to operate in both the navigation and communication frequency bands. For the purpose of this experiment, the VHF antenna is connected in the communication band. The “Bertz mobile” is accompanied by a metal platform located outside, in the rear of the vehicle. This platform is used to accommodate a Mitsubishi MGE4800 AC fuel-based power generator used to supply power to the GRIS airborne unit located inside the van. Usually, fuel-based generators cause harmonic distortions as a function of the demanded output power [4]. In order to protect the expensive and sensitive measurement equipment from faulty and highly distorted input power, an uninterruptible power supply (UPS) unit is placed between the generator and the GRIS airborne unit.

The van test was conducted on November 13th, 2000. The weather conditions were partially sunny, no significant wind or any precipitation. The temperature was around 50°F. The route used during this experiment is illustrated in Figure 13.

![Figure 13, Plan view of the van route during van test](image-url)
The experiment started in front of the AEC hangar facility. The van was than driven onto U.S. Route 50, where it proceeded in the northeast direction for about 4 kilometers from the base station. At this point, the van was turned around, and proceeded in a southwest direction. At a distance of approximately 6.8 kilometers in the southwest direction, the line-of-sight between the mobile platform and the base station was lost and the VHF communication was interrupted. The van was turned around and proceeded back to the Ohio University airport. Shortly thereafter, the VHF communication was re-established and sustained in that mode until the end of the experiment. The van was brought back to the airport, where it continued the experiment around the hangar and surrounding buildings in order to simulate the taxiing of an aircraft. Finally, the van was brought back to its starting location and the experiment was concluded. The test lasted over 30 minutes and provided approximately 1900 data points, which was sufficient to determine the reliability of the GRIS system.

The real-time data set was examined shortly after it was collected. With the exception of a few missing epochs of a second at-the-time and the complete loss of the VHF data link over 6.8 kilometers away from the base station in the southwest direction, the collected data seemed reliable. The complete loss of the VHF communication link between the two units at the previously mentioned distance was expected, considering the topography of the area. The execution of the GRIS system was considered more than satisfactory, and this conclusion enabled the start for the preparation of the flight-testing.

5.3. Flight Test Setup

The flight test was performed on November 30th, 2000. The weather conditions were partially cloudy, with relatively strong winds, and light rain precipitation. The temperature was around 30°F.

In conducting the flight test, a Piper Saratoga (PA-32) single-engine aircraft was employed. This aircraft was equipped with a dual-band GPS antenna installed in the
front part of the roof of the aircraft. A VHF bent whip antenna was mounted on the under side of the left wing of the aircraft. The two antennas were dedicated to the GRIS system and had no effect on the performance of the essential aircraft electronic equipment. The Saratoga aircraft used during the flight-testing is illustrated in Figure 14.

Figure 14, Photograph of Saratoga aircraft used during the flight test

Inside the aircraft, a metal equipment compartment provided the housing for the GRIS airborne unit. Two antenna cables connected to the GPS antenna and VHF antenna, respectively, were routed to the GRIS airborne component. A power meter was placed between the VHF antenna and the GRIS airborne sub-system as an indicator to demonstrate proper functioning of the radio-transmitting device. The power required by the GRIS airborne sub-system was provided by the aircraft's AC power generator. Prior to takeoff, the airborne enclosure along with the power meter was weighted to verify proper weight and balance of the relatively small Saratoga aircraft. Their combined weight measured approximately 30 pounds, virtually insignificant in comparison to the
other components inside the aircraft. The general setup of the GRIS airborne sub-system is presented in Figure 15.

![Figure 15, Photograph of the airborne unit setup within Saratoga aircraft](image)

The general idea behind the flight test was to fly a circular pattern, 20 miles in radius from KUNI at an altitude of 1000 feet AGL. Some difficulties were encountered during the flight test, and the desired flight pattern was adjusted to accommodate for those difficulties. This subject is described in more detail in Section 5.5. The flight test lasted for approximately 1 hour 25 minutes, and over 4000 valid data points were collected.

5.4. Flight Test Data Post-Processing

In order to test the performance of the GRIS real-time processing system, data collected and recorded in both the base station and airborne GPS receivers were processed using PRISM 2.0.00 post-processing software by Ashtech, Inc [12]. In this case, the navigation
algorithm was implemented in a post-processing manner where synchronization was accomplished by referring to the GPS time-tag. The navigation solution obtained with this method was used as a truth reference in an error analysis of the GRIS real-time system.

Data received during the flight test were processed utilizing a navigation algorithm embedded in the RTPNAV real-time processing software. Real-time processed data were recorded and used later in the performance study of the GRIS system. In conducting the flight test, data from 66 separate one-second epochs were lost, as were the data from a total of 1080 epochs on two other occasions. The missed epochs are shown in Table 7.

