Impacts of Station Dependent Error Sources on the Implementation of the National Height Modernization Program

THESIS

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By

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Abstract

Accurate, reliable, and up-to-date heights are essential for a wide range of economic activities in many professions, including: surveying, engineering, emergency managers, Earth scientists, and natural resource managers [Veilleux, 2013b]. Historically, accurate orthometric heights have been obtained by tying into the control benchmarks of a vertical datum. Spirit leveling and gravity readings are used to establish, maintain, and update the heights of the benchmarks, which is a costly and time consuming process. Contemporary heights can also be established with the Global Positioning System (GPS) and can be combined with a geoid model for a quick and cost effective method of obtaining the orthometric heights used in a vertical datum.

The National Height Modernization Program enables access to accurate, reliable, and consistent heights [Veilleux, 2013b]. This program is being employed by the National Geodetic Survey (NGS), with the goal of implementing a new vertical datum by computing the orthometric heights through the combination of GPS and gravimetric data. The expected result is a high accuracy vertical datum that will establish the orthometric heights with an accuracy that will be sufficient for a multitude of applications in science, engineering, mapping, etc. The accuracy of such a vertical datum is, therefore, dependent on the accuracy of the underlying GPS and geoid models and a better understanding of the error sources associated with the GPS ellipsoidal height and the geoid model may enable orthometric heights to be obtained with a high accuracy. This thesis will assume
that an accurate geoid model exists and will focus on any inaccuracies in orthometric heights caused by the GPS-derived height. There are many error sources that may enter into the GPS observable, including: satellite and receiver clock errors, satellite orbit errors, atmospheric delays of the GPS signal caused by the ionosphere and troposphere, receiver bias, environmental multipath, and antenna phase center variation [Grejner-Brzezinska, 2011]. These error sources must be accounted for, if high accuracy heights are to be established through GPS.

This thesis principally examines the effects of station dependent error sources, including phase center variations (PCV), far-field multipath reflection, and near-field multipath reflection [Berglund, 2011]. The effects of neglecting the PCVs particular to an antenna with a radome will be examined to see how much height deviation is caused by not properly accounting for how the radome alters signal reception at the antenna. The effects of multipath caused by the following near-field error sources will be examined: GPS signal interference caused by high voltage power lines, multipath reflection from a snow-covered field, the effects of a robin sitting on an antenna, and the effects of a seagull sitting on an antenna that will be modeled through simulation. In addition, an investigation will be conducted to analyze the level of height variation caused by using different antenna models to determine the height of the same point.

The results of the near-field multipath experiments show that small changes in the snow depth of an area result in a consistent pattern of multipath, while drastic changes in the snow depth of the surrounding environment will alter the magnitude of the multipath reflection. Data collected around high voltage power lines suggests that major
obstructions to a GPS signal could perhaps be avoided through site planning and using only those satellites less likely to be obstructed by the high voltage power lines. The test with the birds sitting on antennas showed that the amount of error a bird causes on GPS-derived heights depends on the size of the bird and that the error will eventually average out when the bird leaves the antenna, but will impact instantaneous height estimation in, for example, real-time kinematic (RTK) GPS applications.
Dedication

Dedicated to my nephew Trennen
Acknowledgements

I would like to express my sincerest gratitude to my advisor, Dr. Grejner-Brzezinska, for her invaluable guidance, encouragement, and advice through my research. I am grateful for her invitation to join the SPIN Lab team and for the knowledge obtained from the various projects.

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Field of Study

Civil Engineering: Geodetic and Geoinformation Engineering
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<td>APC</td>
<td>Antenna Phase Center</td>
</tr>
<tr>
<td>ARP</td>
<td>Antenna Reference Point</td>
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<tr>
<td>C/A-code</td>
<td>Course/Acquisition-code</td>
</tr>
<tr>
<td>CORS</td>
<td>Continuously Observing Reference Station</td>
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<td>DGPS</td>
<td>Differential GPS</td>
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<td>DoD</td>
<td>Department of Defense</td>
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<tr>
<td>ECEF</td>
<td>Earth-Centered Earth-Fixed</td>
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<tr>
<td>FAA</td>
<td>Federal Aviation Administration</td>
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<tr>
<td>GIS</td>
<td>Geographic Information System</td>
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<tr>
<td>GNSS</td>
<td>Global Navigation Satellite System</td>
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<td>GPS</td>
<td>Global Positioning System</td>
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</table>
L5……………………………………………………….L5 frequency of GPS antennas
MC………………………………………………………Multiple Comparisons
NAD83…………………………………………………North American Datum 1983
NAVD88…………………………………………….North American Vertical Datum 1988
NGS…………………………………………………National Geodetic Survey
NGVD29…………………………………………National Geodetic Vertical Datum 1929
NOAA………………………………………………National Oceanic and Atmospheric Administration
NSRS……………………………………………….National Spatial Reference System
ODOT………………………………………………Ohio Department of Transportation
OSU……………………………………………….The Ohio State University
PAGES………………………………Program for the Adjustment of GPS Ephemerides
PCO……………………………………………………Phase Center Offset
PCV…………………………………………………Phase Center Variation
RINEX………………………………Receiver Independent Exchange Format
RDOP………………………………………………Relative Dilution of Precision
RSGPS……………………………………………..Rapid-Static GPS
RTK………………………………………………Real-Time Kinematic GPS
SV………………………………………………Space Vehicle
UTC………………………………………………Coordinated Universal Time
UV………………………………………………Ultraviolet
WGS84…………………………………………World Geodetic System 1984
Chapter 1 Introduction

1.1 The National Height Modernization Program

The National Height Modernization Program is an initiative to implement a new North American Datum, overseen by the National Geodetic Survey (NGS), which is focused on establishing accurate, reliable heights using Global Navigation Satellite System (GNSS) technology in conjunction with traditional leveling, gravity, and modern remote sensing information [Veilleux, 2013a]. A primary mission of NGS is to define, maintain, and provide access to the National Spatial Reference System (NSRS) to meet the economic, social, and environmental needs of the nation. NGS has been responsible for defining the official vertical reference frames since the first general adjustment of the geodetic leveling network in 1900.

Over the years, NGS has been responsible for the creation of two additional datums: the National Geodetic Vertical Datum of 1929 (NGVD29) and the North American Vertical Datum of 1988 (NAVD88). NVD29 was defined by the mean sea level over a 19 year period from 21 tidal gauges in the US and 5 in Canada. The multiple origins to which this datum resulted in an accumulation of errors that were never accounted for, since the datum was not referenced to a true zero surface. Each of the origins was defined as a zero surface, but since sea level is not a level surface and varies by location due to temperature, salinity, atmospheric pressure, etc., the origins did not all
refer to the same zero surface. NAVD88 was defined by a single origin and included several thousand kilometers of new leveling to expand the network in addition to the existing benchmarks. The need for new datums arises from the dynamic nature of the Earth. Over the years the slow movements of the Earth’s crust will gradually change the locations of some benchmarks, while other benchmarks will be inadvertently destroyed through construction projects, such as road widening.

The orthometric heights used in a vertical datum are traditionally established through spirit leveling and gravity measurements. This process yields precise results, but is quite labor intensive and is not economically feasible to conduct today. Even in the best of cases, cross-country leveling results in a build-up of systematic errors—errors inherent to the data model and collection process that cannot otherwise be avoided—as the leveling moves away from the origin.

Contemporary orthometric heights can be established through GPS observations combined with a geoid model. Orthometric heights derived in this way depend on the accuracy of the GPS measurements, the accuracy of the geoid model, and the accuracy of the NAVD88 control. NGS has technical guidelines in place in Technical Memorandums NGS-58 and NGS-59 that define the equipment, field procedures, data collection requirements, control requirements, and processing and analysis procedures needed to obtain an accuracy at a 2 or 5 cm level. NGS constructs geoid models based on the collection of gravity data and so called hybrid geoid models, augmented with GNSS measurements at control points, to enable a fit to NAVD88.
The accuracy of GNSS observations and geoid models were limited in the early days of their implementation to establish orthometric heights. Accuracy of the geoid models was particularly troublesome, as they were accurate to the decimeter level in the best of cases and this accuracy declined in some parts of the country. Over the years, techniques have been implemented and refined to improve the accuracy of GNSS observations. GNSS-derived heights are 1.5 to 2 times less accurate than GNSS-derived horizontal coordinates due to satellite geometry and the unmodeled errors caused by the ionosphere and troposphere that will map directly to GNSS-derived heights. As the GNSS-derived heights became more accurate, due to expanding the GNSS constellation and better error modeling, the need for a more accurate geoid model became obvious. The current poor conditions of the vertical network further emphasized the need for improved geodetic control.

The Height Modernization Program has been implemented on a state-by-state basis, with most of the funding received by academic institutions and state or local governments. This implementation strategy has allowed for focus on the needs of the individual users and states, while NGS provides technical expertise and support. Additional coordination is ongoing at a regional level to the point that states with similar needs and challenges are being more collaborative and extend their resources to promote the creation of stronger regional networks. The Height Modernization implementation strategy has been crucial in allowing the program to address a variety of needs for an accurate height reference system throughout the country.
NGS has developed a set of fundamental goals and guidelines for the Height Modernization Program to follow in order to keep up with the diverse needs and regional interests being simultaneously pursued, and is oriented towards the objective of creating a new, high accuracy, vertical datum that is not hindered by the same problems as previous datums. These goals are:

- To provide access to accurate, reliable heights nationally
- To develop standards that are consistent across the nation
- To provide data, technology, and tools that yield consistent results, regardless of terrain and circumstances, and
- To establish a system or process that is maintainable overtime

1.2 Earth Models

1.2.1 Introduction

The shape and surface of the Earth are complicated to model, but they must be accurately modeled in order to determine the position of a point on the Earth. Geodetic datums or reference systems have been specifically defined to handle this task. A geodetic datum defines the shape, size, position, and orientation of a (mathematical) reference surface (e.g., ellipsoid) [Grejner-Brzezinska, 2011]. Hundreds of datums have been defined and vary in terms of the reference surface used and the origin of the reference surface with respect to the geographical extents of the Earth they are created to model. Contemporary geodetic datums range from flat-earth models used for plane
surveying to complex models used for international applications, which completely describe the size, shape, orientation, gravity field, and angular velocity of the Earth. In addition, the mathematical reference surface of a geodetic datum can be defined on a local or global basis. A global reference surface is an ellipsoid created with its origin at a set point, so that it can serve as a best fit to the entire Earth. Local datums use a variety of reference surfaces with an origin positioned to best represent a specific geographically defined region of the Earth.

Two types of Earth models will be considered for determining heights: the ellipsoid and the geoid. Both of these models will be discussed in more detail in the following subsections, as well as the type of height computed from each reference surface. In addition, the relationship between these two models will be presented to relate GPS-derived ellipsoidal heights to orthometric heights.

1.2.2 Ellipsoidal Earth Models and Ellipsoidal Heights

Ellipsoidal Earth models are required for precise distance and direction measurements over long distances [Ramirez, 2010]. An ellipsoid is a mathematical figure generated by rotating an ellipse around its polar or minor axis. These models account for the slight flattening of the Earth at the poles and serve as a better representation of the shape of the Earth than spherical Earth models. While these models do allow for accurate distance and direction measurement, they are not able to provide an accurate height. The best global ellipsoidal models can represent the shape of the Earth over the smoothed, averaged sea-surface to within about 100 m [Ramirez, 2010].
Any height that is referenced to any ellipsoid is called an ellipsoidal height. Ellipsoid heights are geometric heights that are expressed relative to the surface of the ellipsoid and measured along a normal to the ellipsoid. The ellipsoid is purely a mathematical surface with no relief. Therefore, ellipsoidal heights are purely geometric quantities that have no connection to the gravity potential. As such, they cannot account for the local variations in gravity caused by topography to determine a true level surface. Historically, these heights were established through differential leveling, as this measures the relative change in heights between points. Today, the ellipsoidal height of a point can also be determined using GPS.

1.2.3 Geoids and Orthometric Heights

The geoid is an equipotential surface of the Earth’s gravity field, which would coincide with the ocean surface, if the latter were undisturbed and affected only by the Earth’s gravity fields [Ho, 2009]. Geoids are physical models with no mathematical expression and represent the Earth as a continuous surface. The geoid surface is the true zero surface for measuring orthometric heights.

Orthometric heights can generally be thought of as the height of a point above mean sea level, although they are actually the height of a point above the geoid. These heights are measured along the normal to the geoid, which is actually a three-dimensional curve. Since the geoid is an equipotential surface, orthometric heights not only represent the height of a point above the true zero, but also define level surfaces. A level surface is defined as an equipotential surface; a surface of the same gravity potential on which
water will not flow. Orthometric heights, therefore, represent the geopotential difference between two points, or the change in the potential of the Earth’s gravity between points. Historically, these heights have been computed through a combination of spirit leveling and gravity observations.

1.2.3: Ellipsoid Geoid Relationship

The relationship between the ellipsoidal and geoid heights used to derive the orthometric height of a point is presented in Figure 1.1. In this figure, the ellipsoidal height of a point is denoted by $h$, the orthometric height of a point is denoted by $H$, and the geoid height of a point is denoted by $N$. The geoid height, $N$, is the measure of the separation between the ellipsoid and geoid for a point on the Earth's surface. By convention, the height is considered to be negative, if the geoid is below the ellipsoid and positive if the geoid is above the ellipsoid. The orthometric height of a point on the Earth's surface can therefore be computed as:

$$H = h - N$$  \hspace{1cm} (1.1)

where:

- $H$ is the orthometric height of the point above the Earth's surface
- $h$ is the ellipsoidal height of the point above the Earth's surface
- $N$ is the geoid height or separation between the geoid and ellipsoid for that point on the Earth's surface.
1.3 Research Objectives

As described in Section 1.1, the use of GPS measurements to compute orthometric heights depends on the accuracy of the geoid model, as well as the accuracy of the GPS measurements. The current US geoid model, Geoid12A, has already been established and is accurate to 1.5 cm across most of the conterminous United States [Doyle, 2012], including Ohio, where the research in this thesis was conducted. This thesis will assume that geoid model meets this minimum accuracy in the environments where the experiments were conducted and that the remainder of the errors in height will be caused by errors in GPS measurements. The research in this thesis will focus on an assessment of station dependent error sources, including far-field multipath, near-field multipath, and phase center variations (PCVs). A better understanding of such error
sources will help to achieve the accuracy standards of GPS-derived heights in the National Height Modernization program and may also contribute to obtaining heights at a greater accuracy than the goal of the National Height Modernization program.

The research presented in this thesis is only part of the ongoing research at the OSU Satellite Positioning and Inertial Navigation Laboratory (SPIN) in support of the National Height Modernization program. The analysis of station dependent error sources presented in this thesis builds upon the results of another phase of research examining techniques to reduce the tropospheric delay error impact on GPS height estimation. The aforementioned research analyzed the required baseline length with respect to duration of the GPS data span and the optimal network configuration to assure proper estimation of tropospheric corrections. Relevant findings include [Ugur, 2012]:

- A several-hundred-kilometer baseline is required to measure the absolute tropospheric delay per station.
- Single base station approach had a major impact on positioning, especially for short observation time spans.
- Dual base station approach improved results.
  - Distant base station for estimation of tropospheric delay.
  - Nearby station also used to enhance the percentage of observations used.
  - Reliability of results is dependent on the level of station dependent error sources, especially at the distant station.
- Multiple base station approach resulted in the best positioning while still estimating the tropospheric delay.
- Enhanced dual base station approach by selecting multiple stations from the IGS network as the distant reference stations.
- This facilitates access to the IGS frame, which is considered to be the most precise reference frame in geodetic applications.

Far-field multipath is considered to be multipath caused by signal reflections from objects located more than a few wavelengths away from the antenna. Such multipath error can generally be suppressed at the antenna through the use of a ground plane, which is designed to suppress the left-hand polarized signals caused by this kind of multipath. Additional proposals to limit the effect of far-field multipath, though less practical and more costly, are to cover reflective surfaces near the antenna with multipath absorbing foam. Such foam would have to be particularly designed to absorb the L band on which the fundamental GPS frequencies are derived. For long term static GPS observations, the high frequency oscillations in phase data from far-field multipath tend to average out over a 24 hour period and tend not to bias a single static position derived from a 24 hour period [Berglund, 2011].

Near-field multipath is caused by objects near the antenna. This type of multipath is caused by signal diffraction and reflection, as well as electromagnetic interaction. Furthermore, the amplitude of near-field multipath is affected by antenna type, monument design, the type of antenna mount, and weather conditions [Berglund, 2011]. The effects of near-field multipath are particularly troublesome to GNSS processing, because they can change the reception characteristics of antennas. Unlike far-field multipath, near-field multipath cannot be removed through averaging over long periods.
The final component of the station dependent error is the PCV. The antenna phase centers (APC) are the internal points of the antenna where the GPS frequencies are received. However, the APCs are not stable points and change as a function of frequency strength as well as the direction and elevation of the received signal with respect to the antenna. Accurate PCVs are needed to connect GPS measurement to physical monuments and ignoring these PCVs can result in vertical errors up to 10 cm [Mader, 1999].

The APC is typically described by a mean phase center offset (PCO) and the PCVs, both of which are directionally dependent [Bilich and Mader, 2010]. The variations in PCOs and PCVs are needed to relate the APC to the antenna reference point (ARP), the point used to connect a GPS measurement to a monument. The antenna frame origin is taken to be the ARP, which is generally taken to be the center of the antenna base at the attachment point. The orientation of the antenna reference frame is typically aligned with the north reference mark on the antenna. The PCO’s are then described by north-east-up offsets from the ARP to the phase center computed for a given elevation angle, azimuth angle, and frequency.

A depiction of the antenna reference frame used to describe PCVs of the phase APC is shown in Figure 1.2. Figure 1.2 (a) indicates the position of the mean phase center for either the L1 or the L2 GPS frequencies by a star. The ARP is shown by a blue circle and is positioned as described above. The elevation angle of incoming signals is defined to be 0° on for signals received horizontal with the antenna base plane and increase to 90° for signals received directly overhead of the antenna. The location of the
north reference point on the antenna is indicated in 1.2 (a) and is used to define the
convention to describe the azimuth of the incoming signals. By convention, the azimuth
of incoming signals increases positively in the clockwise direction from this point when
viewing the antenna from above (1.2(b)).

![Figure 1.2](image)

Figure 1.2: Establishment of antenna reference frame to describe the phase center variations of a particular antenna phase center. (a) Inverted side view of an antenna displaying the ARP, north reference point, hypothetical APC (star), and convention to define the elevation angle of the incoming signal. (b) Top view of an antenna showing convention to define azimuths from the north reference point.

The antenna PCVs are determined through antenna calibration. There are two
classes of antenna calibration: absolute antenna calibration and relative antenna
 calibration. Absolute antenna calibrations are conducted with the antenna mounted on a
robot that will tilt and rotate the antenna so that GPS signals can be measured from every
azimuth and elevation angle in order to describe the PCVs as a function of the elevation
and azimuth of the incoming signal. Relative antenna calibrations utilize a stationary
antenna and only describe the PCV as a function of the elevation angle of the incoming
signal. The result of antenna calibrations is a phase center map, used to apply corrections
to raw measurements depending on the elevation angle and azimuth angle of the received signal.

The objectives of this thesis are to assess the magnitudes of specific station dependent error sources in selected environments relevant to the Ohio CORS. An analysis of the epoch-to-epoch deviation of the GPS-derived heights in each of these environments will be conducted to determine if a particular error source has a significant impact with respect to the accuracy standards of the National Height Modernization program. In addition, the analysis will contribute to the development of recommended data collection procedures in these environments.

The station dependent error sources considered include:

- The effects of not accounting for radome specific GPS antenna calibration parameters on GPS-derived heights.
- Variations in GPS-derived heights caused by changing the antenna model used at a control point when applying PCVs obtained through relative antenna calibrations.
- GPS height variations caused by high voltage power lines.
- Multipath reflection from a snow-covered field.
- Effects on GPS heights caused by a bird sitting on a GPS antenna.

1.4 Overview

This thesis consists of five chapters. Chapter 1 gives an overview of the National Height Modernization Program, introduces the two major Earth models used in surveying
and geodesy, the heights obtained from these models, and relates these heights to obtain the orthometric height of a point, and lists the objectives of this research. Chapter 2 deals with GPS models and observations. This chapter will provide an introduction to GPS and how positional observations are computed. This chapter will also give an overview of the experiments conducted to support the objectives of this research and describe the different GPS software used to process the data collected in the experiments. Chapter 3 will present an overview of the different statistical analysis procedures used. Chapter 4 will present the results and analysis of the different experiments. Finally, Chapter 5 presents the conclusions regarding the antenna calibration parameters used, measured effects of environmental multipath, antenna specific height variations, and a discussion of possible field procedures to overcome these error sources.
2.1 Introduction

The NAVSTAR Global Positioning and Satellite System (GPS) is a satellite-based radio-positioning and time transfer system, designed, financed, deployed, and operated by the U.S. Department of Defense (DoD). It was designed to be an all-weather, continuous, global radio navigation system [Wooden, 1985].

GPS was designed so that the satellites would have a near circular orbit at approximately 22,000 km, with a period of 12 sidereal hours. GPS was originally designed to have a full constellation of 24 satellites: 21 in the full constellation and 3 spares. However, the current GPS constellation has 32 satellites as of November 30, 2013 (http://navcen.uscg.gov/?Do=constellationStatus). The satellites are deployed into six orbital planes with an inclination of approximately 55° and spaced at 60° intervals along the equator.

The configuration of the satellite orbits was chosen to allow visibility of at least four satellites at all times from most of the Earth, provided that the environment is open enough; that is, the signal is not being obstructed by natural or manmade artifacts, such as trees, tall buildings, etc., that may block out large portions of the sky. It takes a minimum of four observed satellites to determine a unique position with GPS. Each of these satellites broadcasts two separate signals: the L1 (1575.42 MHz) and L2 (1227.60 MHz)
microwave carrier signals. In addition, there are currently three satellites that also broadcast the L5 (1176.45 MHz) microwave carrier signal. All three signals are derived from the fundamental L band frequency (10.23 MHz). The L5 signal was not used in this research, because the receivers and the GPS processing software used only supported the L1 and L2 signals. Two pseudorandom noise codes are superimposed on the carrier frequencies: the Coarse/Acquisition-code (C/A-code) and the Precision code (P(Y)-code). The P(Y)-code is the precise and protected code reserved for military applications and the C/A-code is a less accurate code reserved for civilian users. The L1 and L2 frequencies both carry the P(Y)-code and an identical navigation message. The C/A-code was historically transmitted on the L1 frequency only. However, there is a new C/A code transmitted on the L2 frequency that began with the launch of the Block IIM satellites and subsequent satellites first launched on September 26, 2005 [Leick, 2004].

As the observations between the satellite and antenna are made, they will be logged to a GPS receiver. What happens to the observations at this point depends upon the receiver and the type of GPS data being collected. For post-processing, data is logged to the receiver and is later downloaded for processing. Real-time kinematic applications will instantaneously compute positions from the GPS observations as they are being logged. The experiments in this thesis collected all data for post-processing.

Position determination with satellites can be visualized as computing the intersection of imaginary spheres formed around each visible satellite, where the radius of the imaginary sphere around a particular satellite is equal to the geometric range between that satellite and the GPS antenna. Each of the visible satellites will have an
imaginary sphere of a different radius around it. The intersection of the spheres from two satellites will result in a circle and will limit the position of the antenna to somewhere on this circle. The intersection of the sphere from a third satellite to the antenna will intersect the circle at two points. At this stage, it is possible to find a unique three-dimensional position in space by using the range from another satellite and the GPS antenna, which will intersect one of the two possible locations determined by the other three satellites, resulting in a unique position. Additionally, the use of a fourth measurement is used to help correct for the receiver clock’s error. The receiver or post-processing software can then compute a unique XYZ position of the antenna phase center from the visible satellites in a global geodetic datum called WGS84. The coordinates can be converted from Cartesian coordinates to the easier to visualize geodetic coordinates (latitude, longitude, and height above the ellipsoid) by applying an iterative or closed form solution that accurately accounts for the WG84 ellipsoid parameters.

2.2 GPS Observations

2.2.1 Basic GPS Measurements

Modern GPS receivers utilize three types of measurements: pseudorange, carrier phase, and Doppler measurements. Only the pseudorange and carrier phase measurements will be discussed here, since the GPS processing software used (Section 2.6) does not support Doppler measurements. A pseudorange is the measure of the geometric range between the transmitting satellite and the antenna of a GPS receiver. This range can be
obtained by multiplying the speed of light with the time difference between the epoch the signal is transmitted by the satellite’s antenna and the epoch it is received by the receiver’s antenna. However, the satellite and receiver clocks are not perfectly synchronized, thus a clock delay error enters into the pseudorange observation. Additional error sources entering into GPS measurements will be discussed later. P(Y)-code pseudoranges can be as good as 20 cm or less, while the L1 C/A code range noise level reaches even a meter or more [Grejner-Brzezinska, 2011].

A carrier phase measurement is the difference between the phase of a carrier signal received from a spacecraft and a reference signal generated by the receiver’s internal oscillator. A carrier phase range can be determined by multiplying the measured carrier phase by the wavelength of the carrier signal. The phase observable is expressed as the sum of the fractional carrier phase and an unknown integer constant representing full waves [Leick, 2004]. The fractional component is what is actually recorded by the receiver and is the phase differences between the arriving phases and internally generated receiver phases. The integer component, also known as an integer ambiguity, is an unknown number of phase cycles at the starting epoch between the satellite and the receiver, which exists because the receiver has no way of knowing when the carrier wave left the satellite. The integer ambiguities are resolved when the carrier-phase data are processed. These integer ambiguities will remain constant for a satellite, as long as the tracking of that satellite is continuous. A positioning solution in which the ambiguities are approximated by real numbers is called a float solution and is less accurate than the fixed solutions, where the ambiguities are found in terms of integer cycles.
A phase cycle slip or a loss of lock will introduce a new unknown ambiguity. A cycle slip is a sudden jump in the carrier phase observable, generally, by an integer number of cycles. This can occur due to signal blockage by buildings, trees, etc. (loss of lock), due to receiver malfunction, such as by severe ionospheric distortion or by signal interference. A cycle slip results in all subsequent measurements being offset by a constant integer number of cycles. Despite the additional complications of solving for an integer ambiguity and cycle slips, carrier phase measurements are typically more accurate than pseudorange measurements, with the typical noise of the measurements being on the order of a few millimeters or less [Grejner-Brzezinska, 2011].

Consider Figure 2.1 below, depicting the relationship between receiver i and satellite k. The GPS observables can then be expressed with the following equations.

\[ P^{k}_{l1} = \rho^{k}_{l} + d\rho^{k} + t^{k}_{l1} + T^{k}_{l} + c(d\tau_{l} - d\tau^{k}) + b_{l,2} + M^{k}_{l1} + e^{k}_{l1} \]  \hspace{1cm}  (2.1)

\[ P^{k}_{l2} = \rho^{k}_{l} + d\rho^{k} + t^{k}_{l2} + T^{k}_{l} + c(d\tau_{l} - d\tau^{k}) + b_{l,3} + M^{k}_{l1} + e^{k}_{l2} \]  \hspace{1cm}  (2.2)
\[
\phi_{i1}^k = \rho_i^k + d\rho^k - I_{i1}^k + T_i^k + \lambda_1 N_{i1}^k + c (d t_i - d t^k) + \lambda_1 (\varphi_{i1}^k - \varphi_{i0,1}) + m_{i1}^k + \varepsilon_{i1}^k
\]  
(2.3)

\[
\phi_{i2}^k = \rho_i^k + d\rho^k - I_{i2}^k + T_i^k + \lambda_2 N_{i2}^k + c (d t_i - d t^k) + b_{i1} + \lambda_2 (\varphi_{i2}^k - \varphi_{i0,2}) + m_{i2}^k + \varepsilon_{i2}^k
\]  
(2.4)

where:

\[
\rho_i^k = \sqrt{(X_i^k - X_i)^2 + (Y_i^k - Y_i)^2 + (Z_i^k - Z_i)^2}
\]  
(2.5)

\(X_i, Y_i, \) and \(Z_i\) are the unknown coordinates of the receiver

\(P_{i1}^k, P_{i2}^k\) are the pseudorange measurements between receiver \(i\) and satellite \(k\) for the L1 and L2 frequencies, respectively

\(\phi_{i1}^k, \phi_{i2}^k\) are the carrier phase measurements between receiver \(i\) and satellite \(k\) for the L1 and L2 frequencies, respectively

\(\rho_i^k\) is the geometric distance between receiver \(i\) and satellite \(k\) for the L1 and L2 frequencies, respectively

\(I_{i1}^k, I_{i2}^k\) are the ionospheric delays between receiver \(i\) and satellite \(k\) for the L1 and L2 frequencies, respectively

\(T_i^k\) is the tropospheric delay between receiver \(i\) and satellite \(k\)

c is the speed of light in vacuum

\(d t_i, d t^k\) are the receiver and satellite clock errors, respectively

\(M_{i1}^k, M_{i2}^k, m_{i1}^k, m_{i2}^k\) are the multipath error for the L1 and L2 frequencies for the pseudoranges and carrier phase ranges, respectively

\(\varepsilon_{i1}^k, \varepsilon_{i2}^k, \varepsilon_{i1}^k, \varepsilon_{i2}^k\) are the measurement noise for the L1 and L2 frequencies for the pseudoranges and carrier phase ranges, respectively

\(\lambda_1, \lambda_2\) are the wavelengths of the L1 and L2 phases, respectively
\(N^k_{l,1}, N^k_{l,2}\) are the integer ambiguities associated with the L1 and L2 carrier phase measurements, respectively

\(\varphi_{i0,1}, \varphi_{i0,2}\) are the initial fractional phases at the receiver \(i\) on the L1 and L2 frequencies, respectively

\(\varphi^k_{0,1}, \varphi^k_{0,2}\) are the initial fractional phases at the satellite \(k\) on the L1 and L2 frequencies, respectively

\(d\rho^k\) is the orbital error of satellite \(k\)

\(b^1_{l,1}\) is the interchannel bias between \(\phi^k_{l,1}\) and \(\phi^k_{l,2}\)

\(b^1_{l,2}, b^1_{l,3}\) are the interchannel biases between \(\phi^k_{l,1}\) and \(P^k_{l,1}\), and \(\phi^k_{l,1}\) and \(P^k_{l,2}\), respectively.

2.2.2 GPS Error Sources

There are many error sources entering into the GPS observables, including satellite and receiver clock errors, satellite orbit errors, atmospheric effects caused by the ionosphere and troposphere, multipath, antenna phase center, and receiver biases. The satellite and receiver clock errors occur due to a lack of synchronization between the precise atomic clocks of the satellites and the lower grade receiver clocks. Satellite orbit errors occur when the course of a satellite deviates from its predicted course in a GPS navigation message, which is used by receivers to predict the position of a satellite at a particular instance in time. These errors can be corrected with precise orbit files, which contain the real, observed satellite orbits. These precise orbits, whose accuracy is approximately 5 cm, deviate from the predicted orbits that are accurate to approximately 2 to 5 m [Grejner-Brzezinska, 2011]. A precise orbit file can be obtained from the
International GNSS Service (IGS)  
(http://igscb.jpl.nasa.gov/components/compindex.html). As a GPS signal passes through the atmosphere, it is slowed down and refracted by the charged particles of the ionosphere and the water vapor in the troposphere. This causes slight deviations to the path of the signal and increases the travel time, resulting in distances that appear larger than they actually are. Multipath error occurs when a signal arrives at a receiver through an indirect path, such as by reflectance from the ground or a building. Additional errors are caused by phase center variations, which cause a variation in the point that the signal is being measured to within the antenna as the satellite changes in elevation, azimuth, and signal strength with respect to the antenna. There are also biases inherent to receivers. GPS observations collected from different receivers or even the same kind of receivers receiving a signal from the same antenna may result in slightly different positions for a point. The determination of high accuracy GPS positions requires that these error sources be mitigated.

