A COMPARISON OF LOCAL AND WIDE AREA GNSS DIFFERENTIAL CORRECTIONS DISSEMINATED USING THE NETWORK TRANSPORT OF RTCM VIA INTERNET PROTOCOL (NTRIP)

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PREFACE

This technical report is a reproduction of an undergraduate senior technical report submitted in partial fulfillment of the requirements for the degree of Bachelor in Science in Engineering in the Department of Geodesy and Geomatics Engineering, April 2007. The research was supervised by Dr. Richard Langley and was supported by Cansel Survey Equipment Inc. and Bundesamt für Kartographie und Geodäsie (BKG)

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Abstract

Psuedorange corrections (PRCs) have long been used to improve the accuracy of GNSS solutions in real time. Today, they continue to be useful for sub-metre level requirements, such as when setting ground control for satellite imagery and for en route navigation on land, in the air and at sea. The transmission of these corrections has traditionally been facilitated using either radio or satellite communications. The Networked Transport of RTCM via Internet Protocol (NTRIP) specification takes advantage of the availability of Internet over digital mobile phones to disseminate PRCs.

In this report, NTRIP has been used to transmit both localized wide area and local PRC corrections over the Internet to a client receiver where they have been applied. The accuracy of different solutions is compared. In addition, the convergence of different solutions is analyzed. This analysis will enable potential users to determine the position and height accuracy that they can expect to achieve under various scenarios as well as the observation times which they should employ.

Results for horizontal positions showed errors at a 95% confidence level to be at the 2-metre level for uncorrected GNSS, 30 cm for GNSS augmented with local corrections generated at UNB and 1.0 m for corrections generated 430 km away. The Canadawide Differential GPS (CDGPS) wide area system produced errors of 60 cm.

Results for heights were of a similar order. However, we found that height solutions were significantly more correlated with observation time than were horizontal positions.

Our work showed that NTRIP could be used easily to both disseminate and use localized wide area and local differential corrections. We believe that as costs for digital mobile service becomes cheaper and more widely available, NTRIP will become commonly used.

In addition, we recommend that the CDGPS service consider supporting NTRIP. Currently, CDGPS has a limited user-base because it is accessible only with the use of receivers containing NovAtel®-based chipsets. We believe that NTRIP can potentially bring CDGPS to a much wider object.

Finally, by far, the best position and height accuracies achieved were with the use of local differential corrections. Even when the reference receiver was 430 km from the user receiver, resulting solutions were better in both accuracy and precision than uncorrected solutions. Canada and New Brunswick each operate an Active Control Network, consisting of many continuously operating GNSS receivers that are already connected to the Internet. We believe that with very little effort, this network can be extended, using NTRIP, to disseminate DGNSS corrections.

Acknowledgements

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Mike provided help from the initial conception of this project. Through CanSel® he provided equipment and software including a Trimble® NetR5 reference station, a Trimble® GeoXT mapping-grade GPS receiver, a GSM mobile phone with service and software to interface with the GeoXT. Mike also configured the equipment for me, showed me how to use it and answered many questions.

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Mr. Waese, in association with George Weber and Denise Dettmering, provided us with mountpoints on the BKG NTRIP caster. Without this help, I would likely have been unable to carry out the CDGPS portion of this work.

Rodrigo Leandro, PhD student, Department of Geodesy and Geomatics, UNB, Fredericton

Rodrigo configured and maintained the Trimble® NetR5 receiver at UNB. He also provided the “known” coordinates for our antenna.

Sandi McKessock

Sandi proofread the draft of this report. Any remaining errors are my own.

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Table of Abbreviations

ACN	Active Control Network
BKG	Bundesamt für Kartographie und Geodäsie (The German Federal Agency of Cartography and Geodesy)
CDGPS	Canada-wide Differential GPS
CSRS	Canadian Spatial Reference System
DGNSS	Differential Global Navigation Satellite System
DGPS	Differential Global Positioning System
€	Currency of the European Union (the “Euro”)
EGNOS	European Geostationary Navigation Overlay Service
FAA	Federal Aviation Administration
GEO	Geostationary Satellite
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GPS*C	The approach used by CDGPS to compute differential corrections.
GSM	Global System for Mobile Communications
HTTP	Hypertext Transfer Protocol
IP	Internet Protocol
ITRF	International Terrestrial Reference Frame
MRTCA	A modified version of RTCA/DO-229 protocol used by CDGPS to encapsulate vector differential corrections
NABU	Notice Advisory to Broadcast Users
NAD83	North American Datum of 1983
NMEA	National Marine Electronics Association
NRCan	Natural Resources Canada
NTRIP	Networked Transport of RTCM via Internet Protocol
PPP	Precise Point Positioning
PRC	Pseudorange Correction
RINEX	Receiver Independent Exchange Format
RRC	Range-Rate Correction
RTCM	Radio Technical Commission For Maritime Services
RTK	Real-Time Kinematic
SNB	Service New Brunswick
TCP/IP	Transport Control Protocol / Internet Protocol
TEC	Total Electron Content
UNB	University of New Brunswick
UNBF	University of New Brunswick at Fredericton
WAAS	Wide Area Augmentation System
WGS-84	World Geodetic System