Table 7, Missed epochs during flight test

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<tr>
<th>Missing Epoch</th>
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<th>Missing Epoch (cont.)</th>
<th>Missing Epoch (cont.)</th>
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</table>
5.5. Results from the Flight Test

Based on the status of the real-time processing software, the performed flight test can be separated into the following stages:

- No wide-lane ambiguity solution of the processed data;
- Wide-lane ambiguities resolved, and solution is unambiguous; and,
- GRIS ground station system is down.

The occurrence of different solution phases can be delineated on an epoch-to-epoch basis, as illustrated in Table 8.

<table>
<thead>
<tr>
<th>Epoch Start</th>
<th>Epoch End</th>
<th>System Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>401051</td>
<td>401131</td>
<td>No wide-lane ambiguity solution</td>
</tr>
<tr>
<td>401132</td>
<td>403203</td>
<td>Wide-lane ambiguities resolved</td>
</tr>
<tr>
<td>403204</td>
<td>404194</td>
<td>GRIS ground station system down</td>
</tr>
<tr>
<td>404195</td>
<td>404415</td>
<td>No wide-lane ambiguity solution</td>
</tr>
<tr>
<td>404416</td>
<td>405428</td>
<td>Wide-lane ambiguities resolved</td>
</tr>
<tr>
<td>405429</td>
<td>405517</td>
<td>GRIS ground station system down</td>
</tr>
<tr>
<td>405518</td>
<td>406255</td>
<td>No wide-lane ambiguity solution</td>
</tr>
</tbody>
</table>

After the power-up of the overall system, and while the plane was on the ground, the elapsed time before resolution of a final set of integer ambiguities was 80 seconds. If this number is compared to the corresponding time after the first and second crash of the ground station sub-system (221 and 738 seconds respectively), it is observed that dynamic motion of the aircraft at altitude (see figures 16 – 18) in combination with a larger separation distance from the ground station, clearly has a negative impact on the time it takes for the inverse DGPS processing software to compute an integer set of ambiguities.
Figure 16, Aircraft's velocity in East direction during flight test (truth)

Figure 17, Aircraft's velocity in North direction during flight test (truth)
In Section 5.4, it was mentioned that 1146 epochs of the aircraft data were never received by the ground station sub-system. A minor number of missed epochs due to the data link, 66 at the one-second-interval occurrence, reflects the performance of the communication data link. This number is only about 1.6% of the total number of valid epochs received, which is well within the performance specifications of the Motorola RNet 9600 radio modem [8]. The number of epochs and their status during the flight test is presented in Table 9.

Table 9, Epoch condition during the flight test

<table>
<thead>
<tr>
<th>Epoch Condition</th>
<th>Number of Epochs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Epochs received by ground station</td>
<td>4059</td>
</tr>
<tr>
<td>Epochs missed due to data link performance</td>
<td>66</td>
</tr>
<tr>
<td>Epochs missed due to system shutdown</td>
<td>1080</td>
</tr>
<tr>
<td>Total number of epochs during flight test</td>
<td>5205</td>
</tr>
</tbody>
</table>
However, over one thousand epochs were lost due to the complete failure of the ground station sub-system. This was a new condition that did not occur at any point during the van test. Thus far, only speculations were made regarding this problem. One possibility is that the number of satellites used in the navigation algorithm exceeded the allowable matrix dimensions, which consequently crashed the system. This theory is somewhat supported by examining Figure 19, which illustrates the change in the number of satellites from 7 to 8 at epoch 403204, exactly at the same instance when the system crashed.

Figure 19, PDOP and number of SVs used in processing during the flight test

Considering that the version of the RTPNAV processing software dates back to 1995, at which time the total number of available GPS satellites was less than during the test, it is possible that a faulty mode was excited in a section of the computer code used for processing high-dynamic aircraft motion.
In regards to this problem, a call was also placed to Dr. Xinhua Qin, Director of Engineering at Ashtech Precision Products, and key-person in the development of RTPNAV processing software. In a brief conversation with Dr. Qin, it was verified that the software used during the GRIS flight test is the most current version available at the present time. His impression was that not enough conventional memory was allocated during the testing. In regards to why this was not an issue with the van test, Dr. Qin commented that due to high dynamics of the aircraft, different functions and parameters are accessed and used by RTPNAV other than those used in the low-dynamic rover motion. His recommendation was to increase available conventional memory above 600 kB.