Some errors can be removed or mitigated from a posteriori information and modeling. For instance, precise satellite orbits are calculated to remove the error caused by deviations in satellite position. Tropospheric error can be mitigated with different types of modeling and corrected for with known values. The ionospheric error is most commonly mitigated through a linear combination of the L1 and L2 frequencies, known as an iono-free combination. The effects of phase center variations can be mitigated through antenna calibration. More troublesome are the effects of multipath, which are difficult to model and change with the surrounding environment. Some receivers utilize
built-in multipath mitigation techniques, which help reduce the effects of multipath, but do not fully remove it from the observables. Antenna ground planes and choke-rings are also employed to mitigate the effects of multipath. Multipath can also result in unpredicted PCV, which can be mitigated through an in-situ, or environmental specific, antenna calibration. In addition, error sources over short baselines can be removed through differential GPS, discussed in Section 2.3. Table 2.1 depicts the magnitudes of some of these error sources.

<table>
<thead>
<tr>
<th>Summary of GPS Error Sources [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Satellite Clocks</td>
</tr>
<tr>
<td>Orbit Errors</td>
</tr>
<tr>
<td>Ionosphere</td>
</tr>
<tr>
<td>Troposphere 0.5 (model)</td>
</tr>
<tr>
<td>Receiver Noise</td>
</tr>
<tr>
<td>Multipath</td>
</tr>
<tr>
<td>Phase Center Variation</td>
</tr>
</tbody>
</table>

2.3 Differential GPS

2.3.1 Introduction

Differential Global Positioning Service (DGPS) is applied in surveying and geodesy for GPS results of the highest accuracy. Data is collected simultaneously in two locations, with one of the receivers on a known location. This data is then processed by differencing the respective observables, either pseudorange or carrier phase, from both stations. DGPS allows for a significant reduction of errors affecting observables caused
by the satellite and receiver clock biases, atmospheric errors, and inter-channel biases. However, multipath and receiver noise are not eliminated by DGPS, as these are site-and-model-specific. The baseline between stations can be any length, as long as the satellites can be simultaneously observed from both stations. However, the size of the baseline between stations becomes important in determining how atmospheric error sources are affected by the differencing techniques described below. The ionospheric effects begin to vary considerably for baselines between 5 and 10 km and can be differenced away or significantly reduced for baselines of this size. The tropospheric effects change less rapidly and remain consistent for baselines shorter than 50 to 60 km, depending on tropospheric conditions at both ends of the baseline [Grjner-Brzezinska, 2011]. DGPS over baselines up to this size can remove or significantly reduce the tropospheric effects.

A summary of the magnitudes of the common error sources for the differenced and standard (undifferenced) GPS observables are given in Table 2.2.

Table 2.2: Summary of the magnitudes of common GPS error sources between undifferenced GPS and differenced GPS [Grjner-Brzezinska, 2011]

<table>
<thead>
<tr>
<th>Error Source</th>
<th>Standard GPS</th>
<th>Differential GPS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Satellite Clock</td>
<td>1.5</td>
<td>0.0</td>
</tr>
<tr>
<td>Orbit Errors</td>
<td>2.5</td>
<td>0.0</td>
</tr>
<tr>
<td>Ionosphere</td>
<td>5.0</td>
<td>0.4</td>
</tr>
<tr>
<td>Troposphere</td>
<td>0.5</td>
<td>0.2</td>
</tr>
<tr>
<td>Receiver Noise</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>Multipath</td>
<td>0.6</td>
<td>0.6</td>
</tr>
</tbody>
</table>
2.3.2 Single Difference

A single difference is obtained by simultaneously collecting data from one satellite at two receivers separated by a baseline. The concept of the single difference is illustrated in Figure 2.2 between two separate receivers (i and j) simultaneously receiving measurements from satellite k. Single differencing eliminates satellite clock and orbit errors, as well as the initial fractional phase term for satellite k at the initial epoch of observation. In addition, atmospheric errors caused by the ionospheric and tropospheric delay can be significantly reduced over short baselines.

![Diagram of the single difference mode geometry in differential GPS between receivers i and j and satellite k](image)

Figure 2.2: Depiction of the single difference mode geometry in differential GPS between receivers i and j and satellite k

The single difference DGPS observable pseudorange and carrier phase measurements between satellite k and receivers i and j are developed below. These observables are shown here only for L1, since the L2 observables can be developed in the same manner.
A single difference measurement for the pseudorange and carrier phase measurements can then be formulated for each pair of observations from satellite k. The L1 single differenced pseudorange and carrier phase measurements for receivers i and j and satellite k are formulated in the equations below.

\[
P_{ij,1}^k = p_{ij,1}^k - p_{i,1}^k
\]

\[
P_{ij,1}^k = \Delta \rho_{ij}^k + \Delta d \rho^k + \Delta t_{ij,1}^k + \Delta T_{ij}^k + c(\Delta t_i - \Delta t_j) + b_{ij,2} + \Delta M_{ij,1}^k + \Delta e_{ij,1}^k
\]

\[
\phi_{ij,1}^k = \phi_{ij,1}^k - \phi_{i,1}^k
\]

\[
\phi_{ij,1}^k = \Delta \rho_{ij}^k + \Delta d \rho^k - \Delta t_{ij,1}^k + \Delta T_{ij}^k + \lambda_1 N_{ij,1}^k + c(\Delta t_i - \Delta t_j) + \lambda_1 (\varphi_{ij,1} - \varphi_{i,1}) + m_{ij,1}^k + \Delta e_{ij,1}^k
\]

where:

\[
N_{ij,1}^k = N_{ij,1}^k + (\varphi_{ij,1} - \varphi_{i,1})
\]

\[
N_{ij,1}^k
\]

is the non-integer bias, including the ambiguity term

\[
p_{ij,1}^k
\]

is the single differenced pseudorange measurement for the L1 frequency

\[
\phi_{ij,1}^k
\]

is the single differenced carrier phase range measurement for the L1 frequency.

Notice that terms for the satellite orbit error, ionospheric error, and tropospheric error are still listed in equations 2.11 and 2.13. Each of the atmospheric error terms remains consistent up to a baseline of a certain length (5-10 km for ionosphere and 50-60 km for troposphere), listed above. For baselines less than or equal to those lengths, the atmospheric error sources at each station will be very similar and their difference will
either be zero or close to zero. Similarly, the satellite clock and orbit errors will be removed through single differencing.

2.3.3 Double Difference

A double differenced measurement is formed by two receivers simultaneously observing two satellites, and is formulated through two steps. First, the single difference is formulated for each satellite. Second, the difference between the two single differences is taken. A double-differenced solution eliminates the satellite clock error, receiver clock error, and reduces or eliminates orbital errors and atmospheric effects. Like single differencing, double differencing DGPS may eliminate or reduce the atmospheric errors depending on the size of the baseline. Any remaining atmospheric error after differencing (for long baselines) may be removed through estimations obtained through modeling the delays. Double differencing observations are the most prevalently used among the differential combinations, due to removing or minimizing as many of the GPS error sources as possible, while still maintaining a reasonable level of noise in the solution.

For the development of the double differenced observations, consider two receivers (i and j) and two satellites (k and l) as shown in Figure 2.3. The double differenced observation equations are developed and once again consider only the L1 frequency, because development of the observations for the L2 equations is similar.
The single differenced equations for satellite k and receivers i and j, and satellite l and receivers i and j are computed for the L1 frequency below, according to equations 2.10 to 2.13.

\[ p_{ij,1}^k = \Delta \rho_{ij}^k + \Delta d \rho^k + \Delta t_{ij,1}^k + \Delta T_{ij}^k + c \cdot \Delta t_{ij} + b_{ij,2} + \Delta M_{ij,1}^k + \Delta e_{ij,1}^k \] (2.15)

\[ p_{ij,1}^l = \Delta \rho_{ij}^l + \Delta d \rho^l + \Delta t_{ij,1}^l + \Delta T_{ij}^l + c \cdot \Delta t_{ij} + b_{ij,2} + \Delta M_{ij,1}^l + \Delta e_{ij,1}^l \] (2.16)

\[ \phi_{ij,1}^k = \Delta \rho_{ij}^k + \Delta d \rho^k - \Delta t_{ij,1}^k + \Delta T_{ij}^k + \lambda_1 \cdot \Delta N_{ij,1}^k + c \cdot \Delta t_{ij} + \Delta m_{ij,1}^k + \Delta \varepsilon_{ij,1}^k \] (2.17)

\[ \phi_{ij,1}^l = \Delta \rho_{ij}^l + \Delta d \rho^l - \Delta t_{ij,1}^l + \Delta T_{ij}^l + \lambda_1 \cdot \Delta N_{ij,1}^l + c \cdot \Delta t_{ij} + \Delta m_{ij,1}^l + \Delta \varepsilon_{ij,1}^l \] (2.18)

The double-differenced pseudorange and carrier phase measurements for the L1 frequency can then be formulated by taking the single difference of the two single differences.

\[ p_{ij,1}^{kl} = \Delta p_{ij,1}^l - \Delta p_{ij,1}^k \Leftrightarrow (p_{ij,1}^l - p_{ij,1}^k) - (p_{ij,1}^k - p_{ij,1}^k) \] (2.19)

\[ p_{ij,1}^{kl} = \nabla \Delta \rho_{ij}^{kl} + \nabla \Delta d \rho^{kl} + \nabla \Delta t_{ij,1}^{kl} + \nabla \Delta T_{ij}^{kl} + \nabla \Delta M_{ij,1}^{kl} + \nabla \Delta \varepsilon_{ij,1}^{kl} \] (2.20)

\[ \phi_{ij,1}^{kl} = \Delta \phi_{ij,1}^l - \Delta \phi_{ij,1}^k \Leftrightarrow (\phi_{ij,1}^l - \phi_{ij,1}^l) - (\phi_{ij,1}^k - \phi_{ij,1}^k) \] (2.21)
\[ \phi_{i,j,1}^{kl} = \nabla \Delta \rho_{ij}^{kl} + \nabla \Delta d \rho_{ij}^{kl} - \nabla \Delta l_{ij,1}^{kl} + \nabla \Delta T_{ij}^{kl} + \lambda_1 \nabla \Delta N_{ij,1}^{kl} + \nabla \Delta m_{ij,1}^{kl} + \nabla \Delta \varepsilon_{ij,1}^{kl} \]  \hspace{1cm} (2.22)

where:

\( p_{ij,1}^{kl}, \phi_{ij,1}^{kl} \) is the double differenced pseudorange and carrier phase measurements for the L1 frequency, respectively.

Note that the atmospheric errors are still listed in equations 2.20 and 2.22. As was the case for the single difference, the atmospheric errors will only cancel out over baselines up to a set length (5-10 km for ionosphere and 50-60 km for troposphere) and will remain for longer baselines.

2.3.4 Triple Difference

A triple difference is obtained by differencing two double differences separated by a time interval, \( dt \). For carrier phase observations, a triple difference will cancel the phase ambiguity biases, \( N_1 \) and \( N_2 \). A triple difference results in a pseudorange and carrier phase observation with only the coordinates of the receiver as an unknown. While the triple difference may seem to be the most ideal of the differential combinations to use it is often not used in practice when the highest accuracy is needed due to its noise level.

The noise for each differential combination is amplified by \( \sqrt{2} \) for each successive difference, due to mathematical correlations according to the law of error propagation. Thus, the noise in a single difference is increased by a factor of \( \sqrt{2} \), a double difference increases the noise by a factor of 2, and a triple difference increases the noise by a factor of \( 2\sqrt{2} \) when compared to the noise level of a non-differential solution. However, triple differences can be used to detect cycle slips in the carrier phase measurements. Recall that an integer ambiguity remains constant until a cycle slip occurs. Each cycle slip
results in an outlier detectable in the triple difference at the instance it occurs [Leick, 2004].

The triple-differenced pseudorange and carrier phase observations are given below. As for the other differential combinations, the observations are given only for the L1 frequency, as the formulation of the equations for the L2 frequency is similar.

\[ p_{ij,1,dt}^{kl} = p_{ij,1,t_2}^{kl} - p_{ij,1,t_1}^{kl} \]  \hfill (2.23)

\[ p_{ij,1,dt}^{kl} = \rho_{ij,dt}^{kl} + \nabla \Delta l_{ij,dt}^{kl} + \nabla \Delta r_{ij,dt}^{kl} + M_{ij,1,dt}^{kl} + e_{ij,1,dt}^{kl} \]  \hfill (2.24)

\[ \phi_{ij,1,dt}^{kl} = \phi_{ij,1,t_2}^{kl} - \phi_{ij,1,t_1}^{kl} \]  \hfill (2.25)

\[ \phi_{ij,1,dt}^{kl} = \rho_{ij,dt}^{kl} - \nabla \Delta l_{ij,dt}^{kl} + \nabla \Delta r_{ij,dt}^{kl} + m_{ij,1,dt}^{kl} + \epsilon_{ij,1,dt}^{kl} \]  \hfill (2.26)

2.4 Continuously Operating Reference Stations

The Continuously Operating Reference Stations (CORS) are a network of GPS stations that are continuously collecting data, whose position coordinates are known with a high accuracy. CORS networks exist at global, national, and regional levels and are used for a variety of purposes. CORS stations are installed and operated by a variety of federal, state, and local agencies, both public and private. Some of the principal agencies include: NGS, NOAA/OAR Forecast Systems Lab, U.S. Coast Guard, the Army Corps of Engineers, the Federal Aviation Administration (FAA), state departments of transportation, counties and cities, and academic institutions.

In the United States, NGS manages the CORS network (http://www.ngs.noaa.gov/CORS/). As such, one of NGS’ responsibilities is to monitor the stability and health of each of the CORS. Each agency operating a CORS site shares
their data with NGS. NGS will analyze the data and distribute the data free of charge. NGS will use the CORS data for a number of data products, including: three dimensional positioning, meteorology, space weather, and geophysical applications. Since the coordinates of these stations are very stable and known to a high accuracy, they are also utilized to realize the National Spatial Reference System (NSRS). CORS are routinely used by surveyors, GIS users, engineers, scientists, etc., to post-process GPS observations with DGPS. This results in horizontal and vertical coordinates accurate to within a few centimeters of the NSRS.

The active CORS in the state of Ohio as of August 2, 2013 are shown in Figure 2.4. Each station is marked with its four letter station designation. Stations marked with a cyan icon are collecting data at a 1 second rate, stations marked with a yellow icon are collecting data at a 5 second rate, and stations marked with a red icon are collecting data at a 15 second rate.

CORS sites on a global level are operated by the International GNSS Service (IGS). The IGS stations are globally distributed and monitored on a 24 hour basis. A subset of the IGS stations was chosen to realize the International Terrestrial Reference Frame 2008 (ITRF2008) based on: the station’s performance, tracking record, and geographical distribution [IGS, 2010]. The IGS08 reference frame, realized through a subset of the IGS stations realizing ITRF2008 and considered to be consistent in definition with ITRF2008, is considered to be one of the most accurate and consistent geodetic frames. The IGS08 frame will be the frame that is used in all data processing for this research.
Figure 2.4: Active CORS in Ohio as of August 2, 2013. The cyan markers designate CORS logging GPS data at a 1 second rate, the yellow markers designate CORS logging at a 5 second rate, and the red markers designate CORS logging at a 10 second rate. CORS coordinates and data acquisition rates were acquired from NGS (http://www.ngs.noaa.gov/CORS/) and plotted in Google Earth.
2.5 Experiment Design

2.5.1 Introduction

This section will describe the specific GPS station dependent error sources that this thesis will focus on. Each of these error sources will be presented as an experiment in one of the following subsections. Each of these subsections will begin with a description of the error source being tested and why it is being tested. Each section will then present a table summarizing the data collected and will explain how the data will be used to evaluate the error source being investigated in the experiment.

2.5.2 Experiment 1: Effects of Not Accounting for Radome Antenna Calibration Parameters on GPS Heights

Radomes have two principal uses: protecting the GPS antenna from the environment and helping to keep the antenna free of birds. The radome fits over the antenna and will keep snow and ice from building up directly on the antenna in the winter. The surface of a radome makes it hard for birds to sit on and will prevent them from nesting in the rings of a choke ring antenna. Radomes, as shown in Figure 2.5, are made in different shapes, made to different thicknesses, and made from different material. All of these choices contribute to how the radome will alter the phase center variations (PCVs) of the antenna. If an antenna is to use a radome, it must be calibrated with the radome in order to account for the change in PCVs induced by the radome. There is also a concern that over time, the ultraviolet (UV) radiation from the sun will
wear the radome thin, which will alter the PCVs characteristic caused by the radome, so that the calibrated PCVs of the antenna with the radome will no longer be accurate and errors will enter into GPS-derived positions. Furthermore, the wear caused by UV radiation does not necessarily affect the radome uniformly and may cause thinner spots across the surface area of the radome, which would result in a stronger directional dependence of the PCVs on the incoming signal. Finally, there is a concern that an antenna on a CORS will be changed by the addition or removal of a radome and the CORS metadata will not be changed to reflect it. This would result in an incorrect set of PCVs being applied to the CORS antenna when using it to post-process GPS observations, which can result in incorrect positions being determined.

Figure 2.5: Depiction of four different kinds of Radomes: (a) SCIS, (b) CONE, (c) TZGD, (d) SNOW. Images acquired from NGS’ Antenna Calibrations page (http://www.ngs.noaa.gov/ANTCAL/Antennas.jsp?manu=Trimble).
The objectives of this experiment were to attempt to characterize the height deviations caused by not accounting for a radome on a GPS antenna in the antenna calibration parameters. This experiment was not intended to focus on the effects of radomes in general, but on the effects seen with a SCIS radome (Figure 2.5 (a)), which is a hemispherical radome, and a Trimble 59900.00 choke ring antenna. A TRM59800.00 choke ring antenna is shown in Figure 2.6. The TRM59900.00 choke ring antenna is very similar to the TRM5980.00 antenna. The TRM59900.00 antenna and SCIS radome combination was chosen for this test because these are the antenna models and radomes that older CORS antennas in Ohio were being replaced with at the time of this research.

Figure 2.6: TRM59800.00 choke ring antenna: (a) side view and (b) top view. Images acquired from NGS’ Antenna Calibrations page (http://www.ngs.noaa.gov/ANTCAL/Antennas.jsp?manu=Trimble).
A summary of the observations, including session, days of observations, session start time, session stop time, session duration, and the data sampling rate, whether the radome was used, and whether the radome PCVs were used in data processing is summarized in Table A.1 in Appendix A. The first session collected data with the radome on the antenna and used the correct radome PCVs, the second session did not use a radome on the antenna and still used the antenna PCVs for the radome, and the third session did not use a radome on the antenna and applied the antenna PCVs without a radome.

Three separate hypothesis tests will be conducted to evaluate the effects of the radome and choice of antenna PCVs on the resulting height, based on the data collected in the three sessions listed above. All three hypothesis tests were conducted with the nonparametric sign test described in more detail in Section 3.3.1. The sign test utilizes paired replicates data, in which a single population is subjected to a treatment and the sign test tells if the treatment effect, the difference in performance between the pre-treatment and post-treatment conditions, was significant. The GPS-derived heights for this experiment can be regarded as a single population subjected to different treatments, with a simplifying assumption explained later. In this case, performance refers to the GPS-derived heights obtained from the different data collection scenarios presented in Table A.1. The pre-treatment effects used in these tests will always refer to GPS-derived heights that were obtained under a controlled condition. There are two controlled conditions that will serve as different pre-treatment effects, both of which were obtained
by applying the correct PCVs in data processing. The first of the controlled conditions used the SCIS radome and applied the calibration parameters for the radome. This will serve as the pre-treatment effect in tests 1 and 3 listed below. The second of the control conditions did not use the SCIS radome and applied the calibration parameters for the antenna only. This will serve as the pre-treatment population in test 1 and as the post-treatment population in test 3 listed below.

- Test 1: Is there a significant difference in GPS heights caused by applying the radome PCVs to an antenna without a radome (post-treatment, scenario 2) compared to the GPS heights obtained using the radome PCVs and an antenna with a radome (pre-treatment, scenario 1)?

- Test 2: Is there a significant difference in GPS heights caused by applying the radome PCVs to an antenna without a radome (post-treatment, scenario 2) compared to the GPS heights obtained using the PCVs and antenna without a radome (pre-treatment, scenario 3)?

- Test 3: Is there a significant difference in GPS heights caused by applying the radome PCVs to an antenna with a radome (pre-treatment, scenario 1) compared to the GPS heights obtained using the PCVs and antenna without a radome (post-treatment, scenario 3)?

Each of the tests will be evaluated with the nonparametric sign test procedure described in Section 3.3.1. The sample populations for all three of the sessions were generated by computing the averaged heights from 100 random intervals between 5 minutes and 1 hour from each of the three days of observations for each of the sessions.
Paired replicates data depends upon the fact that only the treatment effect, the change in performance being tested under the different conditions, is changing and that all other factors remain constant.

To ensure that only the treatment effect changed, the same visible satellite constellation will be used for the data obtained from each day. This is accomplished by applying a sidereal shift to the observation times. A solar day is defined by a revolution of the Greenwich meridian around the sun. A sidereal day is defined as a revolution of the Greenwich meridian around the vernal equinox. A sidereal day is approximately 4 minutes shorter than a solar day, because the Earth’s orbit is not perfectly symmetrical and the effects of precession and nutation shift the location of the vernal equinox from day to day. Since satellite orbits follow a sidereal day, the same visible satellite constellation can be maintained by applying a four minute shift from day to day. This method was used to obtain the sample populations used in the hypothesis test from each scenario. It was assumed that maintaining a consistent satellite constellation throughout the day would eliminate any changes in GPS-derived heights due to a different satellite constellation. Since the weather was consistent for the days of data collection it was further assumed that similar atmospheric delays would be encountered on a daily basis.

Each of the scenarios had a single population of 300 samples, with 100 samples being taken from each day. Each of the 100 samples for a given day were obtained by averaging the heights over a randomly selected interval of the GPS solution between 5 minutes and 1 hour. The random time intervals were only selected for day 1 of scenario 1
and the 4 minute sidereal shift was applied to these times to obtain populations from the remaining days when the same satellite constellation was visible.

2.5.3 Experiment 2: Antenna Specific Variations in GPS Heights

The objective of this experiment is to examine how the GPS-derived height of a control point may change as a result of changing the model of GPS antenna used. Encountering a change in antenna types may happen over time as the antenna models at the CORS are updated or in repeated surveys, such as updates to the International Great Lakes Datum (IGLD). In the case of repeat surveys, such as the IGLD, both the reference antennas at the CORS stations as well as the antennas at the points being surveyed may change.

This experiment will focus on quantifying the magnitudes of any observed change in heights of control points caused by changing the antenna model used at the control. The change in heights caused by four types of antennas will be examined in this experiment: NOV600, LEIAS10, TRM41249.00, and TRM22020.00+GP. Each of these antennas will be observed over fixed points at three distinct heights: two meters above the ground, one meter above the ground, and at ground level. Also, the TRM41249.00 and TRM22020.00+GP antennas will be used at an additional height of two-and-a-half meters above the ground. There are a total of 4 distinct control points used for this experiment, each of which will always have an antenna setup at the same height above it for each day of data collection. Each antenna will then observe data from each point for approximately a 10 hour session over a 2 to 3 day period. Afterwards, the data from each
of the control points will be analyzed to see how the height of a particular point may change as the type of GPS antenna changes. A summary of the data collected for this scenario, including the day of data collection, the control point, the antenna model used, the session start time, stop time, and duration, and the data sampling rate are provided in Table A.2 in Appendix A.

The number of treatments per control point in this experiment will be equal to the number of antenna models used over that control point. Therefore, three of the control points have four treatments and the remaining control point will have two treatments. These treatments will be evaluated using the nonparametric Kruskal-Wallis test described in Section 3.3.3 to determine if there is a significant difference among the treatment effects. A one-way layout multiple comparisons test will be conducted to determine which pairs of treatment effects are different only, if the Kruskal-Wallis test concludes that treatment effects are not all equivalent. Details about the multiple comparisons test and how it is used are described in Section 3.3.3. For these tests, the different treatment effects are the performance of the different antenna models used at each of the control points. The populations used in the nonparametric hypothesis tests for each antenna at each control point consist of 100 hundred heights, where each sample in each population was obtained by averaging the heights over random intervals between 5 minutes and 1 hour.
2.5.4 Experiment 3: GPS Height Variations Caused by High Voltage Power Lines

The objective of this experiment was to analyze the variation in GPS-derived heights caused by proximity to a high voltage power line. This test is of interest because there are some environments where GPS data is collected and proximity to power lines cannot be avoided. An example is commonly seen in precision agriculture applications. Some fields will have power lines running through them that may interfere with GPS applications, such as ensuring that fertilizer is being applied evenly or controlling the cuts made to top soil in precision leveling applications.

Data for this scenario was collected in the open fields of the Hilliard Soccer Complex, Hilliard, Ohio, with three different antenna models set up directly underneath the high voltage power lines running across the fields. The GPS-derived heights for these antennas will all be analyzed with respect to each other using the sample statistics described in Section 3.2 and the level of noise in two of the antenna models used, the NOV600 and TRM59900.00 with SCIS radome, will be compared to the level of noise in the observations from these antennas collected in the open field used in experiments 1 and 2. A summary of the data collected for this experiment, including the date of data collection, antenna types used, type of radome used, session start time, stop time, and stop time, and the data sampling rate are provided in Table A.3 in Appendix A.

2.5.5 Experiment 4: Multipath Reflection from a Snow-Covered Field

This scenario was designed to determine the sidereal repetition of multipath from a snow-covered field and the accuracy of GPS-derived heights in such an environment.
Multipath reflection from snow is a seasonal effect on the near-field multipath of CORS stations. As such, it is of interest to analyze for CORS stations in Ohio and any other location where snow accumulation occurs. This experiment was specifically designed to analyze how a change in the existing snow depth of an environment affects GPS-derived heights.

Data collection for this scenario occurred in an open field at a farm in Orient, Ohio. Two antenna types were used in this experiment on different days with a different snow depth on the ground. A summary of the data collected for this scenario, including the date of data collection, antenna model used, snow depth, session start time, stop time, and duration, and the data sampling rate are available in Table A.4 in Appendix A.

The results of this experiment will be evaluated using the Kruskal-Wallis and one-way layout multiple comparisons hypothesis tests described in Sections 3.2.3 and 3.2.4, respectively, for both antenna types as appropriate. In this experiment, the snow depth will serve as the different treatments per antenna. Each population will contain 100 heights obtained by averaging the heights over randomly generated intervals between 5 minutes and 1 hour.

2.5.6 Experiments 5 and 6: Effects on GPS Heights Caused by a Bird Sitting on a GPS Antenna

These experiments will consider the variations in height deviations caused by a bird sitting on a GPS antenna. This has been observed to happen frequently along the Lake Erie shoreline, where seagulls may sit on an antenna for long periods of time. It is a
bigger concern in these areas, because they are sitting on the CORS antennas, which affects the data that will be used for a variety of other GPS applications. These experiments analyze the effects of a bird sitting on an antenna under two circumstances: the effects of a robin sitting on a CORS antenna (experiment 5) and the effects of a simulated seagull on the heights of three different antenna models (experiment 6).

A summary of the data collected for experiment 5 is available in Table A.5 in Appendix A. The robin was observed on the antenna only during day 3 and the time intervals around the period it was observed were cut out of the solution for processing. This experiment contains two scenarios: the first uses a 1 hour buffer period to either side of the time the robin was observed on the antenna and the second uses a 5 minute buffer period to either side of the time the robin was observed on the antenna.

A summary of the data collected for experiment 6 is available in Table A.6 in Appendix A. Seagulls were simulated in this experiment by placing Cornish hens on the tops of three different antenna models for different durations. Cornish hens were chosen because they have a similar mass to seagulls. In this experiment, measurements from the unobstructed observations will form the control populations for each antenna and measurements from the observations with the simulated seagulls on the antennas will form the treatment populations for each antenna.

Experiment 5 has three treatments: the robin sitting on the COLB antenna during day three and the corresponding times from days one and two when the robin was not observed sitting on the antenna. These treatments will be evaluated using the Kruskal-Wallis and one-way layout multiple comparisons hypothesis tests described in Sections
3.2.3 and 3.2.4, respectively, for both antenna types as appropriate. The full set of observations from each day was taken as the sample populations in both scenarios, since the observation sessions were so short.

Experiment 6 has two treatments per antenna: a control session in which the antenna was unobstructed and a test session in which a Cornish hen was placed on the antenna to simulate a seagull sitting on the antenna. Since the observation times were short, the sample populations will use the full set of observations per antenna for the open and simulated seagull sessions. These populations will be used for two separate hypothesis tests. First, the Wilcoxon rank-sum test will be used to evaluate the height populations with and without the Cornish hen for each antenna. This hypothesis test is testing whether the height distributions for the Cornish hen and unobstructed populations are equivalent in magnitude, but offset to one side of the height distribution of the unobstructed population or if the distributions from the two populations are different. In the first case, the Cornish hen would cause the heights of a given antenna to be strictly greater or less than the heights from the corresponding epochs of the unobstructed population. In the second case, the Cornish hen will only be adding noise to the height level observed in the unobstructed population.

Experiment 6 will use the Kruskal-Wallis and one-way layout multiple comparisons tests as appropriate for all antennas for both populations. It is desired to see if any uniform response in antenna performance is noticed with the simulated seagulls on the antennas. Performing the tests first on the unobstructed populations and then on the simulated seagull populations will determine if the antennas are performing at an
equivalent level and give a benchmark to compare the performance of the simulated seagull population to. Applying the test to the simulated seagull populations will then tell if the antennas are still performing at the same level and allow for their relative performance to be ranked from the antenna with the least amount of noise to the antenna with the greatest amount of noise.

2.6 GPS Processing Software

2.6.1 Introduction

This section will discuss the different GPS processing software used in this research. Specifically, it will include the overall concepts and strategies employed by the software, as well as the minimum required user input. Detailed processing procedures and parameters will not be discussed in this section, as these are oftentimes dependent on the data collected and must be changed at the discretion of the user. However, recommended default parameters, as well as the parameters used to process the data from each observation, will be provided in the appendices. The following GPS processing tools will be discussed in this section: Online Positioning User Service (OPUS) (http://www.ngs.noaa.gov/OPUS/), KinTools [Mader 2013a], and RTKLIB (http://www.rtklib.com/).

2.6.2 Online Position User Service (OPUS)

NGS’s Online Position User Service (OPUS) is a web based application for static data processing that enables access to the high accuracy NSRS coordinates [NGS, 2013].
OPUS was selected as a processing tool and is typically used by surveyors to process static GPS observations. OPUS will compute a single height for static points for the observation period. One of the objectives of the data analysis is to compare the single height obtained from static data processing with the epoch-to-epoch height deviations obtained from processing the same data in kinematic mode to see how much height deviation is occurring in environments with different levels of multipath.

Figure 2.5 shows the form used to upload data to OPUS located at http://www.ngs.noaa.gov/OPUS/. There are five steps involved in submitting a file to OPUS for processing: selecting an observation file, specifying the antenna type used, entering the height to the antenna reference point, specifying an e-mail to return the solution to, and choosing a processing option.
The first step is uploading a GPS observation file. This can either be in a RINEX 2.x format or it can be almost any of the raw data formats used by the different GPS manufacturers. The receiver independent exchange format (RINEX) is a data interchange format for raw satellite observation and navigation data (ftp://ftp.unibe.ch/aiub/rinex/rinex211.txt). Currently, OPUS can only handle files with dual-frequency (L1 and L2) observations. OPUS can only process static observations,
which is when the antenna remains stationary for the observation session. As such, OPUS will return a single latitude, longitude, and height for the entire observation time. Additional requirements are that the observation time be between 15 minutes and 48 hours and that the observation rate must be 1, 2, 3, 5, 10, 15, or 30 seconds.

The antenna type used can be selected from the antenna type dropdown list. This list is kept up-to-date with all available antennas on the market. This information must be provided so that the correct antenna calibration information can be used. This will account for the phase centers changes as the satellites move through the sky and is needed for high accuracy coordinates.