CHAPTER 1
1.0 INTRODUCTION

A vast range of techniques enables users to obtain point positions using a Global Navigation Satellite System (GNSS) at various levels of accuracy. At one end of the spectrum lies code-based autonomous GNSS yielding accuracies in the range of several metres, while at the other end lies dual-frequency phase post-processed static solutions yielding accuracies of a few millimeters. Somewhere in the middle lie techniques of pseudorange correction (PRC) often called “differential correction”. Accompanying each technique is a cost in both time and dollars. A cheap handheld GPS unit can compute autonomous solutions in real time for a cost of less than two hundred dollars, while static solutions might require equipment costing tens of thousands of dollars with solutions only becoming available after-the-fact.

In this report, accuracy will be defined as the bias, or difference, of an observed position from a known position. For horizontal positions this bias will be the horizontal RMS distance of an observation from its known position. For vertical positions, the height observed above the known position will be used. Uncertainty, or precision, will be defined as the difference between the observed value and the mean of all observed values. In addition, all uncertainties will be presented at a 95% confidence level. Thus, the uncertainty presented is the value inside which 95% of all observations lie. A statement that a position was measured at $1.2m \pm 1.8m$ means that the mean difference between the observed value and the known value was 1.2m while the 95% of the observations lie within 1.8m of the mean position of all observations in the data set.

Differential corrections are often used to improve autonomous GNSS positions. The resulting combination is known as differential GNSS[*] (DGNSS). Pseudorange corrections (PRCs), to be employed in this report, generally produce horizontal accuracies in the 0.5m to 2.0m range and can be applied to either code or phase measurements. Real Time Kinematic (RTK) methods can result in accuracies in the centimetre range but can only be used in conjunction with phase measurements.

Although less accurate than RTK, PRCs still occupy a solid position in the modern GNSS market because of their relative low cost and ease of use when compared to RTK. Applications that are appropriate for these corrections are in establishing ground control for satellite imagery, providing positioning information for hydrographic surveys, and providing en route positioning for land, ocean and aerial navigation.

Pseudorange corrections can be broken down into two broad categories: *wide area* and *regional*. Typical examples of wide area DGNSS systems are WAAS (Wide Area Augmentation System) and CDGPS (Canada-wide Differential GPS). As the name implies, wide area systems are intended to cover large regions such as all states of the U.S.A, as in the WAAS case, and most of Canada, as in the CDGPS case. Regional systems are intended for use in a specific region, such as within the vicinity of a city or airport. In general, local corrections provide better accuracy than wide area corrections.

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[*] The term DGPS (differential global positioning system) is in common use. However, this term specifically applies to the United States' GPS system. Since there are now other systems worldwide, such as Russia's GLONASS and the European Union's Galileo system (which is currently under development), the more generic term DGNSS will be used here since differential techniques apply to all systems.

For DGNSS corrections to be applied in real time, they must first be computed and then transmitted to the roving GNSS receiver. Both WAAS and CDGPS use geostationary satellites (GEOs) to broadcast corrections to users. This may cause significant problems for some terrestrial users since GEOs can be low on the horizon in northern latitudes, such as Fredericton, causing the signals to be blocked by terrain and buildings. For example, GEO-based signals were unavailable for 51.8% of the positions computed during a 6100 km course driven in Finland (>60ºN) [Chen and Li, 2004].

Due to the wide availability of digital mobile phone availability in both North America and Europe, this technology has recently come under close scrutiny as a viable transmission medium for differential corrections. The German Federal Agency of Cartography and Geodesy has defined and implemented a method of employing the Hypertext Transport Protocol (HTTP) to disseminate DGNSS corrections via an Internet Protocol (IP) connection [Weber, 2005]. To accomplish this, they have devised a client-server model; chosen the Radio Technical Commission For Maritime Service (RTCM) standard [RTCM, 2001] as a correction format (allowing both PRC and RTK-type corrections); and devised syntax to extend the ubiquitous HTTP protocol. This model is known as *Network Transport of RTCM via Internet Protocol* (NTRIP). In experiments carried out by Chen and Li, it was found that NTRIP-delivered differential corrections were available for 98.6% of the position solutions during a 6100km course driven in Finland (>60ºN).