The influence of the missed epochs due to the data link performance is almost insignificant due to their short length of their occurrences. The complete failure of the ground station sub-system, on the other hand, had a great impact on the obtained navigation solution over the whole flight test. In Figure 20, the ground station outages are indicated on the aircraft ground track.

Figure 20, Plan view of the aircraft route during flight test (truth)
The change of the individual position components over time is shown in Figure 21 and Figure 22. These graphs illustrate the post-processing solution for the complete flight test.

Figure 21, East and North components of aircraft position during flight test (truth)

Figure 22, Vertical component of aircraft position during flight test (truth)
Figures 23 through 25 portray position differences in east, north, and vertical directions, respectively.

Figure 23, Position difference in East direction during flight test

Figure 24, Position difference in North direction during flight test
The position differences illustrated in the previous three figures represents the difference between the respective position components obtained through RTPNAV real-time processing and PRISM post-processing. The six vertical lines of the dash-dot type represent the transition of the processing status of the RTPNAV navigation solution as previously described in Table 8.

Under ideal system operating conditions and once the wide-lane set of ambiguities has been resolved, the ground station tracking system would have performance curves depicted between epochs 401132-403203 and 404416-405428 in the previous three figures. Therefore, epochs representing a complete failure of the system and an ambiguous solution after the operation of the system has been reestablished are discarded in the analysis of the position/velocity differences of the GRIS system. Valid epochs provide 3085 data points or 51 minutes 25 seconds of test time, which is sufficient for the performance study. The results of the position differences (i.e., bias and standard deviation) are presented in Table 10.
Table 10, Analysis of the position differences

<table>
<thead>
<tr>
<th>Component</th>
<th>Bias [meters]</th>
<th>Standard Deviation [meters]</th>
</tr>
</thead>
<tbody>
<tr>
<td>East</td>
<td>0.007</td>
<td>0.069</td>
</tr>
<tr>
<td>North</td>
<td>-0.002</td>
<td>0.043</td>
</tr>
<tr>
<td>Up</td>
<td>-0.004</td>
<td>0.066</td>
</tr>
<tr>
<td>3-D RMS</td>
<td>0.008</td>
<td>0.105</td>
</tr>
</tbody>
</table>

Table 10 shows that the bias difference between RTPNAV and PRISM is very small, on the order of millimeters, which indicates that there are no significant systematic errors in RTPNAV. Note that post-processing techniques were previously verified against other tracking systems to within 0.1 m [13]. Therefore, it is possible that both RTPNAV and PRISM have bias errors up to 0.1 m. The standard deviation in Table 10 represents the combination of PRISM and RTPNAV noise. Assuming that both systems have equal noise performance, the actual RTPNAV noise is lower by a factor of $\sqrt{2}$ with respect to the numbers listed in Table 10. Because there are no significant systematic errors between PRISM and RTPNAV, and PRISM was previously verified to be accurate to within 10 cm, it can be concluded that RTPNAV also has an accuracy on the order of 10 cm.

Using a similar approach as the one used for the position difference analysis, the velocity differences were computed as the difference between the respective velocity components obtained through RTPNAV real-time processing and PRISM post-processing. The individual velocity difference components are presented in figures 26 through 28.
Figure 26, Velocity difference in East direction during flight test

Figure 27, Velocity difference in North direction during flight test
The results of the velocity differences are presented in Table 11.

Table 11, Analysis of the velocity differences

<table>
<thead>
<tr>
<th>Component</th>
<th>Bias [meters/second]</th>
<th>Standard Deviation [meters/second]</th>
</tr>
</thead>
<tbody>
<tr>
<td>East</td>
<td>-0.010</td>
<td>0.075</td>
</tr>
<tr>
<td>North</td>
<td>0.015</td>
<td>0.103</td>
</tr>
<tr>
<td>Up</td>
<td>-0.013</td>
<td>0.155</td>
</tr>
<tr>
<td>3-D RMS</td>
<td>0.022</td>
<td>0.200</td>
</tr>
</tbody>
</table>

It is noted that the noise of the velocity differences is larger than expected. Based on differencing positions over time, 3-D velocity noise should be on the order of $\sqrt{2} \times (10.5) [\text{cm}] = 14.8 [\text{cm}]$, where the position noise from Table 10 was used.
6 SUMMARY AND CONCLUSIONS

The GRIS system as implemented in this project concentrates on the tracking of a single aircraft. Inverse differential GPS (DGPS) was implemented to obtain decimeter-level tracking performance.

The main emphasis of this research was to design and assemble a prototype GRIS, troubleshoot necessary hardware and software components, perform testing of the system and examine the results obtained. The objective of the project was to demonstrate the concept of an aircraft tracking system using inverse DGPS technology, as well as to establish a baseline for future research.