The antenna height is simply the height from the point being surveyed to the antenna reference point (ARP). As described in Section 1.3, the ARP is a point on the antenna, typically on the base plane at the bottom of the threads, where the offsets to the phase center are measured from. The offsets from the ARP to the antenna are given by mean phase center offsets (north-east-up) in the antenna reference frame illustrated in Figure 1.2. When processing, OPUS will use a height entered to reduce the computed GPS height from the ARP to the ground. If a value of zero is entered here, the solution returned will refer to height of the ARP.

The fourth step is to enter an e-mail address for OPUS to send the solution to. With the conclusion of this step, the user will need to select a processing mode: Upload to Rapid-Static, or Upload to Static. A rapid-static solution is for GPS observations between 15 minutes and two hours and a static solution is for GPS observations between two hours and 48 hours.
Static solutions submitted to OPUS are processed using the PAGES software [NGS, 2013]. The program for adjustment of GPS ephemerides (PAGES) is the double difference orbit/baseline estimation software developed and used by NGS (http://www.ngs.noaa.gov/GRD/GPS/DOC/pages/pages.html). The computed coordinates will be the averaged coordinates from three independent, single-baseline solutions, each computed by double-differenced carrier phase measurements from nearby CORS [NGS, 2013]. Nearby IGS stations may also be selected for processing, in addition to the CORS. Static solutions will attempt to use the three nearest CORS/IGS stations, but will expand the search space for additional CORS/IGS stations for each of the single-baseline solutions from PAGES that fails to meet a quality threshold [Mader et al, 2003].

Rapid-static solutions submitted to OPUS are processed using the RSGPS rapid-static software [Martin, 2007]. The RSGPS software applies stricter constraints to resolve carrier phase ambiguities than in the static processing. However, there are also stricter requirements on data continuity and geometry than for static processing, which may limit the ability to perform rapid-static processing in remote areas of the country [NGS, 2013]. The rapid-static algorithm begins by selecting CORS/IGS stations until either six stations have been selected or the distance of a station from the user’s position exceeds 200 km. A solution will then only process, if the user’s station is inside the polygon formed by the selected reference station or no more than 50 km outside of it [Martin, 2007]. RSGPS is then run twice to determine a solution. The first run only uses the selected reference stations in a network mode to resolve the integer ambiguities and
solve for the ionospheric and tropospheric delays. The second run performs the
differential GPS processing treating the position of the user’s station as unknown. This
will incorporate the ionospheric and tropospheric delays solved for in the previous
network solution to estimate the delays at the user’s station. Afterwards, a full network
solution is computed for the user’s station, instead of an average from single-baselines.

2.6.3 Kintools

KinTools is a program developed for kinematic GPS processing and was made
available for data processing by NGS. Kinematic data processing is when the position of
an antenna, called the rover, is moving with respect to a reference station. GPS
observations from a kinematic antenna will not actually be processed with KinTools in
any of the experiments. Instead, GPS observations from static stations will be processed
in kinematic mode to see how the coordinates of a point are changing on an epoch-to-
epoch basis as a result of multipath and other GPS error sources.

The other GPS processing software considered so far can only process GPS
observations in static mode and will only display the single averaged height of the
observation time span. KinTools was chosen as the kinematic GPS processing software
at the advice of NGS [Mader, 2013a]. This software is used in nearly every experiment
to process the observations in kinematic mode.

As with OPUS, data processing is done in a double differencing mode. However,
only a single baseline is considered for processing. KinTools is more flexible than the
other programs discussed so far, in terms of input and uses single or dual-frequency
pseudorange and carrier phase observations. The KinTools software can be used to determine carrier phase ambiguities automatically and allows for some data editing [Mader, 2013b]. KinTools solutions are most accurate over short baselines between the reference station and rover, where the ionospheric corrections for the two GPS observations are similar. Increasing the baseline between the reference station and the rover beyond a few tens of kilometers often results in a decreased rate of successful data processing and the accuracy of solutions deteriorates. However, the rate of successful processing and the accuracy of the resulting solution over long baselines can be greatly improved by incorporating a priori information for the atmospheric corrections at the reference and rover stations [Mader, 2013c].

KinTools requires the user to input a minimum of 4 files: a broadcast navigation file for the timespan the data were collected, an antenna model file from NGS, the RINEX observation file from the reference station, and the RINEX observation file from the rover. A precise ephemeris file may be optionally included as well. All required input files, except for the rover observation file, can be downloaded from the CORS data products on NGS’s webpage at the following address:


The antenna model file contains the phase center variations of all available GPS antennas. KinTools only supports the use of the relative antenna calibration file, which lists the phase center variations, as the elevation angle of the satellite changes with respect to the GPS antenna for both fundamental frequencies. The ANTINFO file,
containing the relative antenna calibrations, is updated regularly by NGS and is available for download from the following link: http://www.ngs.noaa.gov/ANTCAL/.

The precise ephemeris file can be included, if the user desires. An SP3 file (http://www.ngs.noaa.gov/orbits/SP3_format.html) contains precise orbits of the GPS satellites and can improve the results of the solution, if used. If a precise orbit file is included, the RINEX navigation file will not be used.

The last two files to upload are the RINEX observation files for the reference station and the rover. Once these files are selected, KinTools will read in additional information from the observation files and attempt to determine the antenna type used and select the appropriate model from the list of antennas in the ANTINFO file. If the wrong antenna type is selected for either antenna, the correct antenna model will need to be selected from the antenna dropdown list for the reference and rover antennas, respectively. In addition, KinTools will read in the initial monument location and vertical offset of the ARP from the header of the RINEX observation file. By default, the coordinates being read in will be assigned to the WGS84 reference frame. The user should check that the appropriate values were read in for the antenna models and vertical offsets and change them as appropriate. The user should ensure that the true coordinates of the reference station were read in and the correct reference frame was selected or enter them in the fields for the reference station and select the appropriate reference frame. KinTools supports a variety of reference frames, including WGS84, NAD83, IGS, and ITRF. By kinematic processing convention, the same coordinates used for the reference station are entered for the initial position of the rover.
The user will next have to enter session processing parameters, including: the elevation mask, type of observation, GPS frequency, tropospheric model to apply, as well as values for the Δ Ion Delay and the GPS Δ Phase-Range for the L1 and L2 frequencies. The Δ Ion Delay is the change in ionospheric delay or the change in apparent path length for the signal from a satellite as it travels through the ionosphere between consecutive epochs. The Δ Phase-Range parameters are the difference in the distance to a satellite computed using carrier phase and pseudorange observations for both the L1 and L2 frequencies.

Both the Δ Ion Delay and the GPS Δ Phase-Range are used for cycle slip detection. The parameter set for the Δ Ion Delay is compared to the signal from each visible satellite as it travels through the ionosphere. A cycle slip is detected for a particular satellite and cycle slip detection is performed if the change in path length for a particular satellite between consecutive epochs is greater than this parameter. Units for this parameter are given in L1 cycles. The GPS Δ Phase-Range has a parameter for both the L1 and L2 frequencies. If the difference in the carrier phase and pseudocode for a single frequency is greater than the GPS Δ Phase-Range parameter for the same frequency, then a cycle slip is detected and cycle slip correction is performed. The Δ Phase-Range parameters for cycle slip detection have the advantage of identifying which frequency has cycle slips, but is not as sensitive for cycle slip detection as the Δ Ion Delay, due to the additional noise in pseudorange observations.
The input settings are discussed in more detail in Appendix B. The description in this Appendix will also introduce the user to the various windows of the KinTools GUI and briefly describe how to interpret results.

2.6.4 RTKLIB

RTKLIB (http://www.rtklib.com/) is an open source Global Satellite Navigation System (GNSS) processing package for standard and precise positioning with GPS, GLONASS, Galileo, QZSS, BeiDou, and SBAS. RTKLIB provides a variety of positioning modes with GNSS for both real-time and post-processing, including: single point positioning, DGPS, static, kinematic, moving baseline, fixed, precise point positioning (PPP) kinematic and PPP static. Like KinTools, RTKLIB offers the user a lot of flexibility in adjusting processing parameters, including: the positioning mode, elevation mask, frequencies used, ionospheric and tropospheric models, satellite ephemeris type, integer ambiguity resolution strategy, and the format of output coordinates. RTKLIB was used to process some static GPS observations in kinematic mode. This software was chosen to process data for experiment 6, which tested the effects of simulated seagulls on GPS-derived heights, because the data was too noisy to be processed by KinTools. The KinTools software was written to maintain a high accuracy standard on the quality of GPS solutions and if the GPS data is too noisy, the processing will abort instead of continuing and producing a lower quality solution. However, RTKLIB will continue to process the noisy data rejected by KinTools and will deliver a float solution, in which the integer ambiguities of the carrier phase observations
have not been resolved. The default settings configured for the processing are described in Appendix C.
Chapter 3 Statistical Analysis Techniques

3.1 Introduction

This chapter will discuss the statistical analysis techniques that have been used to analyze the data. These techniques can be divided into two groups: parametric or classical statistics and nonparametric statistics. The parametric statistics will be used to analyze every solution and will be used to obtain descriptive statistics about that solution. The nonparametric statistics will be used for hypothesis testing, since these statistical techniques are distribution free and do not assume a normal distribution of data as the parametric statistics do.

3.2 Parametrical Statistics

The data for a given GPS observation will be simultaneously processed in kinematic mode using KinTools and in static mode using OPUS. The OPUS solution will return a single position over the entire observation period, whereas the kinematic (epoch-to-epoch) solution will return a new position at each epoch. Data was collected at two different sampling rates: 1 second epochs and 30 second epochs. The kinematic solution will be plotted with the static OPUS solution in order to show how the height of a GPS observation changes throughout a solution. In this case, the OPUS solution will
serve as a mean value, since it is a single value obtained from the average position of each epoch and since OPUS is the national standard for processing static GPS data.

Once the two solutions are plotted, descriptive information about the epoch-to-epoch height variations must be extracted for comparison with the static OPUS solution, as well as any additional epoch-to-epoch height variations from observations over the same point on additional days. The statistics computed for each of the post-processed kinematic solutions will include: an absolute minimum and maximum, a mean, a standard deviation, and a peak-to-peak change in heights. The absolute minimum and maximum will describe the most extreme observations to either side of the mean of the kinematic solution.

The peak-to-peak statistic will be computed as the range of heights within two standard deviations of the mean value used. The peak-to-peak range is deliberately used in place of the range between the absolute maximum and minimum heights, because it can be reasonably assumed to be free of outliers and a better representation of the distribution of height deviations. A two standard deviation interval encompasses approximately 95.45 percent of the values of a normal distribution. Normally, data in the geomatics field is assumed to be normally distributed, which would also be assumed about the GPS-derived heights. However, it is unknown how the station dependent error sources may affect the distribution of the heights. It is also known by the central limit theorem that large samples of independent observations can be approximated by a normal distribution and that this approximation increases in accuracy as the sample size increases. Since the sample statistics were generated using the entire set of observations
per antenna, it is reasonable to assume that each data collection session consists of more than a sufficient number of observations for the distribution of the heights to be considered normally distributed under the central limit theorem, even though it is unknown exactly how much the heights may be altered by the less than ideal environments being tested. As such, the 95.45 percent of the heights considered in the peak-to-peak statistic will be those heights closest to the mean and any outliers will be discarded. The peak-to-peak error will therefore give an underestimation of the range of heights from the mean. However, it will not be influenced by any major outliers, as the range of heights between the absolute minimum and maximum may be.

The final column of this table is the OPUS height. This is the height that was computed by submitting a GPS observation to OPUS for processing. This height has been included to demonstrate the deviations in the epoch-to-epoch heights, compared to a single static height, and to help illustrate that station dependent error sources are not necessarily static and may change over the observation period.

3.3 Nonparametric Statistical Techniques

Nonparametric statistical procedures offer a stronger and more flexible analysis than their corresponding parametrical procedures, because they do not include as many assumptions about the underlying distribution. The assumption of normality is a particularly costly assumption to make about a distribution that is avoided with the nonparametric procedures used here. Nonparametric statistical procedures can be thought of as a more generalized version of the corresponding parametric or normal
theory procedures. If a distribution would prove to be normal, both procedures should agree on the outcome of a test. However, the normal theory procedures will be more efficient on data that is normally distributed. Also, we will be able to conclude a result to a specified accuracy with fewer samples than the corresponding nonparametric procedure would require [Critchlow, 2013].

While data in geomatics is usually assumed to be normally distributed, this assumption was not made for the GPS-derived heights in these experiments, because it is not known how the sources of noise and multipath in other experiments may affect the distribution of heights. In addition, the populations used in all of the hypothesis tests are only subsets of the full observation sessions, which may not guarantee a reasonable approximation of a normal distribution through the central limit theorem. Finally, the heights in the sample populations were extracted from randomly chosen intervals from the full observations, which may result in a higher number of outlier heights being selected for certain populations.

There are four types of nonparametric procedures used in the analysis of the results in this research: the sign test, the Wilcoxon rank-sum test, the Kruskal-Wallis test, and the one way layout multiple comparisons [Hollander and Wolfe, 1999]. Each of these procedures will be discussed in more detail below, including why each of these procedures was chosen.
3.3.1 The Nonparametric Sign Test

The nonparametric sign test is a statistical analysis procedure concerned with the location of the median of the population. The sign test utilizes paired replicates data to determine if a particular treatment results in a significant shift in the median of the population. Paired replicate observations are those for which the population has been observed under two different treatments. The first observation is the pre-treatment, or control case, and the second observation is the post-treatment, which is the treatment being tested for a difference against the control population. The sign test is, therefore, concerned with measuring the treatment effect between the pre-treatment and post-treatment.

This test was chosen to evaluate the radome effects in experiment 1 (Section 4.1). In this experiment, the treatment will jointly consist of the use of an SCIS radome and the choice of the PCVs for the antenna. With the assumptions made in Section 2.5.2, the data can be reasonably regarded as pair replicates data and an answer can be obtained to the effects of treatment on resulting GPS heights for each of the three tests posed in that section.

Let the pre-treatment and post-treatment be denoted by $X_i$ and $Y_i$, respectively. The difference in treatment effects for a given pair of observations is then given by

$$Z_i = Y_i - X_i \quad for \quad i = 1 \ldots n$$  \hspace{1cm} (3.1)

where:

$Z_i$ is the difference in treatment effects for the $i^{th}$ observation.

$Y_i$ is the post-treatment effect for the $i^{th}$ observation.
$X_i$ is the $i$th pre-treatment effect for the $i^{th}$ observation

$i$ is the number of samples in the population.

It is assumed that each of the $Z_i$'s are mutually independent of each other and that each of the $Z_i$'s comes from a continuous probability distribution. The $Z_i$'s do not necessarily all come from the same probability distribution; however, all of the distributions have a common median, $\theta$, which is referred to as the unknown treatment effect.

The sign statistic, $B$, for a population of size $n$ is computed as follows:

$$B = \sum_{i=1}^{n} \psi_i$$

(3.2)

where $\psi_i$ is computed as follows:

$$\psi_i = \begin{cases} 1, & \text{if } Z_i > 0 \\ 0, & \text{if } Z_i < 0 \end{cases}$$

(3.3)

From equations 3.3 and 3.2, it is seen that two similar treatments will have a sample statistic close to $n/2$, indicating that there is a small treatment effect between the two treatments. Similarly, if the post-treatment is significantly greater than the pre-treatment, than the sign statistic will be greater than $n/2$ and the sample statistic will be less than $n/2$, if the pre-treatment is significantly different than the post-treatment. It is seen that if the two treatments have the same effect ($Z_i=0$) that $\psi_i$ is not assigned a value. This is because by convention, ties between the treatments are discarded from the population and $n$ is reduced by the number of ties. Thus, a two-tailed hypothesis test for any significant change caused by the treatments can be constructed as follows:

$$H_0: \theta = 0 \ vs. \ H_1: \theta \neq 0$$

(3.4)

where:
$H_0$ is the null hypothesis of no change in median due to the treatment effect

$H_1$ is the alternative hypothesis of a change in median due to the treatment effect

$\theta$ is the unknown treatment effect.

This two-tailed procedure is a symmetric test with $\alpha/2$ of the probability in each tail of the null distribution of $B$. The null hypothesis, $H_0$, will be rejected if:

$$B \geq b_{\alpha/2,1/2} \text{ or } B \leq n - b_{\alpha/2,1/2} \quad (3.5)$$

where:

- $B$ is the sign test sample statistic computed in equation 3.2
- $n$ is the size of the population
- $b_{\alpha/2,1/2}$ is the upper-tail probability for the binomial distribution with a probability $p=0.5$ and an error rate of $\alpha/2$. Here, $\alpha$ refers to the likelihood of committing a type 1 error, that is, the chance of concluding the alternative hypothesis when the null hypothesis is true.

The exact procedure listed above is only valid for small sample sizes. Hypothesis testing with larger populations can be done with the large sample approximation with reasonable accuracy. The large sample approximation of the sign test uses the standard normal distribution. The sign statistic is converted to a standard normal statistic by:

$$B^* = \frac{B - E_0(B)}{\sqrt{\text{var}_0(B)}} = \frac{B - \frac{n}{2}}{\frac{n}{\sqrt{4}}} \quad (3.6)$$

where:

- $n$ is the size of the population
- $B$ is the sign statistic
- $E_0(B)$ is the expected value of $B$, given by $n/2$
\[ \text{var}_0(B) \text{ is the variance of } B, \text{ given by } n/4. \]

A two-tailed hypothesis test for the large sample approximation is then evaluated as follows:

\[ \text{Reject } H_0 \text{ if } |B^*| \geq z_{\alpha/2}; \text{ otherwise do not reject} \quad (3.7) \]

3.3.2 The Wilcoxon Rank-Sum Test

The Wilcoxon rank-sum test is a nonparametric hypothesis test for a change in the distribution of a population caused by a particular treatment. This test considers two random populations: a control population and a treatment population. It is assumed that the data from each population are independent and identically distributed, that the two populations are mutually independent, and that the two populations are continuous [Critchlow, 2013].

This test was chosen to evaluate the results of the simulated seagulls sitting on the antennas in experiment 6 (Section 4.6). This test will be carried out on each antenna, using a control population constructed from random intervals selected from the open/unobstructed session(s) and a treatment population constructed from the random intervals selected from the Cornish hen/simulated seagull session(s). This test will be used to determine if the additional noise from the Cornish hen results in a distribution of heights for both treatments up to an arbitrary scalar shift or if it only amplifies the amount of noise seen in the height distribution of the open session.

The first step in computing the Wilcoxon sample statistic is to compute the joint ranking of the magnitudes of the samples in both populations. All samples tying in
magnitude will be determined through the method of average ranks, in which the sequential ranks that would have been assigned to the values in the absence of ties are averaged and assigned to each of the tied values. The Wilcoxon sample statistic is then computed by summing the value of the ranks in the treatment population. Thus, the sample statistic is given by the following equation:

\[ W = \sum_{j=1}^{n} S_j \]  

(3.8)

where:

- \( W \) is the Wilcoxon sample statistic
- \( n \) is the number of samples in the treatment population
- \( S_j \) is the joint ranking of the \( j^{th} \) element in the treatment population.

A two sided hypothesis test of no change caused by the treatment against a change caused by the treatment is then constructed as:

\[ H_0: \Delta = 0 \text{ vs. } H_1: \Delta \neq 0 \]  

(3.9)

where:

- \( H_0 \) is the null hypothesis that the treatments have identical height distributions up to an scalar shift
- \( H_1 \) is the alternative hypothesis that the treatments do not have identical height distributions up to a scalar shift
- \( \Delta \) is the shift in the treatment population from the control population.

The decision to accept or reject the null hypothesis is as follows:

\textit{Reject } \( H_0 \) \textit{ if } W \geq w_{a/2} \textit{ or } W \leq n(m + n + 1) - w_{a/2}  

(3.10)

where:
m is the number of samples in the control population

\( w_{a/2} \) is the upper-tail probability of the null distribution for the Wilcoxon statistic.

The large sample approximation procedure is computed as follows:

\[
W^* = \frac{W - \frac{n(m+n+1)}{2}}{\sqrt{\frac{m(n(m+n+1))}{12}\frac{n(m+n+1)}{12}}}
\]  
(3.11)

The decision to accept or reject the null hypothesis is then as follows:

\[
\text{Reject } H_0 \text{ if } W^* \geq \left| z_{a/2} \right|
\]
(3.12)

where:

\( z_{a/2} \) is half the probability of the upper \( a \) tail of the standard normal distribution.

The large sample approximation procedure must also have a correction applied to it for the case of tied ranks. In the ties correction, the denominator of equation 3.12 is replaced with:

\[
\sqrt{\frac{mn}{12}\left[ m + n + 1 - \frac{\sum_{j=1}^{g} t_j(t_j-1)(t_j+1)}{(m+n)(m+n-1)} \right]}
\]
(3.13)

where:

m is the sample size of the control population

n is the sample size of the treatment population

\( g \) is the number of distinctly observed ranks

\( t_j \) is the number of samples tied for the \( j^{th} \) distinct rank.
3.3.3 The Kruskal-Wallis Test for General Alternatives

The Kruskal-Wallis test for general alternatives is a nonparametric statistical test that considers \( n_i \) independent samples from \( k \) different populations. The test assumes that there are \( N = \sum_{i=1}^{k} n_i \) observations total, that each sample comes from a continuous distribution, and that the populations all have the same shape, but may differ with respect to their location [Critchlow, 2013]. This procedure tests for no difference among the different treatment effects against the general alternative that at least one of the treatment effects is not equal to the others. The null and alternative hypotheses are therefore formed as follows:

\[
H_0: \tau_1 = \tau_2 = \cdots = \tau_n \ vs. \ H_1: \tau_1 \ldots \tau_k \ are \ not \ all \ equal
\]  

(3.14)

where:

- \( H_0 \) is the null hypothesis that all of the treatment effects are equal
- \( H_1 \) is the alternative hypothesis that at least one of the treatment effects is not equal to the others
- \( \tau_i \ for \ i = 1 \ldots n \) are the different treatments.

This test was chosen, since many of the experiments have multiple treatments that will be evaluated. The treatments in these experiments have no control population to compare to so this test is being used to make a relative assessment about the performance of all of the treatments. This test is being done as a precursor to the one-way layout multiple comparisons test. If the Kruskal-Wallis test concludes the null hypothesis that there is no significant difference among the different treatments, then all treatments are performing at the same level and there is no need to perform a multiple comparisons test.
to determine which pairs of treatments differ significantly. Otherwise, the Kruskal-Wallis test concludes that there is a difference among the treatments and that a multiple comparisons test must be performed to determine which treatments are performing at a different level.

The Kruskal-Wallis procedure first requires that the N observations from the k samples be jointly ranked based on the magnitudes of the values. Once this is done, the sample statistic, H, can be computed as follows:

\[
H = \frac{12}{N(N+1)} \sum_{j=1}^{k} \frac{R_j^2}{n_j} - 3(N + 1)
\]

(3.15)

where:

N is the total number of observations from all populations
k is the total number of populations
\(R_j^2\) is the square of the sum of all the joint ranks for a given population
\(n_j\) is the size of the \(j^{th}\) population.

In the case of ties in rank, the rank of the tying elements is determined through the method of average ranks. Each tying element will receive a rank computed from the average of the sequential ranks that would have been assigned in the absence of ties. A ties correction is then computed as follows:

\[
H' = \frac{H}{1 - \left( \sum_{j=1}^{q} \frac{t_j^3 - t_j}{(N^3 - N)} \right)}
\]

(3.16)

where:

H is computed according to equation 3.15
N is the total number of observations from all populations
\( t_j \) is the size of the \( j^{th} \) tied group

g is the number of occurrences of tied ranks.

Notice that equation 3.16 can be used in place of equation 3.15 even if there are no ties. If there are no ties, the denominator reduces to one and \( H' \) is equal to \( H \).

The decision rule regarding the null and alternative hypotheses is:

\[
\text{Reject } H_0 \text{ if } H \geq h_\alpha \quad (3.17)
\]

where:

\( h_\alpha \) is the upper-tail probability at an error level \( \alpha \) from the null distribution of the Kruskal-Wallis H statistic. Here, \( \alpha \) is the probability of committing a type 1 error.

The large sample approximation for the Kruskal-Wallis H statistic is then given by a chi-square distribution with \( k-1 \) degrees of freedom. \( H \) or \( H' \) is first computed according to equation 3.15 or 3.16. A criteria for the null hypothesis is then:

\[
\text{Reject } H_0 \text{ if } H \geq \chi^2_{k-1, \alpha}; \text{otherwise do not reject} \quad (3.18)
\]

where:

\( \chi^2_{k-1, \alpha} \) is the upper \( \alpha \) percentile of a chi-square distribution with \( k-1 \) degrees of freedom.

3.3.4 One-Way Layout Multiple Comparisons

Recall that the Kruskal-Wallis test described in the previous section compares samples from multiple populations to determine if the different treatments effects are equivalent or if at least one of the treatments differs significantly form the others. This test is limited in that it only describes the relationships between all treatments, but does not provide any information about how the various treatments compare to each other.
Such comparisons will be accomplished through the one-way layout multiple comparisons (MC) procedure. This procedure will compare each of the \( \binom{k}{2} \) pairs of treatments, where \( k \) is the total number of treatments, and determine which pairs of treatments are different. This procedure was chosen as a way of evaluating the experiments with multiple treatment effects where there is no control data to compare the treatments to and the treatments will be ranked relative to each other.

The first step of the MC procedure is to compute the pairwise ranks of each pair of treatments, \( i \) and \( j \). By convention, we will take \( R_{i1}…R_{in} \) to be the ranks of the elements in treatment \( i \) and \( R_{j1}…R_{jn} \) to be the ranks of the elements in treatment \( j \). The Wilcoxon rank sum statistic is then computed by summing the ranks of the \( j \)th sample as:

\[
W_{ij} = \sum_{k=1}^{n} R_{j,k}
\]

where:

- \( W_{ij} \) is the Wilcoxon rank sum statistic of treatments \( i \) and \( j \)
- \( n \) is the total number of samples in the \( j \)th treatment
- \( R_{j,k} \) is the pairwise rank of the \( k \)th element in the \( j \)th treatment.

The sample statistic of interest is then computed as follows:

\[
W_{ij}^* = \frac{W_{ij} - \frac{n_j(n_i+n_j+1)}{2}}{\sqrt{\frac{n_i n_j (n_i+n_j+1)}{2^4}}}
\]

where:

- \( W_{ij} \) is the Wilcoxon rank-sum statistic for the ranks of \( j \) between treatments \( i \) and \( j \)

computed in equation 3.9
\( n_i \) is the number of samples in the \( i^{th} \) treatment

\( n_j \) is the number of samples in the \( j^{th} \) treatment.

Ties in the pairwise rankings will be dealt with by the method of average ranks.

No additional ties correction will be applied to the computed sample statistic [Critchlow, 2013].

The hypotheses used for this test will therefore be:

\[
H_0: \tau_i = \tau_j \; \text{vs.} \; H_1: \tau_i \neq \tau_j
\]  

(3.21)

where:

- \( H_0 \) is the null hypothesis that a given pair of treatments are equivalent
- \( H_1 \) is the alternative hypothesis that a given pair of treatments are not equivalent
- \( \tau_i \) for \( i = 1 \ldots n \) are the different treatments.

The decision rule regarding the null and alternative hypotheses is:

\[
\text{Conclude } \tau_i \neq \tau_j \text{ if } |W_{ij}^*| \geq w_{\alpha}^*
\]  

(3.22)

where:

- \( w_{\alpha}^* \) is the upper-tail probability of an experiment wise error rate (EER), \( \alpha \), of the Steel-Dwass-Critchlow distribution

The EER, \( \alpha \), is defined as follows:

\[
P_0(|W_{ij}^*| < w_{\alpha,u,v}^*) \; \text{for} \; i = 1, \ldots, k - 1; \; j = i + 1, \ldots, k
\]  

(3.23)

The \( \alpha \) for the EER has a slightly different interpretation than the \( \alpha \) used in other tests. This does not refer to the probability of committing a type 1 error for a single pair of treatments, but rather, the probability of committing a type 1 error for a single pair of
treatments for all the \( \binom{k}{2} \) pairs of treatments. Therefore, \( \alpha \) refers to the change of reaching a false conclusion for at least one of the pairs of treatment effects.

It is also possible to rank the relative performance of the antennas by the sample statistics computed for the MC test. With the way the sample statistic for each pair was computed, a positive sample statistic means that the treatment effects of the first treatment were smaller than the second treatment and a negative sample statistic means that the treatment effects of the second treatment were smaller than the first treatment. In terms of the GPS data, a positive sample statistic means that the first antenna of the pair being tested in the antennas column of the table showed less height variation than the second antenna listed in the pair and the opposite is true for a negative samples statistic. The relative antenna ranking is then determined by evaluating how each antenna performs with respect to the others.

3.3 Application of the Statistical Analysis Techniques

The statistical analysis techniques described in this chapter will be used to analyze the GPS-derived heights from the experiments presented in the next chapter. All of the GPS observations were collected in static mode, in which the antenna remains stationary. However, the data was post-processed in kinematic mode for analysis. This will allow for an analysis of how the GPS-derived height of a point is changing at each epoch of observation during the observation session.

The parametric sample statistics described in Section 3.2 will be applied to the kinematic solutions to characterize how the GPS-derived heights are changing on an
antenna-by-antenna basis. These sample statistics will also facilitate a basic comparison of the different antenna models tested in each experiment.

The nonparametric statistical analysis techniques will be used to further analyze the height deviations of the GPS antennas in the experiments described in Section 2.5. These hypothesis tests will be used to test for a significant difference in performance of the treatments under the different test conditions in each experiment. Each experiment will utilize different hypothesis tests, depending on the treatments being tested and on whether or not there is a reasonable control population to compare to.
Chapter 4 Experiments and Results

4.1 Experiment 1: Effects of not Accounting for Radome Antenna Calibration Parameters on GPS Heights

Data collection for this experiment occurred at ODOT's Office of CADD and Mapping Services shown in Figure 4.1. This facility was chosen for this experiment for use of the COLB test pole (red rectangle in Figure 4.1), which is a pole at the same height as the nearby COLB CORS station (blue rectangle in Figure 4.1). This facility also presents an open area with minimal multipath interference and the receiver was able to record data continuously. In addition, the antenna was able to be mounted in a stable location so that the antenna phase center is consistently at the same height. The data was processed in KinTools using the processing parameters given in Table D.1 in Appendix D. The COLB CORS station was used as the reference station and the test pole was used as the rover station in all of the data processing.
As described in Section 2.5.2, the orbits of GPS satellites follow a sidereal day, which is approximately four minutes shorter than a solar day. This results in the same constellation of satellites being seen 4 minutes earlier from day-to-day. An analysis of the data required that all observations referred to the same sidereal day, so that the same satellites would be visible at the same time for each day of observations. The convention used in this analysis was to adjust the satellite visibility of each three-day observation period to align with the first day of those three days.

A numerical summary of the epoch-to-epoch height deviations with the parametric sample statistics listed above is included in Table 4.1. The table has been formatted so that it lists the different antenna and radome and calibration parameter
pairings discussed in Section 2.5.2 by scenario number and lists the dates of data
collection for each observation as well as the radome and calibration parameters used.
The table then proceeds to list the sample statistics computed for each day of each
scenario.