For the work described in this report, both local and localized wide area pseudorange corrections were disseminated using NTRIP. The accuracy and convergence of position and height solutions was analyzed. In addition, some consideration is given to the latency of corrections since they must travel through the Internet in a manner that is not under the control of either the purveyor of the DGNSS corrections or the end user.

Chapter 2 provides background information on DGNSS. Pseudorange corrections are discussed, as are errors expected and their correlation with the distance between user and reference station. Chapter 3 provides background information on the NTRIP specification. Each component of the model is discussed so that the reader can become familiarized with a technology that will likely become prevalent in the near future. Chapter 4 discusses the procedures followed when collecting data, as well as computational procedures and results obtained. Chapter 5 contains conclusions and recommendations for future work.

CHAPTER 2
2.0 DIFFERENTIAL GNSS AND STANDARDS

2.1 Pseudorange Corrections

2.1.1 Determination of user position using GNSS

Trilateration is a technique used to determine position through the measurement of ranges. As shown in Figure 2.1.1, a user measures the distance between himself and several reference stations whose coordinates are known.

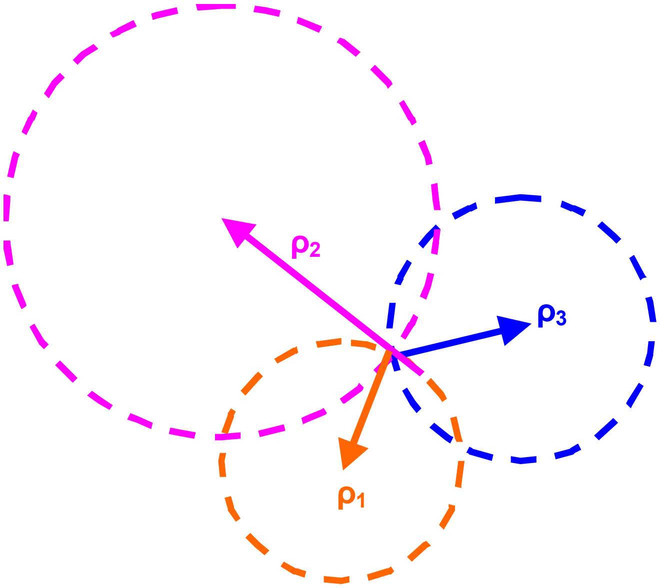


Figure 2.1.1: Determining position through trilateration.

Mathematically, each range is represented by the following equation:

$$\rho_i = \sqrt{(x_i - x)^2 + (y_i - y)^2 + (z_i - z)^2} \qquad (2.1)$$

Where:

ρ_i	Is the distance observed between the user and a reference station whose coordinates are known.
x, y, z	Are the coordinates of the user in some Cartesian coordinate system.
x_i, y_i, z_i	Are the coordinates of a reference station.

Equation (2.1) fits nicely into a parametric least squares paradigm, with:

a) Three unknowns – the coordinates of the user position

b) One observation – the distance between the user and the reference station, and

c) Three constants – the coordinates of the reference station.

Obviously, with only one observation and three unknowns, the user position cannot be uniquely determined. For each additional observation, no new unknowns are added. Hence, by adding observations to two additional reference stations, a unique solution can be obtained. Adding still more observations results in redundancies that allow uncertainties to be estimated.

This technique can be used to compute a user position from orbiting satellites. Each satellite continuously broadcasts a signal at a well-known frequency. Modulated on the signal is a coded message that contains information including: the location of the satellite, the time at which the message was sent, and orbital parameters for all satellites. The receiver can determine which satellite is being observed by means of a pseudo-random number (PRN) that is used to decode messages, and that uniquely identifies each satellite. Upon receiving and decoding this message, the user can determine the length of time that the signal took to travel from the satellite to the user. Using the speed of light in a vacuum, the range to the satellite can be approximated. Since this range contains significant error it is called the *pseudorange*.

Pseudorange observations are commonly modeled as follows [Misra and Enge, 2001]:

$$\rho_i = r_i + c\left(dt - dT_i\right) + I_i + T_i + \varepsilon_i \tag{2.2}$$

Where:

ρ_i	Is the observed range between the user and satellite 'i'.
r_i	Is the geometric range between the user and the satellite (shown in equation 2-1).
c	Is the speed of light in a vacuum.
dt	Is the difference between the user's receiver's clock and true GNSS time.
dT_i	Is the difference between the satellite's clock and true GNSS time.
I_i	Is extra effective distance traveled by the satellite signal due to refraction in the ionosphere.
T_i	Is the extra effective distance traveled by the satellite signal due to the troposphere.
ε_i	Represents any terms not modeled, such as noise caused by the receiver's electronics and multipath.