Two independent sub-systems were designed and implemented: the airborne unit and the ground station. GPS receivers were integrated with the communication system, and the control and manipulation of data information were achieved through a micro-controller and processing PCs.

In examining system performance by means of flight-testing, difficulties were encountered in the implementation of the navigation algorithm on the RTPNAV processing unit. This, however, was not a continuous problem; and when its occurrence was not present, the overall system performed very well. The flight test results show that there were no significant systematic errors between RTPNAV and PRISM. Since PRISM was previously verified to be accurate to within 10 cm, it can be concluded that RTPNAV also has an accuracy of better than 10 cm. Velocity noise, which was computed as the difference between the respective velocity components obtained through RTPNAV real-time processing and PRISM post-processing, was on the order of 20 cm/s (3-D RMS). It is noted that velocity could also be obtained by differencing the position solutions, which should result in velocity noise on the order of 15 cm/s or better (3-D RMS).
7 RECOMMENDATIONS FOR FUTURE RESEARCH

Based on the project requirements and results outlined in this thesis, the following recommendations are provided for further research:

- Resolve the problem of the failing RTPNAV processing software. The use of additional computer memory should first be considered, as recommended by the manufacturer of RTPNAV software package;

- Investigate methods to improve the velocity performance of RTPNAV;

- Expand the application of the system to include multiple airborne platform tracking capabilities;

- Evaluate the performance of the GRIS system as a function of the number of available satellites, geometry, and aircraft dynamics; and,

- Evaluate the performance of the system and its accuracy dependence on a greater operating range. Perform new flight testing with aircraft locations up to 200 nmi away from the ground station.
8 REFERENCES


APPENDIX A: EQUIPMENT LIST

Ashtech Z-12 GPS Receiver (quantity 2)

Active Dual-band L1/L2 GPS Antenna (quantity 2)

Z-world μ-controller
Model LP3130
Development board included

Motorola RNet 9600 Single Channel Radio Modem (quantity 2)
Model K43GNM1001
138-143 MHz

COMAT Bent Whip Antenna (modified)
VSWR 2.0 or better between 138-143 MHz

FAA Circularly Polarized VHF Antenna (custom made)
VSWR 2.0 or better between 138-143 MHz

Pentium 90 (or faster) PC Unit (quantity 2)

Switching Power Supply
Manufactured by SWITCHING POWER INC
Model OFSX-100D-UF
Input: 115-240 VAC at 50/60 Hz, 4 Amps
Output: 5 VDC / 31 Amps, or 12 VDC / 3 Amps

DC Power Supply (generic brand)
Input: 115-240 VAC at 50/60 Hz
Output: 12 VDC

Mitsubishi MGE4800 Generator
Max. 4.8kW rated at 4.1kW output
120 V at 60 Hz, 34.2 Amps
Ser.No: 1002261

Hewlett Packard Network Analyzer
Model 8753D
30 kHz – 3 GHz
Hewlett Packard Spectrum Analyzer
Model 8562A
9 kHz – 22 GHz

Hewlett Packard Digital Oscilloscope
Model 54510B
300 MHz / 2 Channels

Single Engine Piper Saratoga Aircraft
Model PA 32-301
S/N 32-8006072
Lycoming IO-540 / 300 Hp
3 Bladed Harzle
Reg.No: N8238C

Bertz-mobile vehicle
Full-size Conversion Van
APPENDIX B: SOFTWARE BLOCK DIAGRAM FOR LP3130

1. Define and initialize all variables
2. Open and set up communication ports
3. Start continuous WHILE loop
4. Is there any data in the input buffer?
   - NO
   - YES
     - Read incoming Z12 data from the input buffer and add it to the message buffer
5. Is there previous data in the message buffer?
   - NO
   - YES
     - Is RTS already SET?
       - NO
       - Set RTS
       - YES
       - Is CTS SET?
         - NO
         - Write message data buffer out to serial port connected to RNet 9600
         - YES
         - Reset RTS
     - Is there any data in the output buffer?
APPENDIX C: SOFTWARE BLOCK DIAGRAM FOR QNX PC

Define data buffers, functions, global and local variables

Open file to write a log of errors

Open and set up communication ports

Is there an external interrupt for stopping the execution of the program?

YES

CLOSE SERIAL PORTS AND ERROR LOG FILE

NO

Read incoming data on serial port from RTPNAV PC, store it in buffer(s), and recreate the message

Decode RTPNAV message (extract individual data fields)

Initialize mission parameters within data buffer

Convert RTPNAV data to Gould code using precision factors

Write data buffer out to serial port connected to Iris GUI

Clear data buffer