Table 4.1: Listing of the parametric sample statistics for GPS heights per scenario for each combination of
the TRM5900.00 antenna and SCIS radome as well as relative antenna calibration parameters used in data
processing. The first four columns provide the scenario number, days the observation were from, the type
of radome used (SCIS of no radome), and the relative calibration parameters used (only for the antenna or
for the antenna and the radome). The remaining columns are the sample statistics discussed in Section 3.2.
All sample statistics are in meters.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Date</th>
<th>Radome Used</th>
<th>Antenna Calibration Parameters Used</th>
<th>Abs Min (m)</th>
<th>Abs Max (m)</th>
<th>Mean (m)</th>
<th>Std Dev (m)</th>
<th>Peak-2-Peak (m)</th>
<th>OPUS Height (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5/3/2013</td>
<td>SCIS</td>
<td>Antenna + Radome</td>
<td>185.123</td>
<td>185.295</td>
<td>185.217</td>
<td>0.013</td>
<td>0.050</td>
<td>185.216</td>
</tr>
<tr>
<td></td>
<td>5/4/2013</td>
<td>SCIS</td>
<td>Antenna + Radome</td>
<td>185.131</td>
<td>185.307</td>
<td>185.217</td>
<td>0.012</td>
<td>0.050</td>
<td>185.219</td>
</tr>
<tr>
<td></td>
<td>5/5/2013</td>
<td>SCIS</td>
<td>Antenna + Radome</td>
<td>185.127</td>
<td>185.309</td>
<td>185.216</td>
<td>0.012</td>
<td>0.047</td>
<td>185.215</td>
</tr>
<tr>
<td>2</td>
<td>5/6/2013</td>
<td>NONE</td>
<td>Antenna + Radome</td>
<td>185.153</td>
<td>185.310</td>
<td>185.216</td>
<td>0.011</td>
<td>0.045</td>
<td>185.218</td>
</tr>
<tr>
<td></td>
<td>5/7/2013</td>
<td>NONE</td>
<td>Antenna + Radome</td>
<td>185.112</td>
<td>185.283</td>
<td>185.218</td>
<td>0.012</td>
<td>0.049</td>
<td>185.223</td>
</tr>
<tr>
<td></td>
<td>5/12/2013</td>
<td>NONE</td>
<td>Antenna + Radome</td>
<td>185.121</td>
<td>185.289</td>
<td>185.222</td>
<td>0.013</td>
<td>0.053</td>
<td>185.227</td>
</tr>
<tr>
<td>3</td>
<td>5/6/2013</td>
<td>NONE</td>
<td>Antenna Only</td>
<td>185.151</td>
<td>185.306</td>
<td>185.210</td>
<td>0.011</td>
<td>0.045</td>
<td>185.218</td>
</tr>
<tr>
<td></td>
<td>5/7/2013</td>
<td>NONE</td>
<td>Antenna Only</td>
<td>185.110</td>
<td>185.277</td>
<td>185.212</td>
<td>0.012</td>
<td>0.049</td>
<td>185.223</td>
</tr>
<tr>
<td></td>
<td>5/12/2013</td>
<td>NONE</td>
<td>Antenna Only</td>
<td>185.119</td>
<td>185.283</td>
<td>185.217</td>
<td>0.013</td>
<td>0.052</td>
<td>185.227</td>
</tr>
</tbody>
</table>

The statistics in Table 4.1 show that there is not a lot of variation between the
different scenarios tested or even within the individual scenarios. The most significant
variation is seen in the absolute minimum and maximum heights, which correspond to the
most extreme outliers in a solution. The mean heights for each day in the first scenario
are the least significant, deviating by 1 mm. The other scenarios have a more noticeable
deviation, cumulating with a maximum of a 4 mm deviation in scenario 3. The standard
deviations between all observations seem to be consistently in the order of a few
millimeters, which results in a very similar two sigma range of around 5 cm, as indicated by the peak-to-peak statistic.

Three separate hypothesis tests were conducted based on the data collected in each scenario to test for a significant difference in GPS heights observed for different combinations of the radome and antenna calibration parameters. The nonparametric sign test was used to test all of these hypotheses. The nonparametric sign test described in Section 3.3.1 tests for a significant treatment effect in a population before and after a treatment has been applied to it. In this case, the treatment effect will be the antenna calibration parameters applied to data processing. The null hypothesis for this test is that the treatment effect is equal to 0 and the alternative hypothesis is that there is a treatment effect. For the data being analyzed, a treatment effect will be a change in the GPS-derived heights of the antenna on the test pole.

Hypothesis tests 1, 2, and 3 listed in Section 2.5.2 were conducted and their results are tabulated in Tables 4.2, 4.3, and 4.4, respectively. An explanation of how to read the data contained in these tables can be found in Appendix E in the discussion of the sign test hypothesis test results.

Table 4.2: Results of the nonparametric sign test for the hypothesis of no significant change in the population median versus the null hypothesis of a significant change in the population median for a GPS antenna with a radome processed with the radome phase center variation parameters and the same antenna without a radome processed with the radome phase center variation parameters.

<table>
<thead>
<tr>
<th>Height Resolution</th>
<th>Samples</th>
<th>Sample Statistic</th>
<th>Error Rates and Thresholds</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>5%</td>
<td>10%</td>
</tr>
<tr>
<td>mm level</td>
<td>276</td>
<td>4.454</td>
<td>-1.96</td>
<td>1.96</td>
</tr>
<tr>
<td>cm level</td>
<td>131</td>
<td>5.330</td>
<td>-1.96</td>
<td>1.96</td>
</tr>
</tbody>
</table>
Table 4.3: Results of the nonparametric sign test for the hypothesis of no significant change in the population median versus the null hypothesis of a significant change in the population median for a GPS antenna without a radome processed with the radome phase center variation parameters and the same antenna without a radome processed without the radome phase center variation parameters.

<table>
<thead>
<tr>
<th>Height Resolution</th>
<th>Samples</th>
<th>Sample Statistic</th>
<th>Error Rates and Thresholds</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>mm level</td>
<td>291</td>
<td>12.721</td>
<td>-1.96 1.96 -1.645 1.645 -1.28 1.28 &lt;0.0002</td>
<td></td>
</tr>
<tr>
<td>cm level</td>
<td>196</td>
<td>12.286</td>
<td>-1.96 1.96 -1.645 1.645 -1.28 1.28 &lt;0.0002</td>
<td></td>
</tr>
</tbody>
</table>

The hypothesis test conducted in Table 4.2 used the TRM59900.00 antenna with the SCIS radome processed with the SCIS radome calibration parameters as the pre-treatment and the TRM59900.00 antenna without the SCIS radome processed with the SCIS radome calibration parameters as the post-treatment. In this case, the pre-treatment will also serve as a control, as the PCVs for the phase center and radome are properly accounted for, which will result in the most accurate positions.

The hypothesis test conducted in Table 4.3 used the TRM59900.00 antenna without the SCIS radome processed without the SCIS radome calibration parameters as the pre-treatment and the TRM59900.00 antenna without the SCIS radome processed with the SCIS radome calibration parameters as the post-treatment. In this case, the pre-
treatment will also serve as a control, as the PCVs for the phase center and radome are properly accounted for, which will result in the most accurate positions.

The hypothesis test conducted in Table 4.4 used the TRM59900.00 antenna with the SCIS radome processed with the SCIS radome calibration parameters as the pre-treatment and the TRM59900.00 antenna without the SCIS radome processed without the SCIS radome calibration parameters as the post-treatment. This hypothesis test uses both of the control cases used in the other two hypothesis tests and is intended to check for consistency in GPS-derived heights when the correct set of antenna calibration parameters is applied with and without a radome.

The results for each of the hypothesis tests in Tables 4.2, 4.3, and 4.4 reject the null hypothesis of no change in the median caused by the treatment effects in favor of the alternative hypothesis that there is a change in the median seen as a result of the treatment effects. The tabulated P-values confirm the conclusion, as there is a 2% chance of the one with the greatest probability to be true under the null hypothesis and less than a 0.2% of the null hypothesis being true in the other tests. This is extremely weak evidence in support of the null hypothesis occurring and supports acceptance of the alternative hypothesis. This was expected for the hypothesis tests in Tables 4.2 and 4.3, which were between scenarios 1 and 2 and scenarios 3 and 2, respectively. Both of these hypothesis tests used scenario 2, which was being processed with the antenna calibration parameters for an SCIS radome and it did not have a radome equipped. This results in an incorrect set of antenna PCV corrections being applied and has the potential to impact heights up to several centimeters [Mader, 1999].
What was unexpected about these results is that the hypothesis test in Table 4.4 constantly rejected the null hypothesis of no significant change in the median caused by the different treatment effects. It was expected that these results should yield a very similar solution to each other, since the antenna is in an open environment with minimal obstructions and processed with the correct antenna calibration parameters with and without the radome. The SCIS radome does not cause much of a delay on the incoming signal, as the relative antenna calibration parameters between the TRM59900.00 antenna with and without a radome deviate by up to 2 mm max for a signal from a given elevation angle and most differences are less than or equal to 1 mm. These differences were obtained by comparing the published relative calibration parameters for the TRM59900.00 antenna with and without the SCIS radome in NGS' ANTINFO file. The published calibration parameters for the antenna with and without the radome were obtained by averaging the calibration results of several TRM59900.00 antennas calibrated with and without the SCIS radomes.

The results of the hypothesis tests in Tables 4.2 to 4.4 also show that the number of samples used decreases and the probability of the null hypothesis appear to decrease as the height resolution decreases. Recall from Section 3.3.1 that ties between the corresponding elements of each population are excluded from the computation of the sample statistic. As the samples are rounded to the centimeter level, more pairs of the samples have the same value and are excluded from the computation of the sample statistic. These were heights that were originally close enough together, so that their difference would be close to zero. Thus, these values would have helped to balance the
distribution. Now, there are fewer samples to balance the population pairs that are further apart, and the population begins to become skewed towards the extreme heights, such that the sample statistic is no longer close to $\frac{n}{2}$ (half of the number of samples in the two populations).

The results of the hypothesis tests were further quantified with the height deviations shown in the sidereal plots included in Figures F.1, F.2, and F.3 in Appendix F for scenarios 1, 2, and 3, respectively. The plots of the height deviations for all three days in scenario 1 (F.1) appear very similar to each other. Two distinct height variation patterns were observed between the plots of the heights from the different days in scenarios 2 (F.2) and 3 (F.3). The first of these is between the second and third days of each of these scenarios. The pattern of the plotted height deviations here closely resembles the pattern seen in all three days of the data plotted for scenario 1. The other distinct pattern of height deviations is between day 1 of scenarios 2 and 3, which has a similar pattern of height deviations to the other days, but does contain some noticeable differences. Two of the more noticeable differences occur between the $8^{th}$ and $9^{th}$ hours as well as between the $18^{th}$ and $19^{th}$ hours.

The populations for the hypothesis testing from each scenario were created by taking the average of the heights obtained from each day so that the first 100 heights are from day one, the second 100 heights are from day 2, and the third 100 heights are from day 3. The samples from the first day of the second and third scenarios will therefore have a greater difference with the samples from day one of the first scenarios. The result
is that 100 of the 300 tested samples may test to be different in one direction, which
would be enough to conclude a significant difference.

This possibility was tested by excluding the samples from day 1 of all three
scenarios and re-computing the hypothesis test using only the 200 paired samples from
days 2 and 3. The results of these hypothesis tests resulted in less extreme sample
statistics being computed in the tests between scenarios 3 and 2 and scenarios 1 and 3,
while the results between scenarios 1 and 2 did not show signs of improvement. With all
samples from the first day removed, the hypothesis test in between scenarios 1 and 3
tested to be significant at an error rate of 5%, and has a P-value 3.2%. This is weak
evidence in support of the null hypothesis, but it does confirm that the unexpected
rejection of the null hypothesis for the test between scenarios 1 and 3 was caused by the
different patterns of height deviations seen in day 1 of scenarios 2 and 3.

With the exclusion of the paired samples from day 1, the hypothesis tests all begin
to conform to their expected results: that using the incorrect antenna calibration PCV
corrections will result in a height that is significantly different from the height obtained
when the antenna calibration parameters are accurately accounted for and antennas using
the correct PCV corrections should result in heights that are similar to each other.

The goal of this experiment was to quantify the height deviations caused by not
accounting for the proper phase center variations. The last hypothesis test was conducted
between the scenarios with and without a SCIS radome and using the correct antenna
PCVs to see how the heights of each solution, which should result in equivalent heights,
deviate from each other. The other hypothesis tests were conducted to see at what level
error caused by using the wrong set of PCVs begin to test to be significantly different and to see if computed heights would be closer to the height computed with the radome correctly accounted for or closer to the height without the radome correctly accounted for. The results in Table 4.1 show that solutions that are close together deviate in height by an amount that is less than or equal to 2 mm, whereas solutions that are significantly different differ in heights by at least 4 mm.

While high accuracy heights should account for the radome PCVs, the results of the experiment indicate that the error for not accounting for them in an open environment is insignificant for consistently obtaining GPS heights at a 2 to 5 cm level with which the Height Modernization program is concerned. However, these height deviations are for the TRM59900.00 antenna and SCIS radome pairing and a more general statement about the significance of neglecting the proper radome PCVs cannot be made from the data collected in this experiment. The observed range of variations is one of the reasons why the hypothesis test between scenarios 1 and 3 had such a small P-value. The magnitude of the deviation in the means of days 2 and 3 from scenario 1 is 1 mm, whereas the magnitude of the deviation in the means of days 2 and 3 from scenario 3 is around 4 mm. The P-value in support of the null hypothesis of no significant difference between scenarios 1 and 3 would have been greater, if the height deviation between days 2 and 3 of scenarios 3 were smaller.
4.2. Experiment 2: Antenna Specific Variations in GPS Heights

The data for this experiment was collected in the field at ODOT’s Office of CADD and Mapping Services, depicted with the control points at all height levels in Figure 4.2 below. The TSG, TSL, TSH, and TST control points are shown in Figure 4.2 by the cyan, yellow, fuchsia, and green icons, respectively. The blue icon is the location of the COLB CORS station. Table 4.5 lists the height of the antenna above the ground at each control point, the number of antenna models tested at each control point, and each type of antenna tested at each control point.

Figure 4.2: Antenna setup locations at the ODOT Office of CADD and Mapping Services facility, Columbus, Ohio. The location of the TSG, TSL, TSH, and TST/Test Pole control points are shown by the cyan, yellow, fuchsia, and green icons respectively. The blue icon is the location of the COLB CORS station.
Table 4.5: Summary of the data collected per control point to test the variation in GPS-derived heights caused by changing the antenna model used at a control point.

<table>
<thead>
<tr>
<th>Control Point</th>
<th>Height Above Ground</th>
<th># of Antenna Models Used</th>
<th>Antenna Types</th>
</tr>
</thead>
<tbody>
<tr>
<td>TSG</td>
<td>0.0 m</td>
<td>4</td>
<td>TRM41249 TRM22020+GP NOV600 LEIAS10</td>
</tr>
<tr>
<td>TSL</td>
<td>1.0 m</td>
<td>4</td>
<td>TRM41249 TRM22020+GP NOV600 LEIAS10</td>
</tr>
<tr>
<td>TSH</td>
<td>2.0 m</td>
<td>4</td>
<td>TRM41249 TRM22020+GP NOV600 LEIAS10</td>
</tr>
<tr>
<td>TST</td>
<td>2.5 m</td>
<td>2</td>
<td>TRM41249 TRM22020+GP</td>
</tr>
</tbody>
</table>

After each antenna collected data over each point, the results were processed in KinTools using the processing parameters provided in Table D.2 in Appendix D using COLB as the base station. The individual kinematic solutions were then analyzed to find the optimum solution, the one with the smallest amount of height variation, per point for each of the antennas being tested. These optimum solutions were then used to analyze the height variation per point per antenna.

The results for every antenna type used at each of the control points will be analyzed in the following subsections. The subsections will be organized in ascending order of the height of the antenna above the control point: TSG, TSL, TSH, and TST. Each of these subsections will begin with the table of parametric sample statistics for that control point, followed by an analysis of the table, and then the hypothesis tests are carried out according to the procedures and tests described in section 2.5.3. There will be a final subsection with the conclusions reached from the above tests. Plots visualizing
the height deviations for each of the control points per antenna type are shown in Figures F.4 to F.7 for the TSG, TSL, TSH, and TST control points respectively.

4.2.1 Antenna Specific Variations in GPS Heights for the TSG Control Point

The parametric sample statistics in Table 4.6 were consulted to better interpret the similarities and differences between the performances of each antenna type at the TSG control point, where the antennas were at ground level. The absolute minimum and maximum heights observed for the different antenna types change by 7 cm and 5 cm, respectively, for the different antennas. The closest height observed to the mean height changes in the mm level for the different antenna types and the height observed furthest from the mean changes significantly between the solutions. The last three antennas tested show a height change for the most extreme heights observed from the mean to be within 2 to 3 cm of each other and the first antenna and the fourth antenna have a maximum height change from the mean that is 7 cm. The mean heights for each of the antennas differ by 13 mm in the most extreme case and that the standard deviations change up to

<table>
<thead>
<tr>
<th>Date</th>
<th>Antenna Model#</th>
<th>Abs Min (m)</th>
<th>Abs Max (m)</th>
<th>Mean (m)</th>
<th>Std Dev (m)</th>
<th>Peak-2-Peak (m)</th>
<th>OPUS Height (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6/17/2013</td>
<td>TRM41249.00</td>
<td>182.654</td>
<td>182.797</td>
<td>182.740</td>
<td>0.013</td>
<td>0.052</td>
<td>182.737</td>
</tr>
<tr>
<td>6/3/2013</td>
<td>TRM22020.00+GP</td>
<td>182.651</td>
<td>182.797</td>
<td>182.742</td>
<td>0.012</td>
<td>0.049</td>
<td>182.749</td>
</tr>
<tr>
<td>6/5/2013</td>
<td>LEIAS10</td>
<td>182.611</td>
<td>182.777</td>
<td>182.724</td>
<td>0.013</td>
<td>0.054</td>
<td>182.739</td>
</tr>
<tr>
<td>5/23/2013</td>
<td>NOV600</td>
<td>182.586</td>
<td>182.830</td>
<td>182.737</td>
<td>0.016</td>
<td>0.062</td>
<td>182.743</td>
</tr>
</tbody>
</table>
three millimeters for the different antenna types. The differences in the standard
deviation for each antenna, as well as the change in heights in the two sigma range,
suggests that the heights computed for each antenna were all in the same relative range.
A visualization of the data used to derive the sample statistics in this table is graphically
presented in Figure F.4 in Appendix F, which shows the NOV600, TRM22020+GP,
LEIAS10, and TRM41249 antennas from top to bottom.

The differences in the means were then most likely caused by the way each
antenna sat on the TSG control point. A small hole was dug for the control point so that
the ground plane of each antenna would sit at ground level. This worked better for the
NOV600 and LEIAS10 antennas than it did for the TRM41249.00 and
TRM22020.00+GP antennas, which had substantially larger ground planes that prevented
the antenna base planes from actually sitting on the control point.

A nonparametric Kruskal-Wallis hypothesis was first carried out to see if there
was any significant difference on the performance of the different antenna types for the
TSG control point. The results of the hypothesis test are presented in Table 4.7. An
explanation of how to read the data contained in these tables can be found in Appendix E
in the discussion of the Kruskal-Wallis hypothesis test results.

<table>
<thead>
<tr>
<th>Height Resolution</th>
<th>Sample Statistic</th>
<th>Error Rates and Thresholds</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>mm level</td>
<td>229.293</td>
<td>7.8 6.3 4.6 6.3 &lt;0.001</td>
<td></td>
</tr>
<tr>
<td>cm level</td>
<td>212.253</td>
<td>7.8 6.3 4.6 &lt;0.001</td>
<td></td>
</tr>
</tbody>
</table>
The Kruskal-Wallis hypothesis test is testing the null hypothesis that all 4 antenna models result in similar heights against the alternative hypothesis that at least one of the antenna models results in significantly different heights. The Kruskal-Wallis test concludes the alternative hypothesis at both levels, since the sample statistics are greater than the thresholds for all three error rates. The P-value at all height resolutions is 0.1%, which is very weak evidence in support of the null hypothesis and justifies the conclusion to accept the alternative hypothesis, that at least one of the antenna models is performing differently.

The next question regarding antenna performance at the TSG control point is which pairs of antennas perform differently from each other. This will be evaluated with a one-way layout MC test for the different treatment populations obtained above. The results of the hypothesis test are given in Table 4.8. An explanation of how to read the data contained in these tables can be found in Appendix E in the discussion of the one-way layout MC hypothesis test results.
Table 4.8: Results of the one-way layout MC hypothesis test for the GPS heights obtained by the different antenna types at the TSG control point with the antennas located at ground level.

<table>
<thead>
<tr>
<th>Height Resolution</th>
<th>Antennas</th>
<th>Sample Statistic</th>
<th>Sample Statistic</th>
<th>Error Rates and Thresholds</th>
<th>P-values</th>
</tr>
</thead>
<tbody>
<tr>
<td>mm level</td>
<td>NOV600 TRM22020.00+GP</td>
<td>10.0623</td>
<td>10.0623</td>
<td>3.633 3.2 2.784</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td></td>
<td>NOV600 LEIAS10</td>
<td>-15.2162</td>
<td>15.2162</td>
<td>3.633 3.2 2.784</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td></td>
<td>NOV600 TRM41249.00</td>
<td>4.6632</td>
<td>4.6632</td>
<td>3.633 3.2 2.784</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td>TRM22020.00+GP LEIAS10</td>
<td>-16.8506</td>
<td>16.8506</td>
<td>3.633 3.2 2.784</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td></td>
<td>TRM22020.00+GP TRM41249.00</td>
<td>-4.0930</td>
<td>4.0930</td>
<td>3.633 3.2 2.784</td>
<td>0.025</td>
</tr>
<tr>
<td></td>
<td>LEIAS10 TRM41249.00</td>
<td>16.8230</td>
<td>16.8230</td>
<td>3.633 3.2 2.784</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>cm level</td>
<td>NOV600 TRM22020.00+GP</td>
<td>8.0322</td>
<td>8.0322</td>
<td>3.633 3.2 2.784</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td></td>
<td>NOV600 LEIAS10</td>
<td>-13.9826</td>
<td>13.9826</td>
<td>3.633 3.2 2.784</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td></td>
<td>NOV600 TRM41249.00</td>
<td>3.4209</td>
<td>3.4209</td>
<td>3.633 3.2 2.784</td>
<td>0.05</td>
</tr>
<tr>
<td></td>
<td>TRM22020.00+GP LEIAS10</td>
<td>-16.1803</td>
<td>16.1803</td>
<td>3.633 3.2 2.784</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td></td>
<td>TRM22020.00+GP TRM41249.00</td>
<td>-4.1742</td>
<td>4.1742</td>
<td>3.633 3.2 2.784</td>
<td>0.025</td>
</tr>
<tr>
<td></td>
<td>LEIAS10 TRM41249.00</td>
<td>15.0901</td>
<td>15.0901</td>
<td>3.633 3.2 2.784</td>
<td>&lt;0.0001</td>
</tr>
</tbody>
</table>

The MC hypothesis test is testing the null hypothesis that a given pair of antennas results in equivalent heights against the alternative hypothesis that a given pair of antennas does not result in equivalent heights. The MC concludes the alternative hypothesis for each antenna pair in the millimeter level, indicating that each pair of antennas results in significantly different heights. This result was concluded because the absolute value of the sample statistics is greater than all of the thresholds for the error rates tested. The conclusion is further supported by the analogue of the P-value, which shows that the most similar performing pair of antennas will still be significantly different at an EER of 2.5%. The null hypothesis was concluded for the NOV600 and TRM41249.00 antenna pair at the centimeter level, meaning that these antennas result in similar heights. The acceptance of the null hypothesis is supported by the analogue of the P-value, which shows that the performance of this antenna pair will only become
significantly different for P-values EERs greater than 5%. Other than this, all other pairs of antennas test to be significantly different at the millimeter level.

It is also possible to rank the relative performance of each of the antennas tested, according to the procedure described at the end of Section 3.3.4. The performance of the antennas will be ranked from the antenna with the smallest amount of height deviations from a mean to the antenna with the greatest amount of height deviations from the mean. The sign of the sample statistic in Table 4.8 was used to determine the relative performance of each pair of antennas. If the sign of a given sample statistic is positive, the left antenna model of the pair of antennas being tested had a smaller amount of height deviations. Otherwise, the right antenna model of the pair of antennas being tested had the smaller amount of height deviations. Each pair of antennas must be ranked this way and the rankings of the individual pairs must be considered with respect to each other to determine the overall ranking of the antennas. The ranking of the relative performance of the antennas from the smallest amount of height variation to the greatest amount of height variation at the cm and mm levels was determined to be: LEIAS10, NOV600 TRM41249.00, TRM22020.00+GP.

4.2.2 Antenna Specific Variations in GPS Heights for the TSL Control Point
The parametric sample statistics in Table 4.9 were consulted to better interpret the similarities and differences between the kinematic solutions for each antenna type at the TSL control point, where the antennas were at a height of 1 m above the ground. The relative change in the absolute minimum and maximum heights observed for the different antenna types was 5 cm and 2 cm, respectively. The first three antennas tested show a height change for the most extreme value observed from the mean to be within 1 to 2 cm of each other and the fourth antenna and the fourth antenna, has a maximum height change from the mean that is 5 cm less than the other antennas. The mean heights for each of the antenna differ by 10 mm in the most extreme case and the standard deviations change up to 4 mm for the different antenna types. This suggests that the distributions of these antennas over this control point are very similar. A visualization of the data used to derive the sample statistics in this table is graphically presented in Figure F.5 in Appendix F, which shows the TRM22020.00+GP, NOV600, LEIAS10, and TRM41249.00 antennas from top to bottom.

A nonparametric Kruskal-Wallis hypothesis was first carried out to see if there was any significant difference on the performance of the different antenna types for the
TSL control point. The results of the hypothesis test are given in Table 4.10. An explanation of how to read the data contained in these tables can be found in Appendix E in the discussion of the Kruskal-Wallis hypothesis test results.

Table 4.10: Results of the Kruskal-Wallis test for a significant difference in performance of the GPS height for the four antenna types used at the TSL control point, with the antennas at 1 m above the ground.

<table>
<thead>
<tr>
<th>Height Resolution</th>
<th>Sample Statistic</th>
<th>Error Rates and Thresholds</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>mm level</td>
<td>123.074</td>
<td>7.8 6.3 4.6</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>cm level</td>
<td>85.909</td>
<td>7.8 6.3 4.6</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

The Kruskal-Wallis hypothesis test is testing the null hypothesis that all 4 antenna models result in similar heights against the alternative hypothesis that at least one of the antenna models results in significantly different heights. The Kruskal-Wallis test concludes the alternative hypothesis at both levels, since the sample statistics are greater than the thresholds for all three error rates. The P-value at all height resolutions is less than 0.1%, which is very weak evidence in support of the null hypothesis and justifies the conclusion to accept the alternative hypothesis.

The next question regarding antenna performance at the TSL control point is which pairs of antennas perform differently from each other. This will be evaluated with a one-way layout MC test for the different treatment populations obtained above. The results of the hypothesis test are given in Table 4.11. An explanation of how to read the data contained in these tables can be found in Appendix E in the discussion of the one-way layout MC hypothesis test results.
Table 4.11: Results of the one-way layout MC hypothesis test for the GPS heights obtained by the different antenna types at the TSL control point, with the antennas at 1 m above the ground.

<table>
<thead>
<tr>
<th>Height Resolution</th>
<th>Antennas</th>
<th>Sample Statistic</th>
<th>Sample Statistic</th>
<th>Error Rates and Thresholds</th>
<th>P-values</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5%</td>
<td>10%</td>
</tr>
<tr>
<td>mm level</td>
<td>TRM22020.00+GP</td>
<td>LEIAS10</td>
<td>-10.5288</td>
<td>10.5288</td>
<td>3.633</td>
</tr>
<tr>
<td></td>
<td>TRM22020.00+GP</td>
<td>NOV600</td>
<td>-9.7151</td>
<td>9.7151</td>
<td>3.633</td>
</tr>
<tr>
<td></td>
<td>TRM22020.00+GP</td>
<td>TRM41249.00</td>
<td>-12.4414</td>
<td>12.4414</td>
<td>3.633</td>
</tr>
<tr>
<td></td>
<td>LEIAS10</td>
<td>NOV600</td>
<td>4.6943</td>
<td>4.6943</td>
<td>3.633</td>
</tr>
<tr>
<td></td>
<td>LEIAS10</td>
<td>TRM41249.00</td>
<td>-6.1300</td>
<td>6.1300</td>
<td>3.633</td>
</tr>
<tr>
<td></td>
<td>NOV600</td>
<td>TRM41249.00</td>
<td>-9.5285</td>
<td>9.5285</td>
<td>3.633</td>
</tr>
<tr>
<td>cm level</td>
<td>TRM22020.00+GP</td>
<td>LEIAS10</td>
<td>-9.2797</td>
<td>9.2797</td>
<td>3.633</td>
</tr>
<tr>
<td></td>
<td>TRM22020.00+GP</td>
<td>NOV600</td>
<td>-6.3166</td>
<td>6.3166</td>
<td>3.633</td>
</tr>
<tr>
<td></td>
<td>TRM22020.00+GP</td>
<td>TRM41249.00</td>
<td>-10.8018</td>
<td>10.8018</td>
<td>3.633</td>
</tr>
<tr>
<td></td>
<td>LEIAS10</td>
<td>NOV600</td>
<td>3.9047</td>
<td>3.9047</td>
<td>3.633</td>
</tr>
<tr>
<td></td>
<td>LEIAS10</td>
<td>TRM41249.00</td>
<td>-2.0232</td>
<td>2.0232</td>
<td>3.633</td>
</tr>
<tr>
<td></td>
<td>NOV600</td>
<td>TRM41249.00</td>
<td>-5.8933</td>
<td>5.8933</td>
<td>3.633</td>
</tr>
</tbody>
</table>

The MC hypothesis test is testing the null hypothesis that a given pair of antennas results in equivalent heights against the alternative hypothesis that a given pair of antennas does not result in equivalent heights. The MC concludes the alternative hypothesis for each antenna pair in the millimeter level, indicating that each pair of antennas results in significantly different heights. This result was concluded because the absolute value of the sample statistics is greater than all of the thresholds for the error rates tested. The conclusion is further supported by the analogue of the P-value, which shows that the most similar performing pair of antennas will still be significantly different at an EER of 0.5%. The null hypothesis was concluded for the LEIAS10 and TRM41249.00 antenna pair at the cm level, meaning that these antennas result in similar heights. The acceptance of the null hypothesis is supported by the analogue of the P-value, which shows that the performance of this antenna pair will only become
significantly different for P-values EERs greater than 20%. Other than this, all other pairs of antennas test to be significantly different at the centimeter level.

It is also possible to rank the relative performance of each of the antennas tested, according to the procedure described at the end of Section 3.3.4. The performance of the antennas will be ranked from the antenna with the smallest amount of height deviations from a mean to the antenna with the greatest amount of height deviations from the mean. The sign of the sample statistic in Table 4.11 was used to determine the relative performance of each pair of antennas. If the sign of a given sample statistic is positive, the left antenna model of the pair of antennas being tested had a smaller amount of height deviations. Otherwise, the right antenna model of the pair of antennas being tested had the smaller amount of height deviations. Each pair of antennas must be ranked this way and the rankings of the individual pairs must be considered with respect to each other to determine the overall ranking of the antennas. The ranking of the relative performance of the antennas from the smallest amount of height variation to the greatest amount of height variation at the cm and mm levels was determined to be: TRM22020.00+GP, LEIAS10, NOV600, TRM41249.00.

4.2.3 Antenna Specific Variations in GPS Heights for the TSH Control Point
The parametric sample statistics in Table 4.12 were consulted to better interpret the similarities and differences between the kinematic solutions for each antenna type. The absolute minimum and maximum heights observed between the four different antenna types change by 6 cm and 3 cm, respectively. The mean heights for each of the antennas differ by 11 mm in the most extreme case and that the standard deviations changes up to nine millimeters for the different antenna types. The standard deviations of all antennas, except for the NOV600, agree to within 2 mm of each other, suggesting that a very similar range of heights is observed. The larger standard deviation of the NOV600 antenna indicates that more height variation occurred with this antenna. Since the mean height for this antenna is so similar to the means of the two other antennas, it suggests that the larger standard deviation was caused by larger outliers in the kinematic solution. 

A visualization of the data used to derive the sample statistics in this table is graphically presented in Appendix F, which shows the LEIAS10, NOV600, TRM41249.00 TRM22020.00+GP, antennas from top to bottom.
A nonparametric Kruskal-Wallis hypothesis was first carried out to see if there was any significant difference on the performance of the different antenna types for the TSH control point. The results of the hypothesis test are given in Table 4.13. An explanation of how to read the data contained in these tables can be found in Appendix E in the discussion of the Kruskal-Wallis hypothesis test results.

Table 4.13: Results of the Kruskal-Wallis test for a significant difference in performance of the GPS height for the four antenna types used at the TSH control point, with the antennas at 2 m above the ground.