In order to employ a parametric least squares approach to equation (2.2), it is necessary to somehow deal with the clock and atmosphere terms. The general prescription is to:

a) Treat receiver clock error as an unknown parameter and solve for it.

b) Use parameters encoded in the GNSS signal to approximate satellite clock error and model the ionosphere.

c) Model the troposphere based on approximate location and time of day and year.

Using this approach, it is typically possible to achieve a position accuracy of 10 metres at 95% confidence in most situations [RTCM, 2001].

While this level of accuracy may be quite acceptable for *en route* navigation in open seas or aloft, it is generally not sufficient for applications such as runway approach or in-harbour navigation [RTCM, 2001]. In an attempt to improve accuracy, researchers have developed a considerable number of approaches. The central method considered in this report is that of differential correction using pseudoranges.

Under this method, a "reference" GNSS receiver is placed at a location whose coordinates (x, y, z) are known by means of a survey or some other external process. Using the satellite's broadcast ephemeris, satellite coordinates (x_i, y_i, z_i) can be computed and thus, the "true" range between the user and satellite can be determined:

$$r_i = \sqrt{(x_i - x)^2 + (y_i - y)^2 + (z_i - z)^2} \tag{2.3}$$

The word "true" is put in quotations because, as will be discussed shortly, broadcast ephemeredes contain error. The reference receiver next observes the pseudorange (ρ_i) and computes the difference between this and equation (2.3) [Misra and Enge, 2001]:

$$\Delta\rho_i = r_i - \rho_i \tag{2.4}$$

These corrections are broadcast to the user (or "roving") receiver and are added to locally observed pseudoranges:

$$\tilde{\rho}_i = \rho_i + \Delta\rho_i \tag{2.5}$$

Finally, the user receiver utilizes the following mathematical model in performing a parametric least squares adjustment to arrive at an estimation of user location (x, y, z) :

$$\tilde{\rho}_i = \sqrt{(x_i - x)^2 + (y_i - y)^2 + (z_i - z)^2} \tag{2.6}$$

Using such techniques, it is possible to obtain uncertainties of 1m to 10m at 95% confidence [RTCM, 2001]. However, typically for separations between user and base of less than 100km, uncertainties in the metre range are obtained [Monteiro et al., 2005].

2.2 DGNSS Sources of Error

Two key assumptions are made when applying pseudorange corrections:

1. Pseudorange corrections ($\Delta\rho_i$) change slowly with time, so that the time required for their computation and broadcast to the user does not render them useless.
2. Because the user and reference stations are "near" each other, pseudorange errors are strongly correlated. Hence, errors in the pseudorange observed at the reference receiver are substantially the same as those observed at the user receiver.

2.2.1 Sources of Error

A brief discussion of the individual errors in a pseudorange measurement follows. With each, is included estimates of size, techniques for mitigation, and rates at which each is expected to change.

2.2.1.1 Satellite clock error

In the case of the U.S. GPS system, each satellite contains redundant cesium and/or rubidium atomic clocks [USNO, 2007]. These free-running clocks are monitored continuously by a Master Control Station, which builds a parametric model of the difference between the on-board clock time and GPS Time. The resulting parameters are uploaded to the satellite and transmitted to all GPS users who can apply them to transmitted satellite clock times. Adjusted values are generally within 5 nanoseconds (ns) of GPS Time [Monteiro et al., 2005]. It is this time that is used together an ephemeris to compute the instantaneous position of a satellite. Thus, a 5ns clock error could result in a 1.5m error in satellite position.

Since time is used to find the position of a satellite along its orbital path, and since pseudranges are generally measured at an angle near ninety degrees to the orbital path, satellite clock error is not likely to contribute significantly to pseudorange error.

More importantly, when both a reference station and a user station compute the position of a satellite, they do it solely based on data broadcast from the satellite. Thus, both receivers should compute *exactly* the same orbital position so long as they are using exactly the same satellite message. For this reason, the pseudorange correction computed at the reference station, which includes the error due to satellite clock error, when applied to a user pseudorange, completely removes the effect (this will be revisited during discussions on spatial decorrelation).

2.2.1.2 Satellite ephemeris error

Each satellite broadcasts an ephemeris, which is a set of Keplarian orbital elements that can be used to compute the position of the satellite at any given time. As with the satellite clock discussed above, the orbit of each satellite is continuously monitored and modeled by the Control Segment. Whenever the orbit changes enough that the current ephemeris is unsuitable, a new ephemeris is uploaded to the satellite. In the current era, GPS ephemeredes generally produce orbital positions with uncertainties in the 2 metre range [Monteiro et al., 2005], though this value may vary substantially with other GNSS systems.