<table>
<thead>
<tr>
<th>Height Resolution</th>
<th>Sample Statistic</th>
<th>Error Rates and Thresholds</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>mm level</td>
<td>141.647</td>
<td>7.8 6.3 4.6</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>cm level</td>
<td>110.177</td>
<td>7.8 6.3 4.6</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

The Kruskal-Wallis hypothesis test is testing the null hypothesis that all 4 antenna models result in similar heights against the alternative hypothesis that at least one of the antenna models results in significantly different heights. The Kruskal-Wallis test concludes the alternative hypothesis at both levels, since the sample statistics are greater than the thresholds for all three error rates. The P-value at all height resolutions is 0.1%, which is very weak evidence in support of the null hypothesis and justifies the conclusion to accept the alternative hypothesis, that at least one of the antenna models is performing differently.

The next question regarding antenna performance at the TSH control point is which pairs of antennas perform differently from each other. This will be evaluated with a one-way layout MC test for the different treatment populations obtained above. The
results of the hypothesis test are given in Table 4.14. An explanation of how to read the data contained in these tables can be found in Appendix E in the discussion of the one-way layout MC hypothesis test results.

Table 4.14: Results of the one-way layout MC hypothesis test for the GPS heights obtained by the different antenna types at the TSH control point, with the antennas at 2 m above the ground.

<table>
<thead>
<tr>
<th>Height Resolution</th>
<th>Antennas</th>
<th>Sample Statistic</th>
<th>Sample Statistic</th>
<th>Error Rates and Thresholds</th>
<th>P-values</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5%</td>
<td>10%</td>
</tr>
<tr>
<td>mm level</td>
<td>LEIAS10 NOV600</td>
<td>-6.0436</td>
<td>6.0436</td>
<td>3.633</td>
<td>3.24</td>
</tr>
<tr>
<td></td>
<td>LEIAS10 TRM41249.00</td>
<td>-14.9207</td>
<td>14.9207</td>
<td>3.633</td>
<td>3.24</td>
</tr>
<tr>
<td></td>
<td>LEIAS10 TRM22020.00+GP</td>
<td>-6.5792</td>
<td>6.5792</td>
<td>3.633</td>
<td>3.24</td>
</tr>
<tr>
<td></td>
<td>NOV600 TRM41249.00</td>
<td>-12.3378</td>
<td>12.3378</td>
<td>3.633</td>
<td>3.24</td>
</tr>
<tr>
<td></td>
<td>NOV600 TRM22020.00+GP</td>
<td>-1.7433</td>
<td>1.7433</td>
<td>3.633</td>
<td>3.24</td>
</tr>
<tr>
<td></td>
<td>TRM41249.00 TRM22020.00+GP</td>
<td>10.5185</td>
<td>10.5185</td>
<td>3.633</td>
<td>3.24</td>
</tr>
<tr>
<td>cm level</td>
<td>LEIAS10 NOV600</td>
<td>-4.5647</td>
<td>4.5647</td>
<td>3.633</td>
<td>3.24</td>
</tr>
<tr>
<td></td>
<td>LEIAS10 TRM41249.00</td>
<td>-13.0306</td>
<td>13.0306</td>
<td>3.633</td>
<td>3.24</td>
</tr>
<tr>
<td></td>
<td>LEIAS10 TRM22020.00+GP</td>
<td>-4.4092</td>
<td>4.4092</td>
<td>3.633</td>
<td>3.24</td>
</tr>
<tr>
<td></td>
<td>NOV600 TRM41249.00</td>
<td>-8.9514</td>
<td>8.9514</td>
<td>3.633</td>
<td>3.24</td>
</tr>
<tr>
<td></td>
<td>NOV600 TRM22020.00+GP</td>
<td>0.1607</td>
<td>0.1607</td>
<td>3.633</td>
<td>3.24</td>
</tr>
<tr>
<td></td>
<td>TRM41249.00 TRM22020.00+GP</td>
<td>9.2589</td>
<td>9.2589</td>
<td>3.633</td>
<td>3.24</td>
</tr>
</tbody>
</table>

The MC hypothesis test is testing the null hypothesis that a given pair of antennas results in equivalent heights against the alternative hypothesis that a given pair of antennas does not result in equivalent heights. The MC concludes the null hypothesis for the NOV600 and TRM22020.00+GP antennas at both height resolutions for all three error rates considered. This result was concluded because the absolute value of the sample statistic for this pairs of antennas is less than the thresholds for all of the error rates. Concluding the null hypothesis for these antenna pairs is further supported by the analogue of the P-value, which is greater than 20%, which is strong evidence in support of the null hypothesis. The alternative hypothesis was concluded for each of the other
antenna pairs at both height resolutions, because the absolute value of the sample
statistics are less than the thresholds at every error rate considered. The conclusion of the
alternative hypothesis for the other antenna pairs is supported by the analogue of the P-
value, which shows that the most similar performing of the antenna pairs will still be
significantly different at an EER of 1%.

It is also possible to rank the relative performance of each of the antennas tested,
according to the procedure described at the end of Section 3.3.4. The performance of the
antennas will be ranked from the antenna with the smallest amount of height deviations
from a mean to the antenna with the greatest amount of height deviations from the mean.
The sign of the sample statistic in Table 4.14 was used to determine the relative
performance of each pair of antennas. If the sign of a given sample statistic is positive,
the left antenna model of the pair of antennas being tested had a smaller amount of height
deviations. Otherwise, the right antenna model of the pair of antennas being tested had
the smaller amount of height deviations. Each pair of antennas must be ranked this way
and the rankings of the individual pairs must be considered with respect to each other to
determine the overall ranking of the antennas. The ranking of the relative performance of
the antennas from the smallest amount of height variation to the greatest amount of height
variation at the cm and mm levels was determined to be: LEIAS10, NOV600,
TRM41249.00 TRM22020.00+GP.

4.2.4 Antenna Specific Variations in GPS Heights for the TST Control Point
Table 4.15: Parametric sample statistics for the GPS heights obtained by switching the antenna model used on the TST control point, with antennas at 2.5 m above the ground.

<table>
<thead>
<tr>
<th>Date</th>
<th>Antenna Model#</th>
<th>Abs Min (m)</th>
<th>Abs Max (m)</th>
<th>Mean (m)</th>
<th>Std Dev (m)</th>
<th>Peak-2-Peak (m)</th>
<th>OPUS Height (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5/28/2013</td>
<td>TRM41249.00</td>
<td>185.088</td>
<td>185.315</td>
<td>185.204</td>
<td>0.015</td>
<td>0.060</td>
<td>185.194</td>
</tr>
<tr>
<td>6/26/2013</td>
<td>TRM22020.00+GP</td>
<td>184.628</td>
<td>185.560</td>
<td>185.212</td>
<td>0.022</td>
<td>0.088</td>
<td>185.205</td>
</tr>
</tbody>
</table>

The parametric sample statistics in Table 4.15 were consulted to better interpret the similarities and differences between the kinematic solutions for each antenna type. The absolute minimum and maximum heights observed for the different antenna types change by 54 cm and 24 cm, respectively. The closest height observed to the mean height changes in the mm level for the different antenna types and the height observed furthest from the mean changes significantly, with an observed 4.7 cm difference. The mean and standard deviation of the antenna heights differ in the order of 7 and 8 mm, respectively. A visualization of the data used to derive the sample statistics in this table is graphically presented in Figure F.7 in Appendix F, which shows the TRM41249 and TRM22020+GP antennas from top to bottom.

A nonparametric Kruskal-Wallis hypothesis was first carried out to see if there was any significant difference on the performance of the different antenna types for the TST control point. The results of the hypothesis test are given in Table 4.16. An explanation of how to read the data contained in these tables can be found in Appendix E in the discussion of the Kruskal-Wallis hypothesis test results.
Table 4.16: Results of the Kruskal-Wallis test for a significant difference in performance of the GPS height for the four antenna types used at the TST control point, with antennas at 2.5 m above the ground.

<table>
<thead>
<tr>
<th>Kruskal Wallis Test for Significance TST Trimble Antennas</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height Resolution</td>
</tr>
<tr>
<td>-------------------</td>
</tr>
<tr>
<td>mm level</td>
</tr>
<tr>
<td>cm level</td>
</tr>
</tbody>
</table>

The Kruskal-Wallis hypothesis test is testing the null hypothesis that both antenna models result in similar heights against the alternative hypothesis that one of the antenna models results in significantly different heights. The Kruskal-Wallis test concludes the alternative hypothesis at both levels, since the sample statistics are greater than the thresholds for all three error rates. The P-value at all height resolutions is 0.1%, which is very weak evidence in support of the null hypothesis and justifies the conclusion to accept the alternative hypothesis that one of the antenna models is performing differently.

The next question regarding antenna performance at the TST control point is which pairs of antennas perform differently from each other. This will be evaluated with a one-way layout MC test for the different treatment populations obtained above. The results of the hypothesis test are given in Table 4.17 below. An explanation of how to read the data contained in these tables can be found in Appendix E in the discussion of the one-way layout MC hypothesis test results.

Table 4.17: Results of the one-way layout MC hypothesis test for the GPS heights obtained by the different antenna types at the TST control point, with antenna heights at 2.5 m above the ground.

<table>
<thead>
<tr>
<th>1 Way Layour Multiple Comparisons TST</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height Resolution</td>
</tr>
<tr>
<td>-------------------</td>
</tr>
<tr>
<td>mm level</td>
</tr>
<tr>
<td>cm level</td>
</tr>
</tbody>
</table>
The MC hypothesis test is testing the null hypothesis that a given pair of antennas results in equivalent heights against the alternative hypothesis that a given pair of antennas does not result in equivalent heights. The MC concludes the alternative hypothesis for the antenna pair in the millimeter and centimeter level, indicating that each pair of antennas results in significantly different heights. This result was concluded because the absolute value of the sample statistics is greater than all of the thresholds for the error rates tested. The conclusion is further supported by the analogue of the P-value, which shows that the most similar performing pair of antennas will still be significantly different at an EER of 0.01%.

It is also possible to rank the relative performance of each of the antennas tested, according to the procedure described at the end of Section 3.3.4. The performance of the antennas will be ranked from the antenna with the smallest amount of height deviations from a mean to the antenna with the greatest amount of height deviations from the mean. The sign of the sample statistic in Table 4.17 was used to determine the relative performance of each pair of antennas. If the sign of a given sample statistic is positive, the left antenna model of the pair of antennas being tested had a smaller amount of height deviations. Otherwise, the right antenna model of the pair of antennas being tested had the smaller amount of height deviations. The antennas were ranked according to this procedure and the ranking of the relative performance of the antennas from the smallest amount of height variation to the largest amount of height variation was determined to be: TRM41249.00, TRM22020.00+GP.
4.2.5 Conclusions for Height Variations Caused by Changing Antenna Models

It is seen from the results of the different MC hypothesis tests that the observed GPS height of a point varies with the antenna used. The change in the mean height of each of the control points per antenna in Tables 4.6, 4.9, 4.12, and 4.15 is seen to change by a few millimeters to 2 cm. Therefore, changing the antenna used over a control point may result in an apparent change in the height of a point that may be significant to the 2 cm accuracy standard of the National Height Modernization program. This would have an impact on heights to the centimeter level when repeated surveys are done over control points with different antennas and the resulting change in height will propagate to all measurements made from the GPS data. Changing antenna models at the CORS stations may have greater ramifications than just causing a change in the GPS height of the station. If the GPS height changes, it could propagate to all other GPS data being post-processed against that CORS.

4.3 Experiment 3: GPS Height Variations Caused by High Voltage Power Lines

The objective of this experiment was to analyze the variation in GPS-derived height caused by proximity to a high voltage power line. An open environment with a high voltage power line running through it was found at the Hilliard Soccer Complex, Hilliard, Ohio. An overview of this area is provided in Figure 4.3. The high voltage power lines have been outlined in a red rectangle and the locations of the three different GPS antennas used are marked by green, cyan, and fuchsia icons, respectively. Figure
4.3 shows that the area is open except for the tree line along the boundaries. The tree line is at a height where it is below a 15° elevation angle and GPS satellites at a reasonably low elevation can still be observed.

The data collected for each of the three antennas used was processed in KinTools using the processing parameters given in Table D.3 in Appendix D. Data processing was done with each of these antennas as the rover and using the COLB CORS as the reference station. The resulting height deviations for these antennas are then plotted in Figures 4.4, 4.5, and 4.6, respectively. The OPUS solution is also shown on each of these plots for comparison of the mean of the kinematic solution. The parametric sample statistics for each of these antennas have been included in Table 4.18.
Figure 4.3: Overview of the Hilliard Soccer Complex where the testing under high voltage power lines took place. The red rectangle outlines the high voltage power lines running across the field and the green, cyan, and fuchsia icons are the locations where the three antennas types used were setup.
Figure 4.4: Height deviations per epoch for the data collected under the high voltage power lines in the Hilliard Soccer Complex with the NOV600 GPS antenna.

Figure 4.5: Height deviations per epoch for the data collected under the high voltage power lines in the Hilliard Soccer Complex with the TRM39105.00 GPS antenna.
Figure 4.6: Height deviations per epoch for the data collected under the high voltage power lines in the Hilliard Soccer Complex with the TRM59900.00 GPS antenna with SCIS radome.

Table 4.18: Parametric sample statistics for the GPS heights for each of the antennas used to collect data under the height voltage power lines in the Hilliard Soccer Complex. All sample statistics are in meters.

<table>
<thead>
<tr>
<th>Antenna</th>
<th>Abs Min (m)</th>
<th>Abs Max (m)</th>
<th>Mean (m)</th>
<th>Std Dev (m)</th>
<th>Peak-2-Peak (m)</th>
<th>OPUS Height (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NOV600</td>
<td>253.053</td>
<td>253.219</td>
<td>253.121</td>
<td>0.02</td>
<td>0.08</td>
<td>253.121</td>
</tr>
<tr>
<td>TRM39105.00</td>
<td>253.002</td>
<td>253.189</td>
<td>253.093</td>
<td>0.021</td>
<td>0.083</td>
<td>253.135</td>
</tr>
<tr>
<td>TRM59900.00</td>
<td>253.099</td>
<td>253.202</td>
<td>253.155</td>
<td>0.018</td>
<td>0.07</td>
<td>253.161</td>
</tr>
</tbody>
</table>

The three antennas used in this experiment were all set up directly underneath the high voltage power lines at different control points separated by 20 m. There is no ground control in this test to compare the accuracies of the GPS-derived heights to. Instead, all three antennas will be evaluated on how much noise exists in the solution.
(indicated by the standard deviation and peak-to-peak statistics) and how well the noise appears to average out for each antenna. In addition, the NOV600 and TRM59900.00 with SCIS radome antennas will be compared to their performance in experiments 1 and 2 to determine how the level of noise observed under the high voltage power lines compares with the level of noise observed in an open field.

These figures show that a fair amount of noise was present in all observations, which is most likely caused by the high voltage power lines. This noise was also mitigated from what it could have been due to the selection of an open site and the ability to use satellites at the lower to middle elevation angles. It is expected that the high voltage power lines will have a greater effect on a signal received closer to the zenith, where it is passing closer to the high voltage power lines overhead, than it would be for satellites closer to the horizon. However, this has not been tested and it is also not known how the signals received from lower elevation angles will be affected when the antenna is placed directly under the power lines nor the level of noise that will enter the GPS observation when some of the visible satellites are high enough for the power lines to interfere with their signals.

The plots of the epoch-to-epoch height deviations per antenna show that the height deviations do average out well with enough observations. While this is seen in the plots, an assessment about the absolute accuracy of the GPS-derived heights under power lines cannot be made. This would require the coordinates of a known point under the power lines to compare the GPS-derived heights to. While the noise in a solution may appear to average out well, it is not known if the interference from the high voltage
power lines may have caused a systematic shift in the heights, relative to the true height of the ground. However, the epoch-by-epoch height varies significantly, as illustrated in Figures 4.4 to 4.6.

A more detailed analysis involving tracking the visible satellites, as well as their elevation angles, is needed to analyze the impact of the high voltage power lines on GPS-derived height. This would allow for the current visible GPS satellites to be viewed with respect to high voltage lines and the potential magnitude on GPS heights could be assessed by how close each of the visible satellites is to the zenith. This could then be tested by excluding the satellites believed to be effected by the high voltage power lines and the solution could then be reprocessed and compared to the original to see how the quality of GPS heights changed during this time. Such an analysis is beyond the scope of this thesis, which is assessing the impacts of station dependent error sources on the accuracy standards of the National Height Modernization program. An assessment of the impacts of the high voltage power lines can be achieved by analyzing the amount of noise they cause in a solution and how well the noise averages out over long static sessions. The process of tracking satellites and selectively excluding the satellites receiving more interference is an optimization problem and is focused on obtaining the best possible solution rather than analyzing the level of impact such environments may have on GPS-derived heights.

The visual results shown in the figures indicate that the mean of the kinematic solutions for the NOV600 and TRM59900.00 antennas are very close to their OPUS solutions (Figures 4.4 and 4.6), whereas the mean of the kinematic solution for the
TRM39105.00 (Figure 4.5) antenna has a noticeable offset from the OPUS solution. This is verified with the sample statistics in Table 4.18. Here it is seen that the mean computed from the kinematic solution of the NOV600 exactly agrees with the static OPUS solution. The TRM59900.00 antenna has a 6 mm difference between the mean of its kinematic solution and its static OPUS solution. However, the difference between the mean of the TRM39105.00 antenna and its static OPUS solution is in the order of 4 cm.

Overall, it appears that the TRM59900.00 antenna performed the best out of the three antennas tested in this environment. This is indicated by examining several different statistics. The height difference between its most extreme observation and its mean (maximum of the difference between the mean and absolute max or mean and absolute min) is the smallest of the three antennas for both the mean of the kinematic solution and when compared with its OPUS solution. The standard deviation of the data for this antenna, as well as the peak-to-peak change in height within two standard deviations of its mean is the smallest of the three antennas. These all indicate that this antenna was performing the best of the three antennas tested. However, this is not necessarily an accurate assessment, because this antenna was not used to collect data for the same amount of time as the rest of the antennas. It is possible that satellite configurations observed for the rest of the interval by the other antennas could have resulted in greater height deviations for this antenna. However, this is unlikely due to how closely the TRM59900.00 resembles the performance of the NOV600 during the time it was collecting data. It is expected that this antenna would continue to perform at a level very close to the NOV600 if it were used to collect data over the entire timespan.
Notice in Table 4.18 that the smallest peak-to-peak height deviation is in the order of 7 to 10 cm. This is a noticeably larger variation of heights than seen for data collected using the same antenna models in an open field at similar heights in experiments 1 and 2. This suggests that the high voltage lines are, indeed, adversely affecting the GPS height and that the distance to power lines, especially high voltage power lines, must be considered when high accuracy GPS heights are needed.

It is clear from the sample statistics and figures above that high voltage power lines do have an impact on GPS heights. The plots show that the effects from high voltage power lines will not cause a constant effect on the quality of GPS-derived heights. The peak-to-peak sample statistic gives more meaningful information about the height variation when compared to the peak-to-peak range of heights observed with the same antenna models at similar heights in the open field used in experiments 1 and 2. The peak-to-peak heights were consistently observed to change between 7 and 8 cm, which can make a profound difference when high accuracy GPS heights are needed.
Figure 4.7: Sky plot of the visible satellites and their elevation angles observed for the data collected under the high voltage power lines in the Hilliard Soccer Complex.

Figure 4.7 shows a sky plot of the visible satellites and their elevation angles for the full observation period. The elevation mask applied to these observations when processing in KinTools was 15° and this same elevation angle was input into the Trimble Planning utility to create the sky plot. The sky plot is showing trajectories of every visible satellite throughout the day and will not indicate which satellites are simultaneously visible. As can be seen from the sky plot, the majority of the visible satellites pass through the middle elevation angles (approximately 40° to 65°) and only a few of satellites pass directly overhead.
From the sky plot, it appears that setting up the antennas underneath the power lines was not the optimal location to measure the effects of the power lines on GPS-derived heights, because so few of the satellites pass directly overhead. The sky plot suggests that a better location for the antennas would have been to the east or west of the power lines so that the power lines would be around a 60° to 70° elevation angle with respect to the antenna. This would result in more satellites passing directly over the power lines and may give a stronger measure of the effect of the power lines have on a GPS signal when the signal has to travel directly through an electromagnetic field to reach the receiver as opposed to only traveling near it.

4.4 Experiment 4: Multipath Reflection from a Snow-Covered Field

An overview of the surrounding environment where the data was collected is given in Figure 4.8. The locations of the two GPS antennas used in the data collection are shown by the green and cyan icons in Figure 4.8. Most of the data collection intervals are between 5 and 7 hours, due to the impact of the cold temperatures on the life of the batteries used to power the antennas. The snow on the ground occurred from a storm at the end of 2012 and no fresh snow fell during the course of the data collection. During the time of this data collection, the snow on the ground remained in a light layer that was not compacted and did not develop a crust due to melting and re-freezing. Table 4.19 has a column listing the snow depth in centimeters obtained by converting the recorded snow depth to the nearest inch for the days of data collection to centimeters.
The recorded snow depth was obtained from the NOAA archived climatological report for Columbus, Ohio for each day of data collection.

![Figure 4.8](image)

Figure 4.8: Overview of the surrounding environment where data collection occurred to analyze the Sidereal effects of multipath on GPS height caused by reflectance from a snow covered ground. The location where the antennas were setup for data collection are shown by the green and cyan icons.

The data was processed in KinTools using the antennas in the fields as the rover antennas and using the COLB CORS as the reference station. The processing parameters used to process each of the observations are listed in Table D.4 in Appendix D. The two data sessions collected with the TRM39105.00 antennas had to be split into separate
sessions for processing due to the time interval of the data collection spanning multiple days. After the data was processed, the data on subsequent days had to be shifted by approximately four minutes per day to account for the change in the visibility time of the same satellite configuration. The first day for each antenna was used as the reference day to adjust all other days to. Once the satellite visibility times of all days were adjusted to the first day, the minimum and maximum overlap extents were found between the solutions and data was plotted from this interval for each day. The sidereal plots for each of the antennas are shown in Figures 4.9 and 4.10 for the TRM41249.00 antenna and TRM31905.00 antennas, respectively.

![Sidereal Multipath Variability Day1](image1)

![Sidereal Multipath Variability Day2](image2)

![Sidereal Multipath Variability Day3](image3)

Figure 4.9: Sidereal multipath repetition of a snow covered field for different depths of snow on different days for the TRM41249.00 antenna. The top plot shows the data collected on 1/2/13 with 17.78 cm of snow on the ground. The middle plot shows the data collected on 1/3/13 with 15.24 cm of snow on the ground. The bottom plot shows the data collected on 1/7/13 with 7.62 cm of snow on the ground.
Figure 4.10: Sidereal multipath repetition of a snow covered field for different depths of snow on different days for the TRM39105.00 antenna. The top plot shows the data collected on 1/6/13 with 10.16 cm of snow on the ground. The bottom plot shows the data collected on 1/7/13 with 7.62 cm of snow on the ground.

In addition to these plots, the standard parametric sample statistics have been included in Table 4.19. The sample statistics for each day of the TRM4129.00 antenna are highlighted in green in the table and the sample statistics for each day of the TRM39105.00 antenna are highlighted in orange.
An examination of Figure 4.9 shows that the multipath reflection from the snow seems to be fairly consistent on a sidereal basis. The first two days especially have a very similar pattern to each other. There is a gradual change seen in the pattern from the data collected on the third day, especially at the end of the observation session. The same general pattern is also seen over the two days of data collected for the TRM39105.00 antenna in Figure 4.10. There are some portions of each day, such as around the 15th hour and for the last few observations for the TRM41249.00 antenna and around the 22nd and 24th hours for the TRM39105 antenna, where the plotted results become noticeable different for each antenna, but this appears at a height level where it could just be noise in the observations.

The sample statistics tabulated in Table 4.19 provide a numerical analysis of what is occurring in the figures. While the most extreme outliers observed by each antenna per day are in the order of a cm, the means and standard deviations of the data per antenna change by up to 8 mm. The biggest of these changes was observed between days one and three for the TRM41249.00, where the mean changed by 8 mm, the standard deviation

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Table 4.19: Parametric sample statistics for the GPS heights for data collected from each of the antennas in a snow covered field. All sample statistics are in meters.

<table>
<thead>
<tr>
<th>Date</th>
<th>Antenna Model#</th>
<th>Snow Depth</th>
<th>Abs Min (m)</th>
<th>Abs Max (m)</th>
<th>Mean (m)</th>
<th>Std Dev (m)</th>
<th>Peak-2-Peak (m)</th>
<th>OPUS Height (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/2/2013</td>
<td>TRM41249.00</td>
<td>18.0</td>
<td>189.154</td>
<td>189.270</td>
<td>189.213</td>
<td>0.014</td>
<td>0.057</td>
<td>189.203</td>
</tr>
<tr>
<td>1/3/2013</td>
<td>TRM41249.00</td>
<td>15.0</td>
<td>189.149</td>
<td>189.287</td>
<td>189.211</td>
<td>0.014</td>
<td>0.058</td>
<td>189.208</td>
</tr>
<tr>
<td>1/7/2013</td>
<td>TRM41249.00</td>
<td>7.6</td>
<td>189.188</td>
<td>189.331</td>
<td>189.237</td>
<td>0.015</td>
<td>0.059</td>
<td>189.231</td>
</tr>
<tr>
<td>1/6/2013</td>
<td>TRM39105.00</td>
<td>10.0</td>
<td>189.600</td>
<td>189.705</td>
<td>189.650</td>
<td>0.014</td>
<td>0.058</td>
<td>189.658</td>
</tr>
<tr>
<td>1/7/2013</td>
<td>TRM39105.00</td>
<td>7.5</td>
<td>189.608</td>
<td>189.700</td>
<td>189.644</td>
<td>0.013</td>
<td>0.053</td>
<td>189.640</td>
</tr>
</tbody>
</table>
changed by 11 mm, and the peak-to-peak range changed by 5 mm. Despite the change in the mean and standard deviations between these solutions, the peak-to-peak range remains at the mm level. However, the larger peak-to-peak range of heights for the data collected on January 7th with the TRM41249.00 suggests that the different snow depths may be causing a different pattern of noise than the data collected on the other days with that antenna. Based on a similar range of a 5 mm peak-to-peak sample statistic and the visual results in Figures 4.9 and 4.10, it is speculated that the performance of the TRM41249.00 antenna on days 1 and 3 and 2 and 3 may test to be significantly different and that the performance of the TRM39105 antenna for both days of data collected may test to be significantly different. In both cases, this difference is the difference in GPS heights obtained by a change in the pattern of multipath reflection from the snow. The evidence in the figures is stronger for a difference in the GPS heights of days 1 and 3 and 2 and 3 of the TRM41249.00 antenna, than it is for both days of the TRM39105.00 antenna.

A Kruskal-Wallis test was conducted to determine if a significant variation exists in GPS heights caused by multipath reflection from different snow depths in the surrounding environment. The results of the Kruskal-Wallis hypothesis test are displayed in Table 4.20. An explanation of how to read the data contained in these tables can be found in Appendix E in the discussion of the Kruskal-Wallis hypothesis test results.
The results of the Kruskal-Wallis test show that at least one of the three treatments (different snow depths) for the TRM41249.00 antenna differs significantly at all error rates for both height resolutions tested. The P-value for each of these height resolutions show that the probability of all the treatments having the same effect is less than 0.01%. This probability is so small that it supports rejection of the null hypothesis, no change in GPS-derived heights as the existing snow depth decreases, in favor of the alternative hypothesis, which is that the antenna did not perform at the same level as the snow depth decreased. The results of the Kruskal-Wallis test for the TRM39105.00 antenna concluded that the antenna performed equivalently for the decrease in snow depth at both height resolutions. This is supported by the P-values for each resolution, as the smallest has a 46% chance of occurring. This is strong support for the null hypothesis that there is no significant treatment effect seen for this antenna for a decrease in the existing snow depth up to 2.5 cm.

The difference in treatments concluded by the Kruskal-Wallis test for the TRM41249.00 antenna merit a one-way layout MC test for the treatments to see which of the three treatments are significantly different. The results of the Kruskal-Wallis for the
TRM39105.00 antenna do not merit further analysis with an MC test, because it has already been verified that the treatment effects for this antenna are performing on the same level. The results of this hypothesis test are tabulated in Table 4.21 below. An explanation of how to read the data contained in these tables can be found in Appendix E in the discussion of the one-way layout multiple comparisons hypothesis test.

Table 4.21: Results of the one way layout multiple comparisons test for the Sidereal repetition of the multipath reflection from a snow covered field with different levels of snow.

| 1 Way Layout Multiple Comparisons for the Trimble Zephyr Geodetic (TRM41249.00) Antenna |
|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
|                                | Day 1                           | Day 2                           | Day 3                           |
|                                | Sample Statistic                | Sample Statistic                | Sample Statistic                |
|                                | |                                | |                                |
| Height Resolution              | Days 1                         | Days 2                         | Days 3                         |
|                                | Sample Statistic                | Error Rates                     | P-values                        |
| mm level                       | 1                              | 2                             | 3                              |
|                                | -1.4697                        | 1.4697                        | 3.314                          | 2.902                          | 2.424                          | >.20                           |
|                                | 5.8788                         | 5.8788                        | 3.314                          | 2.902                          | 2.424                          | <.0001                         |
|                                | 5.8788                         | 5.8788                        | 3.314                          | 2.902                          | 2.424                          | <.0001                         |
| cm level                       | 1                              | 2                             | 3                              |
|                                | -1.2247                        | 1.2247                        | 3.314                          | 2.902                          | 2.424                          | >.20                           |
|                                | 5.8788                         | 5.8788                        | 3.314                          | 2.902                          | 2.424                          | <.0001                         |
|                                | 5.8788                         | 5.8788                        | 3.314                          | 2.902                          | 2.424                          | <.0001                         |

The results of the MC hypothesis test in Table 4.21 show that the first two days of data collection with the TRM41249.00 tested to be equivalent with each other, while the third day tested to be significantly different from the other two. The P-values support the conclusions regarding the null and alternative hypotheses. The null hypothesis is that there is not a significant difference in GPS-derived heights between two specific snow depths and the alternative hypothesis is that there is a significant difference in GPS-derived heights between specific snow depths. The comparison of the heights from day three with the heights from either of the other two days has a probability of less than 0.01% of occurring. This indicates extremely weak evidence in support of the null
hypothesis. The probability that the multipath reflection observed on the first two days being equivalent is greater than 20%, which is extremely strong evidence in support of the null hypothesis. Finally, the signed magnitudes of the sample statistics indicate that the third day has a greater treatment effect than the first two and that this difference has a similar magnitude for both days.

The results of the hypothesis tests show that when the amount of multipath reflection from the snow is similar for days where the surrounding snow depth decrease by up to 2.5 cm from the existing snow depth and becomes different when the surrounding snow depth decreases by a greater amount between observation sessions. This is not to say that a significant result would not be noticed between a day with no snow on the ground and a day with an inch of snow on the ground. No control data was able to be obtained in this field after the snow had melted, so it cannot be tested for a height change compared to some amount of snow depth. The results in Table 4.19 show a change of up to 5 mm occurring in the observed range of heights, even when the snow depth changes by only 2.5 cm. However, it is not the change in the range of observed values that is important, so much as how the mean of these values changes. A significant difference was noticed for a mean changing by more than 5 mm. However, the mean change in height may only be on the level of 1 mm, depending on the depth of the snow on the ground. The parametric sample statistics and nonparametric hypothesis tests support that minute decreases in the existing snow depth in the surrounding environment will lead to small fluctuations in the GPS height determined for a point and that a larger change in snow depth will lead to more noticeable changes in GPS heights. Based on
these conclusions and an unknown deviation in performance compared to when there is no snow on the ground, it is recommended to avoid GPS observations in a snow-covered area if high accuracy GPS heights are needed.

4.5 Experiment 5: Effects of a Robin on the Height of a CORS Station

The objective of this experiment was to determine how a bird sitting on a GPS antenna affects the heights obtained from the antenna. Data for this scenario was collected at ODOT’s Office of CADD and Mapping Services on June 28, 2013 when a robin was observed on the COLB CORS station for different timespans. The antenna setup used the Test Pole and COLB CORS station shown in Figures 4.1 and 4.2 above. The first observation was approximately from 10:40 a.m. to 10:42 a.m. and the second observation was approximately from 10:48:40 a.m. to 10:58:50 a.m. Both of these times are GPS times, which is an atomic scale time equal to coordinated universal time (UTC) plus a number of leap seconds.

The CORS data for this day, as well as the CORS data for the two previous days where a bird was not observed on the antenna were used for processing. The initial processing extracted the timespans where the robin was observed sitting on the antenna. A one hour buffer around this timespan was sidereally shifted to extract the corresponding timespan from the observations of the previous two days. The data for each of these days was processed in KinTools using the data collected form the TRM22020.00+GP antenna on the COLB test pole as the reference station. The processing parameters used are given in Table D.5 in Appendix D. Figure 4.11 displays
the plot of the sidereal variation in the heights from the COLB CORS stations for the 1 hour buffer region around the time period when the robin was observed on the GPS antenna. The time interval corresponding to when the robin was sitting on the antenna is marked with vertical bars. The robin was only on the antenna on day 3, where the red bars are used. The bars on days 1 and 2 are blue, indicating that this is the corresponding time when the robin would have been on the antenna.

Figure 4.11: Sidereal plot of the COLB solution processed in KinTools over a three day period for the 1 hour buffer around the time the robin was observed sitting on the CORS station. The robin was only observed sitting on the CORS station in this time period on day 3, plotted on the bottom. The red bars show the time the robin was observed on the antenna in day 3 and the blue bars show the corresponding time interval in days 1 and 2.
A common multipath signal is not seen repeating for the same time session for all three days in Figure 4.1. The signal from the second half of the solution to the end appears to repeat fairly consistently on a daily basis, but the signal from the first half of the solution shows significantly more variation. This is expected for the solution from the third day, as this would include the time period where the robin was observed on the antenna. However, there are some peaks that have repeated in the first and second days that do not appear to have repeated in the third day. These peaks appear before the time the robin was observed on the antenna and should be repeated in a static environment.

The standard parametric sample statistics have been included in Table 4.22 to help quantify the observations in Figure 4.11.

**Table 4.22: Parametric sample statistics computed for the GPS heights from the two days when a robin was not observed on the COLB CORS station (6/26 and 6/27) and the day that it was (6/28). All statistics are in meters.**

<table>
<thead>
<tr>
<th>Date</th>
<th>Abs Min (m)</th>
<th>Abs Max (m)</th>
<th>Mean (m)</th>
<th>Std Dev (m)</th>
<th>Peak-2-Peak (m)</th>
<th>OPUS Height (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6/26/2013</td>
<td>185.201</td>
<td>185.327</td>
<td>185.261</td>
<td>0.016</td>
<td>0.064</td>
<td>185.255</td>
</tr>
<tr>
<td>6/27/2013</td>
<td>185.202</td>
<td>185.329</td>
<td>185.262</td>
<td>0.018</td>
<td>0.072</td>
<td>185.253</td>
</tr>
<tr>
<td>6/28/2013</td>
<td>185.202</td>
<td>185.329</td>
<td>185.261</td>
<td>0.017</td>
<td>0.067</td>
<td>185.235</td>
</tr>
</tbody>
</table>

From Table 4.22, it is seen that the most extreme heights in all solutions agree to each other to within a millimeter or two. This suggests sidereal repetition in that all days had the same maximum range of values between height extremes. However, Figure 4.11 shows that the peak of day one occurs at a different location than in days 2 and 3. The
mean, standard deviation, and peak-to-peak height range all show that the heights observed on the first and third days agree with each other very strongly, while the heights observed on the second day differ more noticeably from the other days. This indicates that the solution from the second day exhibits a different magnitude of height deviations than the solutions from the first and third days, as shown by the larger range of heights in the peak-to-peak sample statistic than seen on the other two days. While the peak-2-peak statistic on the second day differs from the others by up to 8 mm, the mean and standard deviation only change on the millimeter level.

Based on the sample statistics, it is not obvious if there is a significant difference between the heights obtained from the different solutions. This was statistically verified through a Kruskal-Wallis hypothesis test, the results of which are presented in Table 4.23. An explanation of how to read the data contained in these tables can be found in Appendix E in the discussion of the Kruskal-Wallis hypothesis test results.

Table 4.23: Results of the Kruskal-Wallis test for a significant difference in GPS solutions from three days when a robin is sitting on the antenna for different timespans on one of the days.

<table>
<thead>
<tr>
<th>Height Resolution</th>
<th>Sample Statistic</th>
<th>Error Rates and Thresholds</th>
<th>P-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>mm level</td>
<td>21.736</td>
<td>6</td>
<td>4.6</td>
</tr>
<tr>
<td>cm level</td>
<td>22.531</td>
<td>6</td>
<td>4.6</td>
</tr>
</tbody>
</table>

The results of the Kruskal-Wallis test indicate that the treatments are significantly different at both height resolutions, which is supported by a P-value of less than a 0.1.
percent chance of occurring. The Kruskal-Wallis test results prompt a one-way MC hypothesis test to be constructed to determine which of the treatments are different. The results of the MC hypothesis test are listed in Table 4.24 for all pairs of treatments for three different height resolutions. An explanation of how to read the data contained in these tables can be found in Appendix E in the discussion of the one-way layout MC hypothesis test results.

Table 4.24: Results of the one-way layout MC test for detecting a change in the heights of GPS solutions when a robin was sitting on the antenna for part of the third day and not on the first two days.

<table>
<thead>
<tr>
<th>Height Resolution</th>
<th>Days</th>
<th>Sample Statistic</th>
<th>Error Rates</th>
<th>P-values</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>5%</td>
<td>10%</td>
</tr>
<tr>
<td>mm level</td>
<td>1 2</td>
<td>5.8737</td>
<td>3.314</td>
<td>2.902</td>
</tr>
<tr>
<td></td>
<td>1 3</td>
<td>0.4313</td>
<td>3.314</td>
<td>2.902</td>
</tr>
<tr>
<td></td>
<td>2 3</td>
<td>-5.5227</td>
<td>3.314</td>
<td>2.902</td>
</tr>
<tr>
<td>cm level</td>
<td>1 2</td>
<td>5.7232</td>
<td>3.314</td>
<td>2.902</td>
</tr>
<tr>
<td></td>
<td>1 3</td>
<td>0.0573</td>
<td>3.314</td>
<td>2.902</td>
</tr>
<tr>
<td></td>
<td>2 3</td>
<td>-5.7164</td>
<td>3.314</td>
<td>2.902</td>
</tr>
</tbody>
</table>

The results of the one-way MC test in the table above indicate that the solutions from the first and third days do not differ by a significant amount for heights at either of the height resolutions considered, and that the heights from the first and second as well as the second and third days do differ by a significant amount at the both height resolutions tested. The P-values at the millimeter and centimeter level give strong support of the null hypothesis that the GPS heights from first day do not differ significantly from those of the third day. The P-values at both height resolutions also give strong support to the
alternative hypothesis for days 1 and 2 as well as days 2 and 3 through the small P-values that are extremely weak support of the null hypothesis.

The results of the hypothesis test did not confirm that a robin sitting on the antenna would cause a significant difference in the in height. This outcome was expected by examining the table of parametric sample statistics above when it was observed that day 3, the session when the robin was on the antenna, closely resembled the day 1, when the robin was not on the antenna. The mean and standard deviation between these days is very similar, suggesting a similar distribution of heights. The fact that the extreme values are also similar indicates that the distribution of values in these solutions is also similar.

To account for the possibility of noise from the robin averaging out of the solution with a 1 hour buffer period to either side, the buffer region to either side of the robin was reduced to 5 minutes. The new buffer region around the robin was once again used to sidereally shifted to the other 2 days in order to extract the intervals observed under the same satellite constellation. The data was then reprocessed in KinTools using the same settings as before. The processing parameters used for this revised data span are listed in Table D.6 in Appendix D. Afterwards, new sample populations for each treatment were obtained as described in Section 2.5.6. The figures of sidereal multipath repetition for the updated interval are given in Figure 4.12 and the updated parametric sample statistics are given in Table 4.25. Vertical bars are once again used to show the approximate time the robin was on the antenna. The red bars in the third plot correspond to the time the robin was observed sitting on the antenna on the third day. The blue bars in the first and
second plots are the time intervals in the first and second days corresponding to when the robin was sitting on the antenna in the third day.

Figure 4.12: Sidereal plots of the COLB CORS station over three days' time, beginning two days before the robin was observed on the antenna and ending the day the robin was observed. These intervals have been concentrated around the time the robin was observed on the antenna. The red bars show the time the robin was observed on the antenna in day 3 and the blue bars show the corresponding time interval in days 1 and 2.

Table 4.25: Parametric sample statistics of the GPS heights for a robin sitting on the COLB GPS antenna from the revised scenario, which has a more direct focus on the time the robin was observed on the antenna. All sample statistics are in meters.

<table>
<thead>
<tr>
<th>Date</th>
<th>Abs Min (m)</th>
<th>Abs Max (m)</th>
<th>Mean (m)</th>
<th>Std Dev (m)</th>
<th>Peak-2-Peak (m)</th>
<th>OPUS Height</th>
</tr>
</thead>
<tbody>
<tr>
<td>6/26/2013</td>
<td>185.216</td>
<td>185.303</td>
<td>185.265</td>
<td>0.015</td>
<td>0.058</td>
<td>185.255</td>
</tr>
<tr>
<td>6/27/2013</td>
<td>185.224</td>
<td>185.327</td>
<td>185.274</td>
<td>0.02</td>
<td>0.08</td>
<td>185.202</td>
</tr>
<tr>
<td>6/28/2013</td>
<td>185.211</td>
<td>185.332</td>
<td>185.266</td>
<td>0.018</td>
<td>0.073</td>
<td>185.229</td>
</tr>
</tbody>
</table>
The sample statistics in Table 4.25 show more deviation in the heights between day one and day three now that the timespan has been narrowed to focus on the time the robin was visible, instead of including an hour window to either side of it. The variation in the absolute minimum values observed each day is in the centimeter level and the variation in the mean and standard deviation from day-to-day is in the millimeter level. The absolute maximum and peak-to-peak range of heights deviate by two to three centimeters between the different days. This indicates a more diverse range of heights, as well as additional outliers, which may potentially be caused by the robin alighting on the antenna. The sample statistics indicate that day 1 still has heights more similar to day 3 than it does to day 2, despite the fact that a robin was not on the antennas during these times for days 1 and 2.

A Kruskal-Wallis test was performed on the treatments in this revised interval to see if any significant difference can be detected among the solutions. The results of this test are tabulated in Table 4.26. An explanation of how to read the data contained in these tables can be found in Appendix E in the discussion of the Kruskal-Wallis hypothesis test results.
Table 4.26: Kruskal-Wallis hypothesis tests results for a significant change in GPS Heights between three days, with a robin sitting on the antenna during one of those days.

<table>
<thead>
<tr>
<th>Height Resolution</th>
<th>Sample Statistic</th>
<th>Error Rates and Thresholds</th>
<th>P-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>mm level</td>
<td>237.371</td>
<td>6</td>
<td>4.6</td>
</tr>
<tr>
<td>cm level</td>
<td>257.067</td>
<td>6</td>
<td>4.6</td>
</tr>
</tbody>
</table>

The results of the Kruskal-Wallis test indicate that at least one of the treatment effects is not equal. The results of the test are consistent at all height resolutions, as seen by the sample statistic. The rejection of the null hypothesis, that at least one of the treatment effects is not equivalent, is supported by the P-value, which gives a 0.1% chance of all the treatment effects being equal. Here, the treatment effects are the GPS-derived heights for the three days. Therefore, the Kruskal-Wallis test was followed up with a one-way layout MC hypothesis test. The results of the hypothesis test are given in Table 4.27. An explanation of how to read the data contained in these tables can be found in Appendix E in the discussion of the one-way layout MC hypothesis test results.

Table 4.27: Results of the one-way layout MC hypothesis test of GPS heights for the revised data interval of a robin sitting on the COLB CORS station.

<table>
<thead>
<tr>
<th>Height Resolution</th>
<th>Days</th>
<th>Sample Statistic</th>
<th></th>
<th>Error Rates</th>
<th>P-values</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5%</td>
<td>10%</td>
</tr>
<tr>
<td>mm level</td>
<td>1</td>
<td>2 21.4036</td>
<td>21.4036</td>
<td>3.314</td>
<td>2.902</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>3 1.4986</td>
<td>1.4986</td>
<td>3.314</td>
<td>2.902</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>3 -18.4965</td>
<td>18.4965</td>
<td>3.314</td>
<td>2.902</td>
</tr>
<tr>
<td>cm level</td>
<td>1</td>
<td>2 20.7298</td>
<td>20.7298</td>
<td>3.314</td>
<td>2.902</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>3 1.7774</td>
<td>1.7774</td>
<td>3.314</td>
<td>2.902</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>3 -17.8512</td>
<td>17.8512</td>
<td>3.314</td>
<td>2.902</td>
</tr>
</tbody>
</table>
The results of the MC test show that the heights in the sample population from the day one test to be significantly equivalent to the heights in the sample population from day three, when the robin was sitting on the antenna. This result was concluded for both of the height resolutions tested and is supported by a P-value that is greater than 20%, which is strong evidence in support of the null hypothesis. All of the treatment pairs at the other height resolutions test to be significantly different, with weak evidence in support of the null hypothesis.

The solutions from days one and three both have a similar range of values with the exception of the maximum observed values. While the shape of these distributions begins to differ after 11:00, they are very similar up to that point. The standard deviation shows that the heights in day three are spread out more than the heights in day one, but the similar means and the similarity in the shapes of the height distributions indicate that this was caused by a difference in extreme heights of day 3.

The results of this test indicate that a robin can alter the observed GPS height by at least a centimeter, even if sitting on the antenna for only a tenth minute period. The radome undoubtedly helped to improve the solution, because it required that the robin had to sit precisely at the top of the radome. This made it so that the robin would interfere most with observations from satellites closer to the zenith and would have allowed the signal from satellites closer to the horizon to be received unobstructed.

While it may not be possible to keep birds off the antennas all the time, it might be possible to mitigate their interference with the antennas by using a radome. A conical radome would make it especially hard for a bird to land on the antenna. It is
recommended that a radome be considered for use with antennas that will be used at permanent stations in order to deter birds from landing on the antenna and interfering with the observed height for applications requiring high accuracy GPS heights. The results of Figure 4.12 must also be taken into account, which show that a major height deviation occurred between days 1 and 3, shortly after the robin left the antenna. This makes it unlikely that the height deviation seen here is caused by the presence of the robin. The effects on GPS height caused by a small bird, such as a robin, sitting on a GPS antenna will range from the millimeter to centimeter level.

4.6 Experiment 6: Effects of a Simulated Seagull on GPS Heights

Three models of GPS antennas were used in the test: a LEIAS10, a TRM41249.00, and a TRM22020.00+GP. Data collection occurred in the Oval at The Ohio State University main campus, Columbus, Ohio. An overview of the test area is given in Figure 4.12, with the location of the TRM41249.00, TRM22020.00+GP, and LEIAS10 antennas marked by the green, cyan, and fuchsia icons, respectively.

Each of the data collection sessions with a Cornish hen on the antenna, used to simulate the mass of a seagull, had such a high amount of noise that the carrier phase data could not be processed in KinTools, and a static solution for these sessions could not be computed in OPUS. The KinTools software was written to return high accuracy solutions and the processing will abort if noisy data is used rather than compute a low accuracy solution, so the data processing was done using RTKLIB instead, which provides carrier phase float solution in case data is too noisy to produce fixed ambiguity
solution. Data processing was done using the default parameters listed in Appendix C for carrier phase processing using the COLB CORS as the reference station. RTKLIB was also used to process the open sessions for consistency between the test and control scenarios and to facilitate consistent results for later comparisons.

![Figure 4.13: Over view of the Oval at The Ohio State University where the data was collected for the three antennas used in the simulated seagull test. The green icon indicates the location of the TRM41249.00 antenna, the cyan point indicates the location of the TRM222202.00+GP antenna, both of which were used on 7/16/13, and the fuchsia icon marks the location of the LEI châu antenna used on 7/18/13.](image-url)
Two standard parametric sample statistics have been included in Table 4.28 to help quantify the height deviations per session per antenna. The statistics are grouped by antenna with the data from the simulated seagull sessions listed first.

Table 4.28: Parametric sample statistics generated for the simulated seagull observations on the OSU Oval using the mean of the kinematic solutions.

<table>
<thead>
<tr>
<th>Antenna Model #</th>
<th>Test Session</th>
<th>Abs Min (m)</th>
<th>Abs Max (m)</th>
<th>Mean (m)</th>
<th>Std Dev (m)</th>
<th>Peak-2-Peak (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TRM22020.00+GP</td>
<td>Simulated Seagull</td>
<td>193.527</td>
<td>193.820</td>
<td>193.645</td>
<td>0.048</td>
<td>0.192</td>
</tr>
<tr>
<td></td>
<td>Open</td>
<td>193.679</td>
<td>193.773</td>
<td>193.726</td>
<td>0.014</td>
<td>0.055</td>
</tr>
<tr>
<td>TRM41249.00</td>
<td>Simulated Seagull</td>
<td>193.166</td>
<td>193.643</td>
<td>193.439</td>
<td>0.087</td>
<td>0.346</td>
</tr>
<tr>
<td></td>
<td>Open</td>
<td>193.478</td>
<td>193.581</td>
<td>193.537</td>
<td>0.014</td>
<td>0.056</td>
</tr>
<tr>
<td>LEIAS10</td>
<td>Simulated Seagull</td>
<td>187.673</td>
<td>208.446</td>
<td>193.875</td>
<td>0.985</td>
<td>3.940</td>
</tr>
<tr>
<td></td>
<td>Open</td>
<td>193.621</td>
<td>193.793</td>
<td>193.710</td>
<td>0.025</td>
<td>0.101</td>
</tr>
</tbody>
</table>

The data in Table 4.28 shows that the repeatability of the absolute minimum and maximum values per antenna may deviate up to 20 cm for the open sessions. The mean values observed when the antennas were unobstructed deviate by up to 20 cm. This may seem like a large amount of height variation between the antennas, but it is consistent with the antenna configuration for the test. The antennas were all placed at different locations over flat terrain. The TRM22020.00+GP and LEIAS10 antennas were setup with approximately the same offset from the ground to the ARP, which had a 20 cm difference from the offset between the ground and the ARP for the TRM41249.00 antenna. This 20 cm difference in offset to the ARP is reflected in the mean heights in Table 4.28. The standard deviations and the peak-to-peak statistic for the TRM41249.00 and TRM22020.00+GP antennas are at a similar level and are consistent with the
standard deviation and peak-to-peak height range observed for these antennas in the open field used in experiment 2. The standard deviation and peak-to-peak height range for the LEIAS10 antenna indicate that it is receiving more noise than the other antennas in this environment, even when its measurements are not obstructed with a simulated seagull placed on the antenna to simulate a seagull.

The sessions with the simulated seagulls on the antennas show significantly more variation in heights. The absolute minimum and maximum change by up to 50 cm between the different antenna models and the mean deviates by up to 40 cm. The change in the means of the TRM22020.00+GP and LEIAS10 antennas, the two with the same offset from the ground to the ARP, was in the order of 1.5 cm when the antennas were unobstructed and change by about 20 cm when the antennas are obstructed by a simulated seagull. This indicates a significant impact caused by the presence of a mid-size bird on the antenna. The observed standard deviations and peak-to-peak height ranges for each antenna increase by at least of factor of 3, which indicates that there is a significantly greater amount of noise in the measurements with the simulated seagulls placed on the antennas.

All appearances of the data indicate that a significant change in heights is occurring as a result of the medium-sized sitting on the antennas. This was tested with a two-sided nonparametric Wilcoxon rank-sum hypothesis test as described in Sections 2.5.6 and 3.2.2. The results of the Wilcoxon rank-sum hypothesis test are provided in Table 4.29. An explanation of how to read the data contained in these tables can be found in Appendix E in the discussion of Wilcoxon rank sum hypothesis test results.
The Wilcoxon rank-sum hypothesis test considers two populations, a control and a treatment, and determines if the populations have a similar distribution up to shift in the distribution, called a location parameter. This test was separately used for all three antenna models in this experiment and used the unobstructed sessions as the control populations and the simulated seagull sessions as the treatment populations. This allowed for a comparison between the noise caused by the presence of the simulated seagulls on the antennas and the normal performance of the antenna models in the test environment. The null hypothesis of this hypothesis test is that the location parameter is equal to zero and the alternative hypothesis is that the location parameter is not equal to zero. In the context of this experiment, the distribution for each test refers to distribution of heights obtained from the kinematic solutions of the antennas. No change in the location parameter would mean that the height distributions for an antenna observed for the open and simulated seagull sessions are identical and overlap perfectly. A change in the location parameter would mean that the distributions are identical, but the distribution from the simulated seagull session is shifted to one side of the height distribution of the open session so that the two height distributions do not overlap.

The results of the Wilcoxon rank-sum test in Table 4.29 show that the simulated seagulls do cause a significant change in the GPS height for all the antennas. The P-value gives a probability of less than 0.02% of no change in heights between the populations, which is strong evidence for rejecting the null hypothesis in favor of the alternative hypothesis.
The logical follow-up question is then whether or not the antennas perform at a similar level with the simulated seagulls on them. This will be tested with a Kruskal-Wallis test using the populations from each antenna as separate treatments and testing the null hypothesis that each antenna performs consistently against the alternative hypothesis that there is a change in antenna performance. The Kruskal-Wallis test was also done for the populations constructed for the open antenna sessions, to test for a similar performance of the antennas when they are not obstructed. The results of the Kruskal-Wallis hypothesis test are displayed in Table 4.30. An explanation of how to read the data contained in these tables can be found in Appendix E in the discussion of the Kruskal-Wallis hypothesis test results.

<table>
<thead>
<tr>
<th>Height Resolution</th>
<th>Antenna Type</th>
<th>Sample Statistic</th>
<th>Error Rates and Thresholds</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>cm level</td>
<td>TRM22020.00+GP</td>
<td>-50.787</td>
<td>1.96 1.645 1.28</td>
<td>&lt;0.0002</td>
</tr>
<tr>
<td></td>
<td>TRM41249.00</td>
<td>-48.319</td>
<td>1.96 1.645 1.28</td>
<td>&lt;0.0002</td>
</tr>
<tr>
<td></td>
<td>LEIAS10</td>
<td>28.955</td>
<td>1.96 1.645 1.28</td>
<td>&lt;0.0002</td>
</tr>
<tr>
<td>dm level</td>
<td>TRM22020.00+GP</td>
<td>-40.334</td>
<td>1.96 1.645 1.28</td>
<td>&lt;0.0002</td>
</tr>
<tr>
<td></td>
<td>TRM41249.00</td>
<td>-40.394</td>
<td>1.96 1.645 1.28</td>
<td>&lt;0.0002</td>
</tr>
<tr>
<td></td>
<td>LEIAS10</td>
<td>23.992</td>
<td>1.96 1.645 1.28</td>
<td>&lt;0.0002</td>
</tr>
</tbody>
</table>

Table 4.29: Results of the Wilcoxon rank-sum hypothesis test for a shift in the distribution of GPS heights caused by a simulated seagull on a GPS antenna.
Table 4.30: Results of the Kruskal-Wallis test for a significant difference in the performance of three different GPS antennas for data collected when they were open and data collected with a simulated seagull sitting on top of the antennas.

<table>
<thead>
<tr>
<th>Height Resolution</th>
<th>Test Condition</th>
<th>Sample Statistics</th>
<th>Error Rates and Thresholds</th>
<th>P-va lle</th>
</tr>
</thead>
<tbody>
<tr>
<td>cm level</td>
<td>Open</td>
<td>7490</td>
<td>6</td>
<td>4.6</td>
</tr>
<tr>
<td>dm level</td>
<td>Open</td>
<td>3150</td>
<td>6</td>
<td>4.6</td>
</tr>
<tr>
<td>cm level</td>
<td>Simulated</td>
<td>1122</td>
<td>6</td>
<td>4.6</td>
</tr>
<tr>
<td>dm level</td>
<td>Seagull</td>
<td>1124</td>
<td>6</td>
<td>4.6</td>
</tr>
</tbody>
</table>

The results of the Kruskal-Wallis tests in Table 4.30 indicate that the antennas perform at a significantly different level for both of the height resolutions considered for the data collected under both test conditions. The P-value, which is consistently less than 0.1%, gives extremely weak evidence in support of the null hypothesis and justifies rejecting the null hypothesis in favor of the alternative hypothesis.

The logical follow up question to the conclusion obtained from the Kruskal-Wallis hypothesis test is to ask about the performance of the antennas with and without the simulated seagulls on them to determine which of the antennas perform at a similar level and which ones perform at a different level. A one-way layout MC test was constructed to answer this question using the height populations extracted for each of the antennas from the open and simulated seagull sessions. The test was carried out for all pairs of antennas with the null hypothesis that a given pair of antennas performed at a similar level against the alternative hypothesis that the performance of the pair of antennas was not equal. The results of the MC test are given in Table 4.31 for the open sessions and Table 4.32 for the simulated seagull sessions.
The results of the MC hypothesis test for the open sessions conclude that all three of the antenna models were performing at a significantly different level. This is supported by a P-value that is consistently less than 0.01%, which is extremely weak evidence in support of the null hypothesis and justifies concluding the alternative hypothesis. The results of the hypothesis test shows that even the TRM22020.00+GP and LEIAS10 antennas, the two that were setup with the same offset from the ground to the ARP and had very similar means and standard deviations, test to be performing significantly different.

The results of the MC hypothesis test for the simulated seagull sessions conclude that all three antenna models are performing at a significantly different height level. This is supported by a P-value that is consistently less than 0.01%, which offers extremely weak support for the null hypothesis and justifies concluding the alternative hypothesis.

The results of the simulation suggest that a seagull sitting on an antenna will affect the heights of different antennas to different degrees. The mean of the height variations computed from the open sessions shows a very similar level of performance for antennas with the same offset from the ground to the ARP. The mean height and the level of noise in the measurements differ significantly for the different antenna models tested, even if the antennas are at the same height above the ground. These observed height differences are significant at the centimeter level, making this a situation that must be addressed when high accuracy GPS-derived heights are needed. This would happen if a person used a CORS station as a reference where a seagull had been sitting on the antenna during the time of data collection. The results also indicate that while the

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seagulls add noise to a measurement, the noise for different pairs of antennas may increase by a relative amount and make it appear as if they were performing unobstructed. It is, therefore, recommended that data from a CORS or other GPS observation in a location where a seagull is sitting on the antenna is in question and should be post-processed in OPUS and compared to the published height of the mark or station before the CORS observations for that time period are used for post-processing.

Based on the sample statistics, it may be possible to determine if a seagull is sitting on an antenna by examining the magnitudes of the standard deviations of the epoch-to-epoch height deviations resulting from post-processing the data in kinematic mode. However, this will need to be verified by processing and plotting GPS-derived heights from a time when a seagull was observed on an antenna and from a time when the seagull was not observed on the antenna. If this analysis is successful, it will provide a way to confirm if a seagull was sitting on a CORS being used for post-processing and identify that a different CORS should be used.

Table 4.31: Results of the one-way layout multiple comparison test for the performance of three different GPS antennas when the antennas were unobstructed.

<table>
<thead>
<tr>
<th>Height Resolution</th>
<th>Antenna Pairs</th>
<th>Sample Statistic</th>
<th>Sample Statistic</th>
<th>Error Rates and Thresholds</th>
<th>P-values</th>
</tr>
</thead>
<tbody>
<tr>
<td>cm level</td>
<td>TRM22020.00+GP</td>
<td>101.9916</td>
<td>101.9916</td>
<td>3.314 2.902 2.424</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td></td>
<td>TRM41249.00</td>
<td>-8.4205</td>
<td>8.4205</td>
<td>3.314 2.902 2.424</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td></td>
<td>LEIAS10</td>
<td>-113.5038</td>
<td>113.5038</td>
<td>3.314 2.902 2.424</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>dm level</td>
<td>TRM22020.00+GP</td>
<td>50.6231</td>
<td>50.6231</td>
<td>3.314 2.902 2.424</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td></td>
<td>TRM41249.00</td>
<td>-6.1798</td>
<td>6.1798</td>
<td>3.314 2.902 2.424</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td></td>
<td>LEIAS10</td>
<td>-65.7480</td>
<td>65.7480</td>
<td>3.314 2.902 2.424</td>
<td>&lt;0.0001</td>
</tr>
</tbody>
</table>
Table 4.32: Results of the one-way layout multiple comparison hypothesis test for the performance of three different GPS antennas when the antennas were obstructed by a simulated seagull sitting on the antennas.

<table>
<thead>
<tr>
<th>Height Resolution</th>
<th>Antenna Pairs</th>
<th>Sample Statistic</th>
<th>Sample Statistic</th>
<th>Error Rates and Thresholds</th>
<th>P-values</th>
</tr>
</thead>
<tbody>
<tr>
<td>cm level</td>
<td>TRM22020.00+GP TRM41249.00</td>
<td>28.5382</td>
<td>28.5382</td>
<td>3.314 2.902 2.424</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td></td>
<td>TRM22020.00+GP LEIAS10</td>
<td>38.7731</td>
<td>38.7731</td>
<td>3.314 2.902 2.424</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td></td>
<td>TRM41249.00 LEIAS10</td>
<td>31.7051</td>
<td>31.7051</td>
<td>3.314 2.902 2.424</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>dm level</td>
<td>TRM22020.00+GP TRM41249.00</td>
<td>24.5420</td>
<td>24.5420</td>
<td>3.314 2.902 2.424</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td></td>
<td>TRM22020.00+GP LEIAS10</td>
<td>40.0548</td>
<td>40.0548</td>
<td>3.314 2.902 2.424</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td></td>
<td>TRM41249.00 LEIAS10</td>
<td>29.2472</td>
<td>29.2472</td>
<td>3.314 2.902 2.424</td>
<td>&lt;0.0001</td>
</tr>
</tbody>
</table>
Chapter 5 Conclusions and Recommendations

The primary goal of this research was to contribute to a better understanding of environmental impacts on GPS height estimation that supports the goals of the National Height Modernization project led by NGS. This was accomplished by focusing on station dependent error sources, which largely focused on near-field multipath and also included a test on antenna phase center variation parameters. The research was conducted in selected test environments and used selected antenna models, both of which were relevant to Ohio CORS. In addition, the experiments conducted only began to analyze the station dependent error sources considered and more experimentation is needed for more definitive conclusions and recommendations.

These components were carried out through the design of different case study experiments that would analyze the effects of multipath under different environments and weather conditions. The experiments designed for this testing were:

1. Effects of not Accounting for Radome Antenna Calibration Parameters on GPS Heights
2. Antenna Specific Variations in GPS Heights
3. GPS Height Variations Caused by High Voltage Power Lines
4. Multipath Reflection from a Snow-Covered Field
5. Effects of a small bird on the Height of a CORS Station
6. Effects of a Simulated Seagull on GPS Heights
The first experiment presented above used a TRM59800 antenna with a SCIS radome. Data was collected using different combinations of the antenna with and without the radome, as well as different combinations of the relative calibration parameters for the antenna with and without the radome. These tests were done to see how neglecting a radome and its specific PCVs affect the computed height of a point. The results of the different combinations showed that the heights deviated by up to 4 mm and the standard deviation of the heights deviated by up to 2 mm. Similarly, the range of elevations within two standard deviations of the mean changes by about 7 mm from the day with the most extreme heights observed under each of the test configurations. While the correct PCVs should be accounted for to obtain the most accurate heights, it was seen that the differences in GPS-derived height by neglecting the proper PCVs for a TRM59900.00 antenna and SCIS radome did not result in an error in height that was significant at the level of accuracy the National Height Modernization program is concerned with. These findings cannot readily be applied to any antenna and radome combination and more experimentation needs to be conducted to extend the analysis presented in this experiment to different antenna and radome combinations so that a more general assessment of the errors of neglecting radome specific PCVs can be made.