As with satellite clock error, reference and user receivers use the same ephemeris and GPS time to compute satellite position. Thus, as long as each are using the same ephemeris, they should calculate exactly the same satellite position. This implies that the errors in pseudorange due to orbital positions are the same at both the reference and user receivers, and hence, application of the pseudorange correction at the user receiver completely removes these errors.

2.2.1.3 Ionospheric Refraction Error

Satellite signals traveling through the ionosphere suffer refraction in much the same way as light suffers refraction when traveling through media with varying speeds of light. However, in the ionospheric case, speed is a function of the total electron content (TEC) encountered along the path of the signal. Electrons are freed from their molecules when solar radiation is absorbed. Thus, TEC is higher during daylight hours and during periods of high solar activity.

The net effect of refraction is that satellite signals must travel a longer distance to arrive at an Earth-based GNSS receiver. Longer distance means longer time for signals to travel from satellite to receiver and hence, the effect is often referred to as *ionospheric delay*.

In general, vertical ionospheric delay has been found to be 3-6m at night and 20-30m during the day [Monteiro et al., 2005]. This effect is therefore a significant factor in the accuracy of any receiver's position solution.

As with optical refraction, ionospheric refraction is a function of signal frequency. Thus, by observing the arrival times of signals on two different frequencies, the delay can be quantified to a high degree of accuracy. However, most mapping and navigation-grade receivers operate on only a single frequency and this error must be dealt with through different methods.

With pseudorange corrections, the assumption is made that signals received at the reference and user locations have traveled the same path through the ionosphere. However, since the ionosphere is relatively low (e.g. 300km) when compared to the height of GNSS satellites (e.g. 25,000km) this assumption is clearly not true. The extent to which errors observed at the reference receiver correlate with those observed at the user receiver depend on the current stability of the ionosphere and the separation of the two receivers. Thus, on a stable day pseudorange corrections can virtually eliminate ionospheric delay for rover receivers sufficiently close to a reference receiver, while on other days the removal might be substantially less.

2.2.1.4 Tropospheric Refraction Error

Like the ionosphere, signals traveling through the troposphere (particularly through the lower 18km) suffer refraction. However, unlike the ionosphere, refraction is not a function of signal frequency because the troposphere is electrically neutral.

The refraction effect can be decomposed into two components [Monteiro et al., 2005]:

a) A dry component, which is a function of air pressure and temperature

b) A wet component, which is a function of water vapour distribution.

The dry component accounts for about 80% to 90% of the total effect and is less variable and therefore easier to model than the wet component. Thus, the usual approach for an autonomous receiver to employ, is to use a mathematical model based on location, time of year, and date to approximate the effect. This can be a very important source of error, since delays can be between approximately 3m vertically and up to about 50m at an elevation of 3 degrees above the horizon [RTCM, 2001].

The extent to which the delay at a reference receiver correlates with that at a user receiver is heavily dependent on their relative elevations. Correlations between two ground-based receivers at sea level may be high, while correlations between a ground-based receiver and an airborne receiver are lower. One author [Misra and Enge, 2001] quantifies residual tropospheric error after pseudorange correction as 0.2m + 2 to 7mm/metre height difference.

2.2.1.5 Multipath Error

Ideally, broadcast from a satellite travels a straight path to an antenna where it is received. However, in reality signals may reflect off nearby objects before impinging on the antenna. Simple antennas have no way of differentiating these two cases and so reflected signals interfere with each other [Wells et al., 1986]. This effect is commonly known as multipath error.

Since multipath error is due to reflective surfaces near the antenna, one can expect no correlation between that seen at the reference receiver and that seen at the user receiver. Not only do pseudorange corrections not reduce this effect at all, any multipath error included in the correction is actually *added* to the user's pseudorange. For this reason, it is extremely important that the reference station take all actions possible to remove multipath before computing corrections.

2.2.1.6 Code, Antenna and Electronic Noise Errors

Several other sources of error exist which are not mitigated by pseudorange corrections. Although various methods have been developed to deal at least partially with each, these are beyond the scope of this report. Often these phenomenon are left unmodelled and treated as random errors.

C/A code, which is used to compute pseudoranges, is modulated onto the microwave signals transmitted from GPS satellites. It has been found that a receiver can resolve timings in this code to approximately 1% of its wavelength [Wells et al., 1986]. Thus, since C/A code has a wavelength of 100m, the errors associated with timings are of the order of 3m.