A more troublesome possibility is of ultraviolet radiation from the sun wearing the radome thinner in some surface areas than others that will eventually result in signals from satellites at certain elevations and directions encountering less delay from the radome than they should, resulting in an inaccurate position determination for those satellites. Additional experimentation needs to be carried out with different antennas.
using particular types of radomes that will compare the GPS-derived heights using a brand new model of that radome compared to a sufficiently weathered version of that radome.

The second experiment focused on the height deviations of a point caused by changing the antenna model over that point. This was tested for GPS antenna setups at different heights from the ground and it was found that the different antennas would receive a similar amount of noise and multipath reflection from the surrounding environment, but that the heights would change by 5 to 20 mm depending on the antenna models used and the heights of those antennas above the ground.

This experimentation can be built upon by including different antenna models and using larger baselines, which would allow for an assessment as to whether or not the change in GPS-derived heights was inherent to the test environment or the different antenna models tested. Additional experimentation will also need to be conducted when the antenna models on both ends of a baseline are changed, as well as how the GPS-derived height of a point changes due to changing the antenna model when processed in a network configuration as opposed to a single baseline.

Using different antenna types need to be considered in two separate cases: for a CORS station and when doing a repeat survey. Even if changing the height of an antenna at a CORS station results in a 5 mm height change, it will carry over to projects using the CORS data. For instance, the antenna on a CORS station being used may be changed between phases of a multiphase project. In this case, care would have to be taken with GPS heights, as the heights of GPS observations made between phases may need to be
accounted for, depending on the required accuracy of GPS heights. This may also have a noticeable impact on the GPS heights of points, such as those used to realize the International Great Lakes Datum (IGLD), which are resurveyed at certain intervals to update the datum and to track subsidence and uplift in the Great Lakes region. Some benchmarks are being repeatedly used with each update to the IGLD, but use different antenna models each time. In addition, the updates are far enough apart that the antennas used on CORS stations may be different. The heights of the antennas at the CORS are very stable and any movement between subsequent updates should be small enough to be considered negligible. By convention, the benchmarks are usually surveyed with the antenna reference point (ARP) at 2 m above the benchmark. The locations of the ARP can be regarded as stable in both cases. False variations of the heights of the CORS and benchmarks may then be determined, based on the types of antennas used. In an extreme example, if a new antenna on a given CORS causes its height to increase by a centimeter and the antenna model used at a benchmark results in its height decreasing by 2 cm (both relative to the true heights of the points), then there is a 3 cm height discrepancy between the points, all caused by the antenna type, that would exist if single baseline processing were used between that particular CORS and the benchmark.

From the third experiment it is seen that high voltage power lines overhead will affect the computed GPS height of a point. This was seen most clearly by comparing the range of heights in a two standard deviation range around the mean to how the antennas performed under the power lines compared to how they performed under better conditions in a more open environment. Here, it was seen that the range of heights varies
between the antenna models tested by up to 6 cm, which makes a critical difference if a
different antenna model is used in such an environment when high accuracy heights are
needed. Also, the amount of noise in the solutions, indicated by the standard deviations
and peak-to-peak statistics, for antenna types tested in an open field increased by up to 2
cm. While the noise may increase by a significant level, it still averaged out of the
solutions even for shorter periods of time.

Based on the results of this experiment for the given antenna types tested, it is
recommended that proximity to power lines should be avoided when possible. Long
static sessions should be used if it is not possible to avoid power lines, such as in an
agricultural field or along a forested rural highway where the only open areas have been
cleared for power lines to run through, so that the noise caused by the power lines will
average out of the solution. Further experimentation is needed to assess the dependency
of satellite geometry and the amount of interference received from the power lines. This
experimentation will need to track satellites as the approach elevation angle of the power
lines relative to the antennas. These satellites can selectively be excluded from the
solution to see if the quality of GPS-derived heights improves as observations satellites
with elevation angles near the power lines are not used. Such an experiment will be able
to determine if the quality of GPS-derived heights around power lines is dependent on
satellite geometry and if there is an optimal envelope of elevation angles around the
power lines to avoid observation angles from. If such an envelope is found, satellites
could be excluded from to improve the quality of heights as long as strong satellite
geometry can still be maintained.
The fourth experiment examined the repeatability of multipath in a snow-covered field with two GPS antennas for different depths of snow. From this scenario it was learned that gradual decreases in snow depth with respect to an existing snow depth do not have a significant impact on the observed height. It was confirmed for both antennas that a decrease in the existing snow depth up to 2.5 cm between successive days results in a similar pattern of multipath reflection and was noted to result in up to a 5 mm change in the height of a point. It was also observed that decreases in the existing snow depth of snow up to 7.5 cm resulted in an 8 mm change in the height of a point.

It was seen with the antenna models tested that it is possible to get reliable relative GPS heights with multipath reflection from the snow, but only for small changes in the surrounding snow depth and subject to the condition that it is a decrease in the existing amount of snow depth. It is recommended that observations in a snow-covered environment be taken with caution, as it is not known how the multipath reflection from the snow may alter the multipath reflection from the surrounding environment. It is possible that there is a relative height offset caused by the presence of snow. Further experimentation is needed to confirm the performance of different antenna models as a function of the change in surrounding snow depth. Additional analysis will also need to include how heights change when there is snow in an environment compared to when there is no snow in the environment, as well as how GPS-derived heights change with an increase in snow depth in addition to a decrease in snow depth.

In this experiment, snow depth was used as a parameter to analyze the effect of snow in the surrounding environment on GPS-derived heights. However, snow depth is
just one of many parameters to analyze how snow can affect the quality of GPS-derived heights. Assuming a constant snow depth, different amounts of multipath reflection will be observed based on whether the snow is loose, compacted, or if there is a surface layer of ice on the snow. In this experiment, the snow remained loosely packed for all GPS observations and additional research needs to be conducted under different snowfall conditions (compressed and ice covered) to see how other conditions affect GPS-derived heights at different snow depths.

The fifth experiment examined the effects on heights at a CORS antenna caused by a robin or similar size bird sitting on it. Only a small deviation in heights in the millimeter level was noticed to be caused by the robin, which is small enough to declare as insignificant for the accuracy standards of the National Height Modernization program. Furthermore, the robin was only sitting on the antenna for a short time and the effects quickly averaged out of the solution. Its minor impact on the GPS height was aided by a hemispherical SCIS radome, which forced the robin to sit towards at the very top, which still allowed unobstructed observations from satellites through the mid-elevation angles. Additional experimentation should be conducted with CORS antennas that do not have radomes to verify if the effects of a bird on GPS heights are dependent on the offset of the bird from the antenna.

The sixth experiment examined the effects of a seagull sitting on an antenna by simulating the seagulls with Cornish hens. Bigger-sized birds, such as seagulls, cause a more pronounced height variation. This scenario was proposed because seagulls had been observed to sit on CORS antennas along the Lake Erie shoreline for long periods of
time with an unknown effect on the GPS height. The results show that the change in the mean of the heights as well as the noise in the solution will change by a significant amount when a Cornish hen is placed on an antenna to simulate a seagull sitting on the antenna. The standard deviation of heights in the Cornish hen sessions at least doubled compared to when the open sessions. For all antenna models, the amplification of the noise in the Cornish hen sessions compared to the open sessions was by a factor of 3 at the minimum and by a factor of 6 at the maximum. However, this is a worst case estimate of how a seagull affects GPS heights. The experiment simulated a seagull using a Cornish hen that was sitting directly on the antenna. In reality, it is much more likely to assume that the seagull would remain standing, in which case there would be a greater separation between the seagull and the antenna. Therefore, it is expected that an antenna will be less impacted by an actual seagull on it and this experiment in fact gives an overestimation of the error caused by a seagull on an antenna.

The possibility of a seagull sitting on an antenna poses a particularly troublesome uncertainty when post-processing GPS observations with CORS data along the Lake Erie shoreline, as there is no way to know if a seagull was sitting on an antenna during the time of data collection being processed. The best available option for keeping seagulls from sitting on CORS antennas is to use a conical radome. Further experimentation needs to be conducted with data from a CORS that had a seagull sitting on it to analyze the effects of a seagull. If a seagull is determined to cause a noticeable effect on the GPS-derived height of an antenna, then it may be possible to identify the presence of a seagull using existing GPS processing tools. It may be possible to identify the presence
of a seagull on an antenna for long periods of time relative to the length of the observation session by processing the GPS data in OPUS. If a seagull is on an antenna for a significant portion of the observation period it is expected that the presence of the seagull on the antenna would cause a noticeable deviation of heights at least at the centimeter level, which would result in a height that does not compare well with the published height for that CORS. However, this will not be as discernible if the seagull is only on the CORS for a short time relative to the GPS observation session being used, as the height offsets will average out and not be visible in the static solution. The best way to detect the presence of a seagull is to post-process the data in kinematic mode and plot the resulting heights to identify noticeable periods where the noise in the solution increases, possibly due to a seagull sitting on the antenna.

**Lessons Learned and Recommendations**

1. Neglecting the antenna radome in the relative calibration parameters applied or using the radome calibration parameters when no radome is used had an effect on heights up to 4 mm for a TRM59900.00 and SCIS radome combination.

2. Neglecting a radome may not necessarily have a huge effect on heights, but this will vary depending on both antenna and radome used and must be accounted for when high accuracy heights are required.

3. Changing the antenna model used at a point was observed to change the GPS height by up to 2 cm for the tested antenna models when using relative antenna calibration parameters for GPS processing.
4. The magnitude of the change in height per antenna may depend somewhat on the height of the antenna above the ground.

5. The difference in the GPS height of a point caused by using different antenna models when relative antenna calibration parameters are used instead of the more accurate absolute antenna calibration parameters must be accounted for when repeat surveys of a point are done with different antennas or when the antenna on a CORS station is changed in order to ensure the highest accuracy observations.

6. Interference from power lines did not cause a constant effect on the quality of GPS measurements for the antenna models tested.

7. The difference in epoch-to-epoch due to the interference from power lines is significant and may have a pronounced impact on short, real-time kinematic positions.

8. A study of the dependency of satellite geometry with respect to the power lines may yield insightful analysis of how heights can be improved by excluding satellites close to the power lines.

9. Small decreases in the existing snow depth (up to 2.5 cm) result in similar multipath reflection.

10. Snow depth changes within these levels were observed to affect heights up to 5 mm.

11. More drastic decreases changes in the existing snow depth (up to 7.5 cm) were observed to affect heights up to 9 mm.
12. A bird of any size sitting on GPS antennas has an effect on heights. Birds of a size smaller than a robin cause no significant error on the GPS-derived height and can be ignored. However, larger birds, such as seagulls, will have a significant effect on GPS-derived heights.

13. Errors in position caused by the bird will average out given enough time, if the bird was sitting on the antenna for a short period of time and does not return.

14. The variance of the heights tripled in the best case among the different antennas tested during the time a simulated seagull was sitting on the antenna.

15. Radomes may prevent seagulls from sitting on antennas. Conical radomes should be considered for the CORS antennas along the Lake Erie shoreline, where there is a higher risk of seagulls sitting on the antennas.

An error budget listing the observed deviations in heights is given in Table 5.1 for each of the six experiments designed to test the effects of environmental multipath.

Table 5.1 shows the minimum, maximum and average changes per experiment for the mean height and the peak-to-peak range of heights. The height columns are based on the differences between the mean or static heights of the antennas in each experiment. The peak-to-peak columns contain the statistics about the change in heights observed within two standard deviations of the mean for all antennas from each experiment. Some of the experiments were subdivided, so that the error budgets would make more sense. A complete list of the experiments corresponding to each scenario number in Table 5.1 follows. Note that scenarios 6.1 and 6.2 used RTKLIB for the data processing, which
may result in a little software dependent bias when comparing the heights obtained in KinTools in the other experiments.

- Experiment 1: Effects of not accounting for radome antenna calibration parameters on GPS heights
- Experiment 2.1: Height variations caused by changing the antenna model used over the TSG control point with the antenna at ground level
- Experiment 2.2: Height variations caused by changing the antenna model used over the TSL control point with the antenna at 1 m above the ground
- Experiment 2.3: Height variations caused by changing the antenna model used over the TSH control point with the antenna at 2 m above the ground
- Experiment 2.4: Height variations caused by changing the antenna model used over the TST control point with the antenna at 2.5 m above the ground
- Experiment 3: GPS height variations caused by high voltage power lines
- Experiment 4: Multipath reflection from a snow covered field
- Experiment 5.1: Effects of a robin on the height of a CORS station with a one hour buffer period around the time the robin was observed on the antenna
- Experiment 5.2: Effects of a robin on the height of a CORS station with a ten minute buffer period around the time the robin was observed on the antenna
- Experiment 6.1: Performance of the selected antennas without a simulated seagull sitting on the antennas
- Experiment 6.2 Performance of the selected antennas with a simulated seagull sitting on the antennas
Table 5.1 The error budgets associated with each scenario listing observed changes in the mean or static antenna height, as well as the observed changes of heights within two standard deviations of the mean.

<table>
<thead>
<tr>
<th>Scenario #</th>
<th>Min Height Change (m)</th>
<th>Max Height Change (m)</th>
<th>Average Height Change (m)</th>
<th>Min Peak-2-Peak (m)</th>
<th>Max Peak-2-Peak (m)</th>
<th>Average Peak-2-Peak (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.000</td>
<td>0.012</td>
<td>0.004</td>
<td>0.045</td>
<td>0.053</td>
<td>0.049</td>
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<td>2.1</td>
<td>0.001</td>
<td>0.018</td>
<td>0.009</td>
<td>0.049</td>
<td>0.062</td>
<td>0.054</td>
</tr>
<tr>
<td>2.2</td>
<td>0.002</td>
<td>0.011</td>
<td>0.006</td>
<td>0.066</td>
<td>0.082</td>
<td>0.073</td>
</tr>
<tr>
<td>2.3</td>
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<td>0.012</td>
<td>0.006</td>
<td>0.065</td>
<td>0.101</td>
<td>0.078</td>
</tr>
<tr>
<td>2.4</td>
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<td>0.008</td>
<td>0.008</td>
<td>0.060</td>
<td>0.088</td>
<td>0.074</td>
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<td>0.042</td>
<td>0.070</td>
<td>0.083</td>
<td>0.078</td>
</tr>
<tr>
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</tr>
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<td>0.001</td>
<td>0.001</td>
<td>0.003</td>
<td>0.008</td>
<td>0.005</td>
</tr>
<tr>
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<td>0.001</td>
<td>0.009</td>
<td>0.006</td>
<td>0.007</td>
<td>0.022</td>
<td>0.015</td>
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<td>0.000</td>
<td>0.046</td>
<td>0.030</td>
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<td>6.2</td>
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<td>0.290</td>
<td>0.154</td>
<td>3.748</td>
<td>2.499</td>
</tr>
</tbody>
</table>
References


Appendix A: GPS Observation Metadata

This appendix contains tables listing specific details about the observations taken in each of the experiments conducted in this thesis. Each table will contain a title to identify the scenario that the data is from and will contain descriptive information about each observation, which shall include at a minimum, the date of the observation, the antenna type used, the observation start time, the observation stop time, the total observation time, and the frequency of GPS observations. The tables will contain additional fields as needed to identify specific additional circumstances unique to particular tests.

Table A.1: Summary of the GPS data collected and used in experiment 1: effects of not account for radome antenna calibration parameters on GPS heights. The antenna calibration and parameters used column gives the relative calibration parameters used. Antenna only is for just the TRM59900.00 antenna and the Antenna + Radome is for the TRM59900.00 antenna and the SCIS radome.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Date</th>
<th>Radome Used</th>
<th>Session Start Time</th>
<th>Session Stop Time</th>
<th>Session Duration</th>
<th>Data Sampling Rate</th>
<th>Antenna Calibration Parameters Used</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5/3/2013</td>
<td>SCIS</td>
<td>0:00:00</td>
<td>23:59:59</td>
<td>24 hours</td>
<td>1 second</td>
<td>Antenna + Radome</td>
</tr>
<tr>
<td></td>
<td>5/4/2013</td>
<td>SCIS</td>
<td>0:00:00</td>
<td>23:59:59</td>
<td>24 hours</td>
<td>1 second</td>
<td>Antenna + Radome</td>
</tr>
<tr>
<td></td>
<td>5/5/2013</td>
<td>SCIS</td>
<td>0:00:00</td>
<td>23:59:59</td>
<td>24 hours</td>
<td>1 second</td>
<td>Antenna + Radome</td>
</tr>
<tr>
<td>2</td>
<td>5/6/2013</td>
<td>NONE</td>
<td>0:00:00</td>
<td>23:59:59</td>
<td>24 hours</td>
<td>1 second</td>
<td>Antenna + Radome</td>
</tr>
<tr>
<td></td>
<td>5/7/2013</td>
<td>NONE</td>
<td>0:00:00</td>
<td>23:59:59</td>
<td>24 hours</td>
<td>1 second</td>
<td>Antenna + Radome</td>
</tr>
<tr>
<td></td>
<td>5/12/2013</td>
<td>NONE</td>
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<td>23:59:59</td>
<td>24 hours</td>
<td>1 second</td>
<td>Antenna + Radome</td>
</tr>
<tr>
<td>3</td>
<td>5/6/2013</td>
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<td>0:00:00</td>
<td>23:59:59</td>
<td>24 hours</td>
<td>1 second</td>
<td>Antenna Only</td>
</tr>
<tr>
<td></td>
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<td>NONE</td>
<td>0:00:00</td>
<td>23:59:59</td>
<td>24 hours</td>
<td>1 second</td>
<td>Antenna Only</td>
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<tr>
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<td>5/12/2013</td>
<td>NONE</td>
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<td>23:59:59</td>
<td>24 hours</td>
<td>1 second</td>
<td>Antenna Only</td>
</tr>
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</table>
Table A.2: Summary of the GPS data collected and used in experiment 2: antenna specific variations in GPS heights.

<table>
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<th>Control Point</th>
<th>Date</th>
<th>Antenna Model#</th>
<th>Session Start Time</th>
<th>Session Stop Time</th>
<th>Session Duration (hours)</th>
<th>Data Sampling Rate</th>
</tr>
</thead>
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<td>0.8949074</td>
<td>10.0056</td>
<td>1 second</td>
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<td>6/3/2013</td>
<td>TRM22020.00+GP</td>
<td>0.4668866</td>
<td>0.8882407</td>
<td>10.1125</td>
<td>1 second</td>
</tr>
<tr>
<td></td>
<td>6/5/2013</td>
<td>LEIAS10</td>
<td>0.4654977</td>
<td>0.8922222</td>
<td>10.2414</td>
<td>1 second</td>
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<tr>
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<td>6/17/2013</td>
<td>TRM41249.00</td>
<td>0.4627199</td>
<td>0.8866319</td>
<td>10.0186</td>
<td>1 second</td>
</tr>
<tr>
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<td>5/24/2013</td>
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<td>10.3642</td>
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</tr>
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<tr>
<td>TSH</td>
<td>5/28/2013</td>
<td>LEIAS10</td>
<td>0.4718056</td>
<td>0.8928356</td>
<td>10.1047</td>
<td>1 second</td>
</tr>
<tr>
<td></td>
<td>6/4/2013</td>
<td>NOV600</td>
<td>0.466875</td>
<td>0.8926273</td>
<td>10.2181</td>
<td>1 second</td>
</tr>
<tr>
<td></td>
<td>6/6/2013</td>
<td>TRM41249.00</td>
<td>0.4690162</td>
<td>0.8968171</td>
<td>10.2672</td>
<td>1 second</td>
</tr>
<tr>
<td></td>
<td>6/17/2013</td>
<td>TRM22020.00+GP</td>
<td>0.462419</td>
<td>0.8863079</td>
<td>10.1739</td>
<td>1 second</td>
</tr>
<tr>
<td>TST</td>
<td>5/28/2013</td>
<td>TRM41249.00</td>
<td>0.4718056</td>
<td>0.8928356</td>
<td>10.1047</td>
<td>1 second</td>
</tr>
<tr>
<td></td>
<td>6/26/2013</td>
<td>TRM22020.00+GP</td>
<td>0.4718056</td>
<td>0.8928356</td>
<td>10.1047</td>
<td>1 second</td>
</tr>
</tbody>
</table>

Table A.3: Summary of the GPS data collected for experiment 3: height variations caused by high voltage power lines.

<table>
<thead>
<tr>
<th>Date</th>
<th>Antenna</th>
<th>Radome</th>
<th>Session Start Time</th>
<th>Session Stop Time</th>
<th>Session Duration (hours)</th>
<th>Data Sampling Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>12/18/2012</td>
<td>NOV600</td>
<td>NONE</td>
<td>13:31:00</td>
<td>23:26:30</td>
<td>9.925</td>
<td>30 seconds</td>
</tr>
<tr>
<td>12/18/2012</td>
<td>TRM39105.00</td>
<td>NONE</td>
<td>13:26:30</td>
<td>23:27:00</td>
<td>10.0083</td>
<td>30 seconds</td>
</tr>
<tr>
<td>12/18/2012</td>
<td>TRM59900.00</td>
<td>SCIS</td>
<td>13:27:00</td>
<td>16:54:00</td>
<td>3.45</td>
<td>30 seconds</td>
</tr>
</tbody>
</table>
Table A.4: Summary of Data Collected for Experiment 4: Multipath Reflection in a Snow-Covered Field. The Snow Depth column lists the recorded snow depth on the ground that day to the nearest inch.

<table>
<thead>
<tr>
<th>Date</th>
<th>Antenna Model#</th>
<th>Snow Depth</th>
<th>Session Start Time</th>
<th>Session Stop Time</th>
<th>Session Duration (hours)</th>
<th>Data Sampling Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/2/2013</td>
<td>TRM41249.00</td>
<td>18.0</td>
<td>14:05:00</td>
<td>20:22:00</td>
<td>6.283</td>
<td>30 seconds</td>
</tr>
<tr>
<td>1/3/2013</td>
<td>TRM41249.00</td>
<td>15.0</td>
<td>13:42:00</td>
<td>19:16:00</td>
<td>5.567</td>
<td>30 seconds</td>
</tr>
<tr>
<td>1/6/2013</td>
<td>TRM39105.00</td>
<td>7.6</td>
<td>20:00:30</td>
<td>0:48:30</td>
<td>5.8</td>
<td>30 seconds</td>
</tr>
<tr>
<td>1/7/2013</td>
<td>TRM41249.00</td>
<td>10.0</td>
<td>13:11:30</td>
<td>23:24:00</td>
<td>10.2083</td>
<td>30 seconds</td>
</tr>
<tr>
<td>1/7/2013</td>
<td>TRM39105.00</td>
<td>7.5</td>
<td>20:22:00</td>
<td>1:20:30</td>
<td>5.975</td>
<td>30 seconds</td>
</tr>
</tbody>
</table>

Table A.5: Summary of GPS data collected for experiment 5: effects of a robin on the height of a CORS antenna. Scenario 1 uses a 1 hour buffer period before and after the robin was observed sitting on the antenna and scenario 2 uses a 5 minute buffer period.

<table>
<thead>
<tr>
<th>Session</th>
<th>Date</th>
<th>Antenna Model#</th>
<th>Radome</th>
<th>Session Start Time</th>
<th>Session Stop Time</th>
<th>Session Duration (hours)</th>
<th>Data Sampling Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6/26/2013</td>
<td>TRM59800.00</td>
<td>SCIS</td>
<td>9:30:01</td>
<td>12:08:00</td>
<td>2.6331</td>
<td>1 second</td>
</tr>
<tr>
<td>1</td>
<td>6/27/2013</td>
<td>TRM59800.00</td>
<td>SCIS</td>
<td>9:26:01</td>
<td>12:04:00</td>
<td>2.6331</td>
<td>1 second</td>
</tr>
<tr>
<td>1</td>
<td>6/28/2013</td>
<td>TRM59800.00</td>
<td>SCIS</td>
<td>9:22:01</td>
<td>12:00:00</td>
<td>2.6331</td>
<td>1 second</td>
</tr>
<tr>
<td>2</td>
<td>6/26/2013</td>
<td>TRM59800.00</td>
<td>SCIS</td>
<td>10:43:00</td>
<td>11:13:00</td>
<td>0.5</td>
<td>1 second</td>
</tr>
<tr>
<td>2</td>
<td>6/27/2013</td>
<td>TRM59800.00</td>
<td>SCIS</td>
<td>10:39:00</td>
<td>11:09:00</td>
<td>0.5</td>
<td>1 second</td>
</tr>
<tr>
<td>2</td>
<td>6/28/2013</td>
<td>TRM59800.00</td>
<td>SCIS</td>
<td>10:35:00</td>
<td>11:05:00</td>
<td>0.5</td>
<td>1 second</td>
</tr>
</tbody>
</table>
Table A.6: Summary of GPS data collected for experiment 6: effects of a simulated seagull on GPS heights. The test session column lists Cornish hen for the sessions where a Cornish hen was used on an antenna and open for sessions when the GPS measurements were unobstructed.

<table>
<thead>
<tr>
<th>Date</th>
<th>Antenna Model#</th>
<th>Test Session</th>
<th>Session Start Time</th>
<th>Session Stop Time</th>
<th>Session Duration (hours)</th>
<th>Data Sampling Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>7/16/2013</td>
<td>TRM41249.00</td>
<td>Seagull</td>
<td>15:30:00</td>
<td>16:00:00</td>
<td>0.5</td>
<td>1 second</td>
</tr>
<tr>
<td>7/16/2013</td>
<td>TRM41249.00</td>
<td>Open</td>
<td>13:50:00</td>
<td>14:50:00</td>
<td>1</td>
<td>1 second</td>
</tr>
<tr>
<td>7/16/2013</td>
<td>TRM22020-00+GP</td>
<td>Seagull</td>
<td>15:30:00</td>
<td>16:00:00</td>
<td>0.5</td>
<td>1 second</td>
</tr>
<tr>
<td>7/16/2013</td>
<td>TRM22020-00+GP</td>
<td>Open</td>
<td>13:50:00</td>
<td>14:50:00</td>
<td>1</td>
<td>1 second</td>
</tr>
<tr>
<td>7/18/2013</td>
<td>LEIAS10</td>
<td>Seagull</td>
<td>16:30:00</td>
<td>18:30:00</td>
<td>2</td>
<td>1 second</td>
</tr>
<tr>
<td>7/18/2013</td>
<td>LEIAS10</td>
<td>Open</td>
<td>13:10:00</td>
<td>15:25:00</td>
<td>2.25</td>
<td>1 second</td>
</tr>
</tbody>
</table>
Appendix B: KinTools Environment

This appendix will cover specific information about KinTools not provided in Section 2.6.3. In particular, it will show the GUI's used to obtain user input and provide recommended default settings to use. Afterwards, the various components of the main GUI will be described in terms of the information seen at run-time. Finally, a description will be provided on how to interpret the results. Whenever a GUI will be discussed, a screenshot of the GUI will precede the discussion.

Figure B.1: RINEX file information form used to get the file locations and additional user supplied information needed to process a kinematic solution in KinTools.
Figure B.1 presents the input form for the observation files. Notice that the fields for the RINEX navigation file (RINEX Nav File), antenna model file (Antenna Model File), and the reference and rover station observation files (Obs File) are pink, indicating that these are required fields, whereas the precise ephemeris field (Ephemeris File) is white, indicating that it is an option field. The antenna dropdown lists can be seen next to the observation file fields for the reference and rover antennas. The correct antenna models will need to be selected from these lists, if the correct models are not selected when the header of the RINEX files are read in. The Monument X, Y, and Z fields correspond to the Cartesian coordinates of the reference system for use in data processing. The values for the reference station should be checked and entered manually, if the correct ones are not read from the header of the RINEX file. By convention, the coordinates of the rover station are set to that of the reference station. There is also a field for the monument antenna reference point offset in height (Mon → ARP: H) that should contain the offset from the ground to the ARP. If a value of zero is entered, the heights will be taken with respect to the ARP. There is a dropdown list under the antenna dropdown list in both the rover and reference antenna field that contains the supported reference frames. Ensure that the correct reference frame is selected for the X, Y, and Z coordinates used for the reference and rover antennas and click OK to advance to the Processing Control form, shown in Figure B.2. All processing in KinTools used the IGS08 reference frame.
The elevation cutoff angle is used to omit observations from satellites whose
elevation above the horizon measured in degrees is lower than this value. The default
elevation angle for any GPS processing is typically 15°, which is the default used by
KinTools. A 15° elevation angle will be used as a default in GPS data processing.
However, there are times when the elevation angle is reduced to 12° to improve the
results. Decreasing the elevation angle cutoff will allow for satellites at lower elevation

angles to be seen, which will enable observations from more satellites to be used to compute the position. However, satellites closer to the horizon must travel through the troposphere and ionosphere for a longer period of time and may experience greater tropospheric and ionospheric delays.

By default, KinTools will process data using code observations. Code observations may be accurate up to 20 cm or less and are applicable to a wide variety of applications. Carrier Phase observations can be used in processing, if the user selects the Use Carrier Phase checkbox. Carrier Phase observations will typically yield results with accuracies between centimeters to millimeters under ideal circumstances and are selected here to achieve the highest obtainable positional accuracy. When the Use Carrier Phase checkbox is selected, the user will be able to select the type of frequency to process: L1, L2, or Ion-Free, which is a linear combination of L1 and L2. Ion-Free is the default selection for the carrier phase observable and was used in all carrier phase solutions with KinTools.

The Ion-Free combination is a linear combination of dual-frequency observations that eliminates the ionospheric effects. This linear combination is useful for removing the ionospheric effects over long baselines (greater than 10 km) where the double-differenced differential ionospheric becomes significant. The Ion-Free linear combination can be derived through applying two conditions to the ionospheric effects of both frequencies. The first condition is that the sum of the ionospheric effects on both frequencies multiplied by constants must be zero. The second condition is either that the sum of the constants is 1 or that one of the constants is set to 1.
\[ \alpha_1 \frac{\delta t_{11}^{kl}}{f_1^2} + \alpha_2 \frac{\delta t_{12}^{kl}}{f_2^2} = 0 \]  

where:

\( \alpha_1 \) and \( \alpha_2 \) are constants

\( \frac{\delta t_{11}^{kl}}{f_1^2} \) and \( \frac{\delta t_{12}^{kl}}{f_2^2} \) are the double-differenced ionospheric terms between receivers \( i \) and \( j \) and satellites \( k \) and \( l \) for the L1 and L2 frequencies, respectively.

By default, no tropospheric correction is applied. A tropospheric correction was not applied in any of the data processing done with KinTools per the advice of NGS [Mader, 2013a]. All of the baselines used are small enough so that the tropospheric corrections should be constant and that the ionospheric correction is the only atmospheric correction that needs to be solved for.

The \( \Delta \) Ion Delay parameter is used for the automatic detection and correction of cycle slips. This parameter represents the change in the apparent path length for the signal from a satellite as it travels through the ionosphere between consecutive epochs [Mader, 2013b]. If the magnitude of this change is greater than the Ion Delay, then KinTools will detect a cycle slip at this location and correct it. The default value of 0.3 cycles works well for most applications and was used for most of the data processing with KinTools in this research. However, there were some extremely short baselines where this parameter had to be changed to 0.2 cycles.

The \( \Delta \) Phase-Range parameters for both signal frequencies also serve as parameters for cycle slip detection. These parameters represent the difference in the computed distance between the satellite and the antenna using carrier phase and...
pseudorange observations for both frequencies. The values for each frequency are set to 10 m by default. Values of 10,000,000 m for both frequencies were recommended by Gerald Mader, the author of KinTools, for use with short baselines.

The User Select Reference Satellite section of this form is used to determine the reference satellites for the double difference. By default, KinTools will use the satellite with the greatest elevation angle as the reference with the double difference. The default for the reference satellite is used in all data processing with KinTools.

Figure B.3: Depiction of the sections of the KinTools GUI. These sections each display information pertinent to evaluating the quality of a solution.