GNSS solutions are computed at the phase center of the antenna used. Due to the advanced electronics integrated with an antenna, the phase center wanders slightly with time [Wells et al., 1986]. The nature of this change is entirely equipment dependent and cannot be generalized other than to say that higher quality antennas produce better results.

Finally, the receiver itself is an electronic device. It is composed of many elements, which serve to amplify and filter the very weak signal transmitted by satellites. These elements add random noise to measurements.

2.2.2 Range Rate Corrections

One of the core principles making pseudorange corrections viable is that they change slowly with time. If this were not the case, corrections would be invalid by the time they reached the user. One researcher found that corrected positions generated by pseudoranges from Portuguese naval coastal stations degraded at a rate of approximately 2 mm per second [Monteiro et al., 2005]. Thus, even after 4 minutes, position estimates had only degraded by one half metre. (It is noted that the situation was much worse when Selective Availability was in effect.)

To help account for the drift in pseudorange corrections, reference stations may monitor corrections over time and generate a *range rate correction* (RRC). Before subsequently applying the correction, a user must modify the correction using the time elapsed since the correction was originally generated:

$$\tilde{\rho}_i = \rho_i + \Delta\rho_i + \frac{d\Delta\rho_i}{dt}(t - t_0) = \rho_i + PRC_i + RRC_i(t - t_0) \tag{2.6}$$

Where:

$\tilde{\rho}_i$	Is the user's adjusted pseudorange after applying reference receiver corrections.
ρ_i	Is the user's observed pseudorange.
$\Delta\rho_i = PRC_i$	Is the pseudorange correction generated by the reference receiver.
$\frac{d\Delta\rho_i}{dt} = RRC_i$	Is the rate at which the pseudorange correction is changing.
t_0	Is the time at which the pseudorange and range-rate corrections were generated.
t	Is the time at which the user is applying the correction.

It is noted that if the reference station is generating corrections at a high rate, it is possible for the receiver to deduce a range rate correction itself. However, since the reference station has a steady and reliable stream of corrections available, it is best if it computes this rate.

2.2.3 Spatial Correlation

A core principle of pseudorange corrections is that errors affecting observations at the reference receiver are highly correlated to those affecting the user receiver. Figure 2.2.1 shows an exaggerated view of the path a satellite signal travels to arrive at each location.

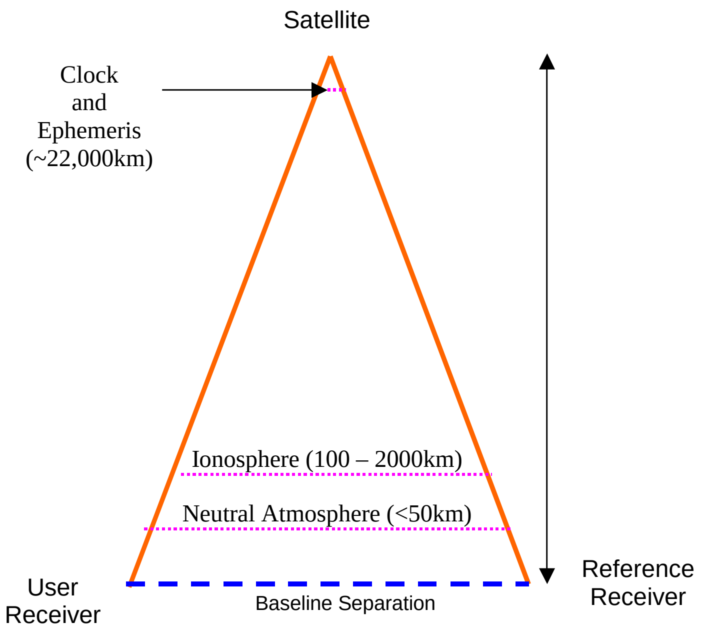


Figure 2.2.1 – Spatial Correlation of Errors

Recall that the pseudorange is a measurement of distance from receiver to satellite. We can see that the signal paths diverge as they move away from the satellite. Thus, near the satellite, signals are spatially close to each other, but as they approach the receivers they move apart. This implies that the errors that suffer the greatest decorrelation are those associated with atmospheric refraction because they are significantly closer to the receiver and therefore the signals travel through different portions of the atmosphere.

The rate of decorrelation is therefore extremely dependent on existing atmospheric conditions. Under good conditions in a coastal region, one group of researchers found that at a 95% confidence level pseudorange corrections as a function of baseline length were: 0.7247 m + 0.0040 S (where S is the baseline distance in nautical miles) [Monteiro et al., 2005]. This translates to about 1 m for a separation of 100 km.

One factor not considered thus far is the intervisibility of satellites. That is, as distances increase it is likely that the user receiver will not be able to see all of the satellites that the reference receiver sees. This is an important issue since a user receiver can only make use of satellites for which it has a correction and must discard the rest. This error is hard to quantify. Monteiro et al. report that from their literature search, a "very rough" approximation would suggest that for every additional 100 km of separation, the user should subtract one degree from their elevation mask to accommodate this problem.

2.2.4 Temporal Correlation

Range-rate corrections and the aging of corrections have already been discussed. However, of further importance is the necessity of the reference and user receivers to use the same epochs for satellite ephemeris information. Using GPS terminology, both the rover and reference station must use the same Issue of Data Ephemeris (IODE) when computing orbital positions; otherwise corrections computed at the reference station will not correlate with errors experienced at the rover.

2.3 Wide Area versus Local DGNSS

Up to this point, we have discussed pseudorange corrections as a scalar number which is added to a user's observed pseudoranges. Such corrections decrease in validity as the separation between user and reference receivers increase. If one were to attempt coverage of a large region, such as an entire country, one has to trade off between accuracy (as a function of baseline distance) and cost (as a function of the number of reference stations). One way to approach this dilemma is to break pseudorange corrections into components so that local users can construct a customized correction for their own purposes.

When one keeps pseudorange corrections intact as a scalar, the system is known as a *local* or *regional* DGNSS system. When one breaks corrections into components, with the intension that they be used over an extended area, the system is known as a *wide area* DGNSS system.

2.3.1 Wide Area DGNSS (Vector)

With a wide area DGNSS system, pseudorange corrections are decomposed into components that are highly dependent on a user's location and components that are not. Because corrections are sent in this manner, these systems are sometimes referred to as *vector* DGNSS systems.

As discussed previously, satellite clock and ephemeris errors affect most users uniformly so long as they are based on values broadcast at the same epoch. Ionosphere and troposphere errors, conversely, are highly dependent on user position.

Because the ionosphere is high above the Earth's surface (i.e. > 100 km), it is possible for a small number of reference stations distributed throughout the intended coverage area to monitor the ionosphere. Generally, a mean height, such as 350 km is chosen to represent this entire atmospheric layer. At each reference station, a dual frequency receiver performs carrier phase observations. For each satellite, a *pierce-point*, representing the intersection of a straight line drawn from the reference station location to the satellite with a sphere whose radius puts it at 350 km above the surface of the Earth, is computed. Because ionospheric refraction is frequency dependent, dual-frequency observations can be used to compute the ionospheric delay for each satellite. Using a mapping function, the observed *slant delay* (i.e. the delay along the signal path) is converted to a *vertical delay* (i.e. the delay a user would experience if the satellite was at his local zenith). Vertical delays from all reference stations are combined to produce an instantaneous model of the ionosphere over the coverage area. From this, a regular grid of points where the vertical delays are known is formed. This is broadcast to the user, who must use his own position to deduce the pierce-point for each satellite he is observing and compute the slant delays that he should be experiencing.

Because the troposphere varies significantly by location and altitude, a dense three-dimensional grid representation would be required. For this reason, tropospheric corrections are not typically transmitted. Instead, a mathematical model based on location, time of day and date is used.

2.3.1.1 RTCA Specification

The Radio Technical Commission for Aeronautics (RTCA) was formed in 1935. Known as RTCA Inc., it serves as an advisory committee to the United States of America Federal Aviation Administration (FAA) as well as serving as an international body that develops recommendations regarding communications, navigation, surveillance and air traffic management [RTCA, 2007]. RTCA Document Number DO-229c [RTCA, 1996] describes a vector-based messaging scheme for communication of differential corrections for wide area augmentation systems. Originally developed for use with the FAA's Wide Area Augmentation System (WAAS), it is now also the basis for Canada's CDGPS (with slight modifications) and the European Union's European Geostationary Navigation Overlay Service (EGNOS).

Because of bandwidth limitations in communicating with satellites, position independent corrections are broken into two parts: *fast* corrections and *long-term* corrections. The only real difference between these is the frequency with which the user receives updates. The ionospheric corrections are handled via a grid of vertical errors as described above. The tropospheric correction is handled by means of a simple model and therefore not transmitted.

It is also noted that the RTCA specification adds error estimation to the differential corrections. Whereas DGNSS alone allows a user to improve the accuracy of their position, RTCA also gives them an indication of the uncertainty in this value. It is this addition that makes RTCA useful for applications such as aeronautics where safety is of prime importance.