The KinTools GUI provides the user with detailed information about the GPS processing and is shown in detail in Figure B.3. The RMS plot displays the observed-
modeled distances from the rover to each satellite used to compute the rover’s position at each epoch. Carrier phase observations are represented with a blue dot and code observations are represented with a green plus sign. This convention will also be used to represent code and phase observations in the Distance + Height, Satellites + RDOP (relative dilution of precision), and the groundtrack plot. The groundtrack plot shows the two-dimensional trajectory of the rover relative to its a priori coordinates. The SV Status section displays all satellites by their satellite identification number, lists the satellite’s elevation and degrees, and uses an up or down arrow to indicate if the satellite is rising or setting. Satellites in gray are currently not visible, satellites in blue have had their ambiguities set to integers and are used in carrier phase observations, satellites appearing in light blue have not yet had the appropriate integers set for carrier phase ambiguities and are excluded from phase observations, and satellites in green are used in pseudorange observations. The Skytrack plot shows the orbits of the satellites across the sky with respect to the rover’s position and uses the same color coding convention as the SV Status section. The Distance + Height section displays the distance of the rover from its a priori position and its height difference relative to the a priori position. The Satellites + RDOP section displays the current number of visible satellites, as well as the RDOP, an indication of the accuracy of the measurements obtained with the visible satellites. The progress bar and current data time sections are used to display progress with processing the solution. The runtime messages section displays information on when new satellites become visible and when integer ambiguities are set or lost for each satellite.
The displays on the GUI in Figure B.3 allow the user to visually inspect processing as it occurs. However, meaningful interpretation of the results comes from the plots accessed from the controls menu. The two most useful are the RMS plot and the ionospheric corrections plot. The RMS plot is the same as the one shown in the RMS section of the GUI and the ionospheric corrections plot displays the ΔIon Delay computed at each epoch per satellite. These plots can be jointly used for satellites with bad ambiguities and cycle slips that are too small to detect. The user will be able to look up the times at which these events occurred and obtain the satellite number from the ionospheric correction plot and edit the integers for the satellite experiencing the cycle slip. The user will be able to access the Edit Integers window from the controls menu and select the time interval for when the problem is occurring. The user then has the ability to exclude the computed integer and select the next best integer set, to omit the satellite from subsequent processing, or to delete the integer set so that KinTools must recompute the integer ambiguity for that satellite. Finally, the user will have the ability to customize the range of the integer edit to include the entire solution, from the start to the epoch where the problem occurred, or from the epoch where the problem occurred to the last observed epoch.
Appendix C: RTKLIB Processing Parameters

This appendix will discuss the default processing parameters that were used for data processing in RTKLIB by going through the different input menu tabs one at a time. Whenever a menu or menu tab is being discussed, a screenshot of it will be given for visual reference prior to describing the processing parameters used. Only menus where settings were changed from the defaults will be discussed here.

Figure C.1: The main GUI displayed in RTKLIB where input files are provided.
The main GUI for RTKLIB is displayed in Figure C.1. This GUI is where the file information will be entered. The RINEX observation files for the rover and reference antennas will be entered in the RINEX OBS: Rover and RINEX OBS: Base Station fields, respectively. If a navigation file and/or precise ephemeris file is being used, they are entered in the first and second fields of the RINEX *NAV/CLK, SP3, IONEX or SBS/EMS section, respectively. Finally, the user will need to provide an output directory and solution name in the last two fields.

The processing settings are obtained by clicking the Options button seen at the bottom of Figure C.1. This will bring up the Options menu shown in Figure C.2.

![Options Menu](image)

Figure C.2: Setting 1 tab of the RTKLIB Options menu.

For the data processing conducted with RTKLIB, the Positioning Mode was set to Kinematic to process the data with double-differenced carrier phase differential GPS.
observations. The Frequencies/Filter Type fields were set to L1+L2 and combined to use both frequencies and to run the solution forward and backward for improved accuracy. The Elevation Mask field was set to 15°, and the Ionosphere and Troposphere Correction fields were set to Broadcast and Saastamoninen, respectively. Since the precise ephemeris file was always used, the Satellite Ephemeris/Clock field was set to Precise.

In the Setting2 tab of the Options menu (Figure C.3), only the Integer Ambuity Res (GPS/GLO) field was changed. This field determines the strategy employed to resolve the integer ambiguities for carrier phase observations. Fix and Hold was selected from the dropdown box, which will solve for the integer ambiguities per satellite and continue to use these same integer ambiguities for the rest of the solution, unless a cycle
slip is detected, in which case a new integer ambiguity for the satellite with the cycle slip must be resolved.

The Output tab of the Options menu in RTKLIB is shown in Figure C.4. All of the settings in this menu will determine the format of data written to the output file of the GPS solution. In this menu the Solution Format field was changed to X/Y/Z-ECEF, where ECEF refers to Earth-Centered Earth-Fixed coordinates. This is a Cartesian coordinate system defined with the origin coinciding with the center of mass of the Earth. The z-axis coincides with the International Reference Pole, which is close to Earth’s rotation axis. The x-axis is aligned with 0° latitude and 0° longitude and the y-axis completes a right-hand coordinate system. The ECEF coordinates in the output solution will be in the IGS08 frame, because the input coordinates, discussed later, are in the
IGS08 frame. The Time Format field was changed to hh:mm:ss GPST, where GPST stands for GPS time, an atomic time scale used by the GPS satellites. Also, the Output Solution Status field was changed to Residuals, so that they can be viewed on a plot to interpret the quality of the solution.

![Image of RTKLIB Options menu](image)

Figure C.5: Files tab of the RTKLIB Options menu for processing parameters and solution output format.

The Files tab of the RTKLIB Options menu is shown in Figure C.5. The only setting changed in this menu was the inclusion of an IGS absolute antenna calibration file in the Satellite/Receiver Antenna PCV File ANTEX/NGS PCV field.
The Positions tab of the RTKLIB Options menu is shown in Figure C.6. This menu contains information about each of the antennas used, including position, antenna model number, and antenna offset. The antenna type for the rover and reference station had to be specified. The reference station used in all processing in RTKLIB will be the COLB CORS station. Therefore, the antenna model used for the reference station will remain constant for all processing. In addition, the base station input coordinates were supplied. These were selected to be X/Y/Z-ECEF (m) and the published IGS08 coordinates for COLB were input as the reference station's coordinates. No antenna offsets were provided, since the interest is in the height of the antenna reference point. Afterwards, the ECEF coordinates were converted into latitude, longitude, and height coordinates by applying the closed form Borkowki transformation [Borkowski, 1989] using the GRS80 ellipsoid parameters.
Appendix D: KinTools Processing Parameters per Observation

This appendix contains tables listing the processing parameters used to process each of the GPS observations used in this research in KinTools per experiment. All of the tables will contain the experiment number, the date of data collection, the antenna model number used, and the ephemeris file used, elevation cutoff angle, frequency, Δ Ion Delay, GPS Δ Phase-Range for L1, and GPS Δ Phase-Range for L2 parameters used. The Δ Ion Delay parameter is the change in the apparent path length for the signal from a satellite as it travels through the ionosphere between consecutive epochs. The Δ Phase-Range parameters for L1 and L2 represent the difference in the computed distance between the satellite and the antenna using carrier phase and pseudorange observations for both frequencies. The Δ Ion Delay and the Δ Phase-Range parameters will all be used in cycle slip detection. The tables for specific experiments may have additional columns in them to further specify the data being used. Some of the observations that extended into the next day had to be split into two sessions for processing. These instances are shown in the tables by a row beginning with cells filled gray and only containing information from the Ephemeris File field to the end of the table. In these cases, the relevant information about the experiment number, data, and antenna model number in these cases can be found in the row above, which contains the first session of these observations.
Table D.1: KinTools processing parameters used for the GPS observations collected for experiment 1.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Date</th>
<th>Antenna Model #</th>
<th>Antenna Calibration Parameters</th>
<th>Ephemeris File</th>
<th>Elevation Cutoff</th>
<th>Frequency</th>
<th>Δ Ion Delay</th>
<th>GPS Δ Phase Range L1</th>
<th>GPS Δ Phase Range L2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5/3/2013</td>
<td>TRM59900.00 SCIS</td>
<td>Antenna + Radome</td>
<td>Precise</td>
<td>15</td>
<td>Iono-Free</td>
<td>0.3</td>
<td>1000000</td>
<td>1000000</td>
</tr>
<tr>
<td></td>
<td>5/4/2013</td>
<td>TRM59900.00 SCIS</td>
<td>Antenna + Radome</td>
<td>Precise</td>
<td>15</td>
<td>Iono-Free</td>
<td>0.3</td>
<td>1000000</td>
<td>1000000</td>
</tr>
<tr>
<td></td>
<td>5/5/2013</td>
<td>TRM59900.00 SCIS</td>
<td>Antenna + Radome</td>
<td>Precise</td>
<td>15</td>
<td>Iono-Free</td>
<td>0.3</td>
<td>1000000</td>
<td>1000000</td>
</tr>
<tr>
<td>2</td>
<td>5/6/2013</td>
<td>TRM59900.00 SCIS</td>
<td>Antenna Only</td>
<td>Precise</td>
<td>15</td>
<td>Iono-Free</td>
<td>0.3</td>
<td>1000000</td>
<td>1000000</td>
</tr>
<tr>
<td></td>
<td>5/7/2013</td>
<td>TRM59900.00 SCIS</td>
<td>Antenna Only</td>
<td>Precise</td>
<td>15</td>
<td>Iono-Free</td>
<td>0.3</td>
<td>1000000</td>
<td>1000000</td>
</tr>
<tr>
<td></td>
<td>5/12/2013</td>
<td>TRM59900.00 SCIS</td>
<td>Antenna Only</td>
<td>Precise</td>
<td>15</td>
<td>Iono-Free</td>
<td>0.3</td>
<td>1000000</td>
<td>1000000</td>
</tr>
<tr>
<td>3</td>
<td>5/6/2013</td>
<td>TRM59900.00</td>
<td>Antenna Only</td>
<td>Precise</td>
<td>15</td>
<td>Iono-Free</td>
<td>0.3</td>
<td>1000000</td>
<td>1000000</td>
</tr>
<tr>
<td></td>
<td>5/7/2013</td>
<td>TRM59900.00</td>
<td>Antenna Only</td>
<td>Precise</td>
<td>15</td>
<td>Iono-Free</td>
<td>0.3</td>
<td>1000000</td>
<td>1000000</td>
</tr>
<tr>
<td></td>
<td>5/12/2013</td>
<td>TRM59900.00</td>
<td>Antenna Only</td>
<td>Precise</td>
<td>15</td>
<td>Iono-Free</td>
<td>0.3</td>
<td>1000000</td>
<td>1000000</td>
</tr>
</tbody>
</table>
Table D.2: KinTools processing parameters used for the GPS observations collected for experiment 2.

<table>
<thead>
<tr>
<th>Date</th>
<th>Control Point</th>
<th>Antenna Model #</th>
<th>Ephermeris File</th>
<th>Elevation Cutoff</th>
<th>Frequency</th>
<th>Δ Ion Delay</th>
<th>GPS Δ Phase Range L1</th>
<th>GPS Δ Phase Range L2</th>
</tr>
</thead>
<tbody>
<tr>
<td>5/24/2013</td>
<td>TSL</td>
<td>TRM22020.00+GP</td>
<td>Precise</td>
<td>15</td>
<td>Iono-Free</td>
<td>0.3</td>
<td>1000000</td>
<td>1000000</td>
</tr>
<tr>
<td>6/4/2013</td>
<td>TSL</td>
<td>LEIAS10</td>
<td>Precise</td>
<td>15</td>
<td>Iono-Free</td>
<td>0.3</td>
<td>1000000</td>
<td>1000000</td>
</tr>
<tr>
<td>6/5/2013</td>
<td>TSL</td>
<td>NOV600</td>
<td>Precise</td>
<td>15</td>
<td>Iono-Free</td>
<td>0.3</td>
<td>1000000</td>
<td>1000000</td>
</tr>
<tr>
<td>6/26/2013</td>
<td>TSL</td>
<td>TRM41249.00</td>
<td>Precise</td>
<td>15</td>
<td>Iono-Free</td>
<td>0.2</td>
<td>1000000</td>
<td>1000000</td>
</tr>
<tr>
<td>5/28/2013</td>
<td>TSH</td>
<td>LEIAS10</td>
<td>Precise</td>
<td>15</td>
<td>Iono-Free</td>
<td>0.3</td>
<td>1000000</td>
<td>1000000</td>
</tr>
<tr>
<td>6/4/2013</td>
<td>TSH</td>
<td>NOV600</td>
<td>Precise</td>
<td>15</td>
<td>Iono-Free</td>
<td>0.3</td>
<td>1000000</td>
<td>1000000</td>
</tr>
<tr>
<td>6/6/2013</td>
<td>TSH</td>
<td>TRM41249.00</td>
<td>Precise</td>
<td>15</td>
<td>Iono-Free</td>
<td>0.3</td>
<td>1000000</td>
<td>1000000</td>
</tr>
<tr>
<td>6/17/2013</td>
<td>TSH</td>
<td>TRM22020.00+GP</td>
<td>Precise</td>
<td>15</td>
<td>Iono-Free</td>
<td>0.3</td>
<td>1000000</td>
<td>1000000</td>
</tr>
<tr>
<td>5/23/2013</td>
<td>TSG</td>
<td>NOV600</td>
<td>Precise</td>
<td>15</td>
<td>Iono-Free</td>
<td>0.3</td>
<td>1000000</td>
<td>1000000</td>
</tr>
<tr>
<td>6/3/2013</td>
<td>TSG</td>
<td>TRM22020.00+GP</td>
<td>Precise</td>
<td>15</td>
<td>Iono-Free</td>
<td>0.3</td>
<td>1000000</td>
<td>1000000</td>
</tr>
<tr>
<td>6/5/2013</td>
<td>TSG</td>
<td>LEIAS10</td>
<td>Precise</td>
<td>15</td>
<td>Iono-Free</td>
<td>0.3</td>
<td>1000000</td>
<td>1000000</td>
</tr>
<tr>
<td>6/17/2013</td>
<td>TSG</td>
<td>TRM41249.00</td>
<td>Precise</td>
<td>15</td>
<td>Iono-Free</td>
<td>0.3</td>
<td>1000000</td>
<td>1000000</td>
</tr>
<tr>
<td>5/28/2013</td>
<td>Test Pole</td>
<td>TRM41249.00</td>
<td>Precise</td>
<td>15</td>
<td>Iono-Free</td>
<td>0.3</td>
<td>1000000</td>
<td>1000000</td>
</tr>
<tr>
<td>6/26/2013</td>
<td>Test Pole</td>
<td>TRM22020.00+GP</td>
<td>Precise</td>
<td>15</td>
<td>Iono-Free</td>
<td>0.3</td>
<td>1000000</td>
<td>1000000</td>
</tr>
</tbody>
</table>
Table D.3: KinTools processing parameters used for the GPS observations collected for experiment 3.

<table>
<thead>
<tr>
<th>Date</th>
<th>Antenna Model #</th>
<th>Ephemeris File</th>
<th>Elevation Cutoff</th>
<th>Frequency</th>
<th>Δ Ion Delay</th>
<th>GPS Δ Phase Range L1</th>
<th>GPS Δ Phase Range L2</th>
</tr>
</thead>
<tbody>
<tr>
<td>12/18/2012</td>
<td>NOV600</td>
<td>Precise</td>
<td>15</td>
<td>Iono-Free</td>
<td>0.3</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>12/18/2012</td>
<td>TRM39105.00</td>
<td>Precise</td>
<td>15</td>
<td>Iono-Free</td>
<td>0.3</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>12/18/2012</td>
<td>TRM59900.00 SCIS</td>
<td>Precise</td>
<td>15</td>
<td>Iono-Free</td>
<td>0.3</td>
<td>10</td>
<td>10</td>
</tr>
</tbody>
</table>

Table D.4: KinTools processing parameters used for the GPS observations collected for experiment 4.

<table>
<thead>
<tr>
<th>Date</th>
<th>Antenna Model #</th>
<th>Ephemeris File</th>
<th>Elevation Cutoff</th>
<th>Frequency</th>
<th>Δ Ion Delay</th>
<th>GPS Δ Phase Range L1</th>
<th>GPS Δ Phase Range L2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/3/2013</td>
<td>TRM41249.00</td>
<td>Precise</td>
<td>15</td>
<td>Iono-Free</td>
<td>0.3</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>1/6/2013</td>
<td>TRM39105.00</td>
<td>Precise</td>
<td>17</td>
<td>Iono-Free</td>
<td>0.3</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>1/7/2013</td>
<td>TRM41249.00</td>
<td>Precise</td>
<td>17</td>
<td>Iono-Free</td>
<td>0.3</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>1/7/2013</td>
<td>TRM39105.00</td>
<td>Precise</td>
<td>15</td>
<td>Iono-Free</td>
<td>0.3</td>
<td>10</td>
<td>10</td>
</tr>
</tbody>
</table>
Table D.5: KinTools processing parameters used for GPS observations collected in experiment 5 for the long session of the robin sitting on the COLB CORS antenna.

<table>
<thead>
<tr>
<th>Date</th>
<th>Antenna Model #</th>
<th>Ephemeris File</th>
<th>Elevation Cutoff</th>
<th>Frequency</th>
<th>Δ Ion Delay</th>
<th>GPS Δ Phase Range L1</th>
<th>GPS Δ Phase Range L2</th>
</tr>
</thead>
<tbody>
<tr>
<td>6/26/2013</td>
<td>TRM59800.00 SCIS</td>
<td>Precise</td>
<td>15</td>
<td>Iono-Free</td>
<td>0.2</td>
<td>1000000</td>
<td>1000000</td>
</tr>
<tr>
<td>6/27/2013</td>
<td>TRM59800.00 SCIS</td>
<td>Precise</td>
<td>15</td>
<td>Iono-Free</td>
<td>0.2</td>
<td>1000000</td>
<td>1000000</td>
</tr>
<tr>
<td>6/28/2013</td>
<td>TRM59800.00 SCIS</td>
<td>Precise</td>
<td>15</td>
<td>Iono-Free</td>
<td>0.2</td>
<td>1000000</td>
<td>1000000</td>
</tr>
</tbody>
</table>

Table D.6: KinTools processing parameters used for GPS observations collected in experiment 5 for the short session of the robin sitting on the COLB CORS antenna.

<table>
<thead>
<tr>
<th>Experiment #</th>
<th>Date</th>
<th>Antenna Model #</th>
<th>Ephemeris File</th>
<th>Elevation Cutoff</th>
<th>Frequency</th>
<th>Δ Ion Delay</th>
<th>GPS Δ Phase Range L1</th>
<th>GPS Δ Phase Range L2</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.1.2</td>
<td>6/26/2013</td>
<td>TRM59800.00 SCIS</td>
<td>Precise</td>
<td>15</td>
<td>Iono-Free</td>
<td>0.2</td>
<td>1000000</td>
<td>1000000</td>
</tr>
<tr>
<td>7.1.2</td>
<td>6/27/2013</td>
<td>TRM59800.00 SCIS</td>
<td>Precise</td>
<td>15</td>
<td>Iono-Free</td>
<td>0.2</td>
<td>1000000</td>
<td>1000000</td>
</tr>
<tr>
<td>7.1.2</td>
<td>6/28/2013</td>
<td>TRM59800.00 SCIS</td>
<td>Precise</td>
<td>15</td>
<td>Iono-Free</td>
<td>0.2</td>
<td>1000000</td>
<td>1000000</td>
</tr>
</tbody>
</table>
Appendix E: Reading the Tables of Nonparametric Hypothesis Test Results

This appendix will describe how to interpret the tables with the results of each of the nonparametric hypothesis tests described in Section 3.1.2. The order of the tables presented will be the sign test, the Wilcoxon rank-sum test, the Kruskal-Wallis test, and the one-way layout multiple comparisons test. The following assumptions can be made about the data contained in these tables unless, stated otherwise in the analysis of the scenario:

- The sample statistics will be computed using the large sample approximation methods
- If a small sample procedure is used, it will be interpreted in the same way as the large sample approximation methods in this chapter
- It should also be assumed that all hypothesis tests are using a two-sided test unless noted otherwise.
- The error rates selected for every hypothesis test will always be 5%, 10%, and 20%.
- By convention, the P-values will always be rounded up if an exact P-value is not found in the appropriate table.
Table E.1: Example of a table with results from a nonparametric sign test hypothesis test.

<table>
<thead>
<tr>
<th>Height Resolution</th>
<th>Samples</th>
<th>Sampl Statistic</th>
<th>Error Rates and Thresholds</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>mm level</td>
<td>276</td>
<td>4.4543</td>
<td>-1.96 1.96 -1.645 1.645 -1.28 1.28</td>
<td>&lt;0.0002</td>
</tr>
<tr>
<td>cm level</td>
<td>131</td>
<td>5.3296</td>
<td>-1.96 1.96 -1.645 1.645 -1.28 1.28</td>
<td>&lt;0.0002</td>
</tr>
</tbody>
</table>

Table E.1 provides a sample of a typical table with results from the nonparametric sign test hypothesis test. The data tested in this test comes from paired replicates data, in which there is a single population observed under two conditions: a pre-treatment and a post-treatment. The post-treatment condition will always be the population (GPS-derived heights) was observed under the station dependent error source being tested. The pre-treatment will be a control case, in which the population (GPS-derived heights) was observed under normal station conditions, without the presence of the station dependent error source being tested. The null hypothesis is that the difference between the pre-treatment and post-treatment has no effect on the median of the distribution. The alternative hypothesis is that the difference between the pre-treatments and the post-treatment has an effect on the mean of the distribution in one direction.

The left side of the table will always begin with the height resolution level the data is being tested at. A millimeter level means the minimum height precision being tested is in the millimeter range and a centimeter level means the minimum height precision being tested has been rounded to the centimeter range. The next column will contain the number of samples used to compute the sample statistic. Since tying samples are discarded from the computation of the sample statistic (Section 3.3.1), this field will give information about how similar corresponding samples are from different populations.
and the number of paired measurements used in the test. The next field in the table lists the sample statistic computed for each of the populations.

The next section of the table consists of error rates and thresholds. Since this test is always using a two-tailed test, the lower and upper thresholds are listed. If the sample statistic is greater than the lower threshold and less than the upper threshold for a particular error rate, the null hypothesis is accepted for that error rate and the cell is filled green to indicate this decision. Otherwise, the null hypothesis is rejected in favor of the alternative hypothesis and the cell is filled red to indicate this. The final column will list the P-value, the probability of observing an equally extreme or more extreme value if the null hypothesis were true. The P-value can therefore be used as a way to verify the decision reached regarding the null hypothesis, because the greater the P-value, the greater the evidence in support of the null hypothesis.

Table E.2: Example of a table with results from a nonparametric Wilcoxon rank sum hypothesis test.

<table>
<thead>
<tr>
<th>Height Resolution</th>
<th>Antenna Type</th>
<th>Sample Statistic</th>
<th>Error Rates and Thresholds</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>5%</td>
<td>10%</td>
</tr>
<tr>
<td>TRM41249.00</td>
<td>5.3549237</td>
<td>1.96</td>
<td>1.645</td>
<td>1.28</td>
</tr>
<tr>
<td>TRM22020.00+GP</td>
<td>-6.504813</td>
<td>1.96</td>
<td>1.645</td>
<td>1.28</td>
</tr>
<tr>
<td>LEIAS10</td>
<td>6.9282032</td>
<td>1.96</td>
<td>1.645</td>
<td>1.28</td>
</tr>
</tbody>
</table>

Table E.2 provides a sample of a typical table with results from the nonparametric Wilcoxon rank sum hypothesis test. The null hypothesis is that the control and treatment
populations have the same distribution, but are offset by a location parameter (scalar shift) whose value is equal to zero and the alternative hypothesis is that the value of this location parameter is not equal to zero. When used, the title at the top of the table will describe what the test is being used for. The leftmost column of the table will contain two different height resolution levels at which the data is being tested: the millimeter level and the centimeter level. A height resolution in the millimeter level means the minimum precision of the heights used in the test is in the millimeter range and the centimeter level resolution means the minimum precision of the heights used in the test have been rounded to centimeters. The next field will contain the antenna type used for each of the tests in the table.

The next section contains the error rates at 5%, 10%, and 20% and the threshold for each of the error rates. Since a two-tailed test was used here, only the upper tail is needed to decide if the two populations are significantly different at an error rate. If the absolute value of the sample statistic of an antenna at a particular height resolution is less than the upper-tail threshold of a particular error rate, the null hypothesis is accepted at that error rate and the cell is colored green to indicate this decision. Otherwise, the null hypothesis is rejected in favor of the alternative hypothesis and the cell will be filled red to indicate this decision.

The final column contains the P-value computed for the sample statistics for each of the antenna types being tested at each of the height resolutions. The P-value is the probability of observing an equally extreme or more extreme value, if the null hypothesis were true. The P-values of each of the sample statistics serves as an indicator to accuracy
of the decision to accept or reject the null hypothesis, because the greater the P-value the stronger the evidence for concluding the null hypothesis.

Table E.3: Example of a table with results from a nonparametric Kruskal-Wallis hypothesis test.

<table>
<thead>
<tr>
<th>Antenna Model#</th>
<th>Height Resolution</th>
<th>Sample Statistic</th>
<th>Error Rates and Thresholds</th>
<th>P-values</th>
</tr>
</thead>
<tbody>
<tr>
<td>TRM41249.00</td>
<td>mm level</td>
<td>23.8901</td>
<td>6</td>
<td>4.6</td>
</tr>
<tr>
<td></td>
<td>cm level</td>
<td>25.8228</td>
<td>6</td>
<td>4.6</td>
</tr>
<tr>
<td>TRM39105.00</td>
<td>mm level</td>
<td>0.6362</td>
<td>3.9</td>
<td>2.7</td>
</tr>
<tr>
<td></td>
<td>cm level</td>
<td>0.1277</td>
<td>3.9</td>
<td>2.7</td>
</tr>
</tbody>
</table>

Table E.3 provides a sample of a typical table with results from the nonparametric Kruskal-Wallis hypothesis test. There is no control used in this hypothesis test. Instead, each treatment is evaluated with respect to the other treatments. The null hypothesis in this test is that all treatments have an equal effect and the alternative hypothesis is that not all of the treatments have an equal treatment effect. The field(s) on the left side will display data about the antenna, conditions, etc. being tested. This test will also be carried out at two distinct height resolutions: 1 mm and 1 cm. A height resolution in the millimeter level means the minimum precision of the heights used in the test is in the millimeter range and the centimeter level resolution means the minimum precision of the heights used in the test have been rounded to centimeters. The sample statistic column lists the computed sample statistic per antenna per height resolution.

The next section of the table lists the error rates chosen for testing and the associated thresholds. If a sample statistic is less than the threshold of a particular error rate, the P-value is less than the chosen error rate.
rate, the null hypothesis is accepted and the threshold cell for that error rate is filled green to indicate this decision. Otherwise, the cell is filled red to indicate that the null hypothesis was rejected in favor of the alternative hypothesis. The last column contains the P-value of each sample statistic. The P-value is the probability of observing an equally extreme or more extreme event, if the null hypothesis were true. As such, a larger P-value indicates stronger support for accepting the null hypothesis than a smaller P-value.

Table E.4: Example of a table with results from a nonparametric one-way layout multiple comparisons hypothesis test.

<table>
<thead>
<tr>
<th>Height Resolution</th>
<th>Days</th>
<th>Sample Statistic</th>
<th></th>
<th>Sample Statistic</th>
<th>Error Rates</th>
<th>P-values</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Error Rates</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>5%</td>
<td>10%</td>
<td>20%</td>
<td></td>
</tr>
<tr>
<td>mm level</td>
<td>1</td>
<td>2</td>
<td>-1.4697</td>
<td>1.4697</td>
<td>3.314</td>
<td>2.902</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>3</td>
<td>5.8788</td>
<td>5.8788</td>
<td>3.314</td>
<td>2.902</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>3</td>
<td>5.8788</td>
<td>5.8788</td>
<td>3.314</td>
<td>2.902</td>
</tr>
<tr>
<td>cm level</td>
<td>1</td>
<td>2</td>
<td>-1.2247</td>
<td>1.2247</td>
<td>3.314</td>
<td>2.902</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>3</td>
<td>5.8788</td>
<td>5.8788</td>
<td>3.314</td>
<td>2.902</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>3</td>
<td>5.8788</td>
<td>5.8788</td>
<td>3.314</td>
<td>2.902</td>
</tr>
</tbody>
</table>

Table E.4 provides a sample of a typical table with results from the nonparametric one-way layout multiple comparisons hypothesis test. The null hypothesis in this test is that a given pair of treatments has an equal effect and the alternative hypothesis is that the given pair of treatments does not have an equivalent effect. This test is repeated for all pairs of treatments. This hypothesis test does not compare the performance of the different treatments to a control population. Instead, it compares the relative performance of each treatment on a pairwise basis.
The leftmost fields will always contain both of the height resolutions the data is being tested at: the millimeter level and the centimeter level. A height resolution in the millimeter level means the minimum precision of the heights used in the test is in the millimeter range and the centimeter level resolution means the minimum precision of the heights used in the test have been rounded to centimeters. The next set of columns will define the pairs of treatments being tested. This might be different days of data collection or it might be data collected with different pairs of antennas. All possible pairs are considered at each height resolution. Additional columns may exist in this part of the table, if more information is needed to specify the data the test is being conducted for.

The sample statistic column lists the computed sample statistic per treatment pair per height resolution and the next column lists the absolute value of the sample statistic.

The next section of the table lists the error rates chosen for testing and the associated thresholds. If the absolute value of a sample statistic is less than the threshold of a particular error rate, the null hypothesis is accepted and the threshold cell for that error rate is filled green to indicate the decision. Otherwise, the cell is filled red to indicate that the null hypothesis was rejected in favor of the alternative hypothesis. The error rate in these tests is in actuality replaced by the experiment wise error rate (EER), which is the probability of falsely concluding the null or alternative hypothesis for at least one of the treatment pairs. The last column contains the analogue of the P-value of each sample statistic for the multiple comparisons test. The analogue of the P-value corresponds to the smallest EER at which the treatment pairs are significantly different.
The magnitudes of the treatment effects can also be ordered from least to greatest. In this context, the magnitudes of the treatment effect refer to the amount of variation about the mean height for a given treatment. The relative ordering of the treatment effects will therefore rank the treatments from the one with the least amount of height variation about the mean to the one with the greatest amount of height variation about a mean. This is done by using the sample statistics computed for all pairs of treatments at a given height resolution. If the sample statistic is less than zero, the second treatment in the second treatment of a particular treatment pair has a smaller treatment effect than the first treatment of that treatment pair. Otherwise the first treatment of the treatment pair has a smaller treatment effect than the second treatment of the treatment pair. Applying this analysis to all treatment pairs will allow the individual treatments to be ranked relatively with respect to each other.
Appendix F: Additional Plots of the Epoch-to-Epoch Height Deviations per Antenna per Scenario

Figure F.1: Epoch-to-Epoch height variations of the data collected from all 3 days of experiment 1 using the TRM59000.00 and SCIS radome and processing the data with radome PCV calibration parameters.
Figure F.2: Epoch-to-Epoch height variations of the data collected from all 3 days of experiment 1 using the TRM59900.00 without the SCIS radome and processing the data with radome PCV calibration parameters.
Figure F.3: Epoch-to-Epoch height variations of the data collected from all 3 days of experiment 1 using the TRM59900.00 without the SCIS radome and processing the data with PCV calibration parameters for the antenna only.
Figure F.4: Plots of epoch-to-epoch height deviations for the antennas used at the TSG control point in experiment 2 plotted at 30 second interval. From top to bottom: NOV600, TRM22020.00+GP, LEIAS10, and TRM41249.00 antennas.
Figure F.5: Plots of epoch-to-epoch height deviations for the antennas used at the TSL control point in experiment 2 plotted at 30 second interval. From top to bottom: TRM22020.00+GP, LEIAS10, NOV600, and TRM41249.00 antennas.
Figure F.6: Plots of epoch-to-epoch height deviations for the antennas used at the TSH control point in experiment 2 plotted at 30 second interval. From top to bottom: LEIAS10, NOV600, TRM41249.00, and TRM22020.00+GP antennas.
Figure F.7: Plots of epoch-to-epoch height deviations for the antennas used at the TST control point in experiment 2 plotted at 30 second interval. From top to bottom: TRM41249.00 and TRM22020.00+GP antennas.