2.3.2 Local-Area/Regional DGNSS (Scalar)

The theory behind the computation of pseudorange corrections (PRCs) was detailed in Section 2.1.1. In addition, the concept of range rate corrections (RRCs) was detailed in Section 2.2.2.

Unlike wide area corrections, local corrections are intended for use only in the vicinity of the reference station. Because errors due to the satellite clock, satellite orbit, ionosphere and troposphere are assumed correlated between the user(s) and reference station, a single correction number (a PRC) can be transmitted. For this reason, local differential systems are often called “scalar”.

2.3.2.1 RTCM Specification

The Radio Technical Commission For Maritime Services (RTCM) is a non-profit organization charged with developing standards for maritime applications. Since its original publication, the “RTCM Recommended Standards for Differential GNSS” has become the *de facto* standard for transmitting differential corrections [RTCM, 2001]. This document describes a binary format for packaging pseudorange corrections (PRCs) and their associated range-rate corrections (RRCs). In addition, it clearly describes how users should apply these to improve their own position solutions.

3.0 THE NTRIP STANDARD

3.1 Overview

NTRIP (Networked Transport of RTCM via Internet Protocol) is a standard specification defining a client-server model for transmitting DGNSS corrections from a reference station to users in the field [RTCM, 2004]. Contrary to the formal title, the design is based on techniques commonly used to stream multimedia over the Internet and is therefore able to stream any type of data and not simply RTCM data. Figure 3.1.1 shows the main building blocks of an NTRIP system. Each will be discussed in the sections that follow.

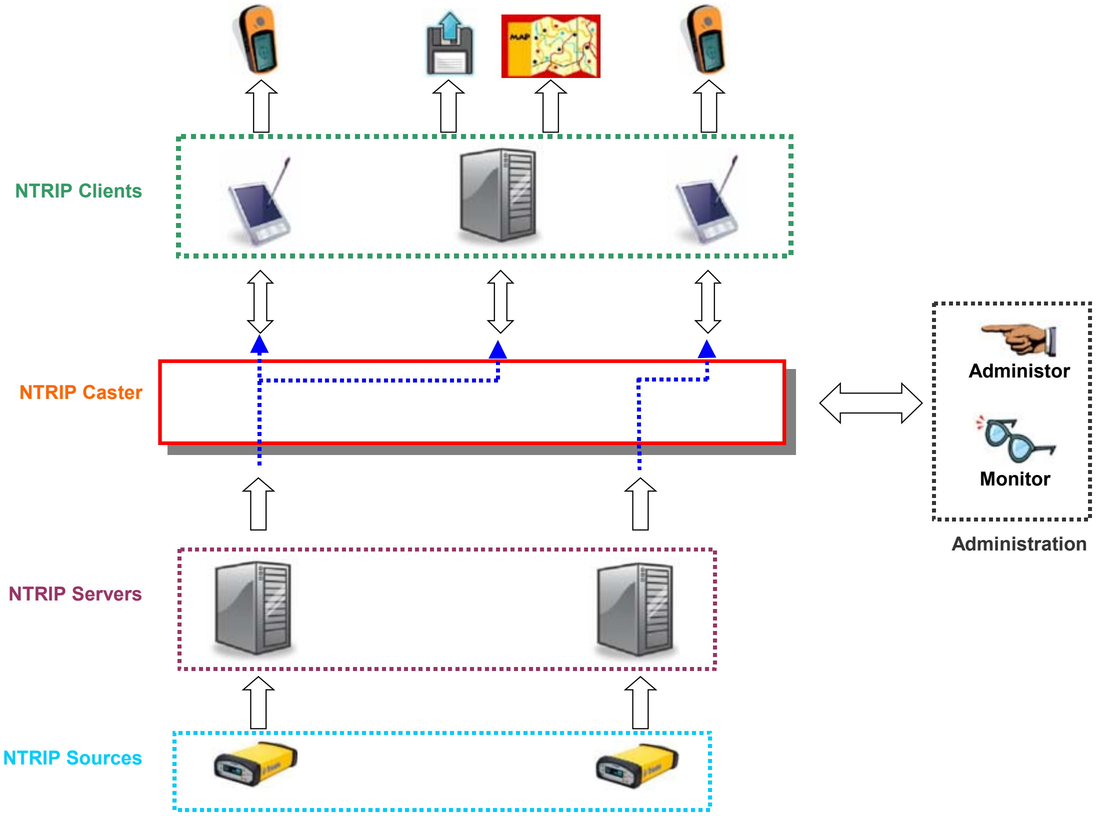


Figure 3.1.1 – The parts of an NTRIP system.

3.2 NTRIP Sources

In the most generic sense, NTRIP sources generate streams of binary information to be transported to clients. Although these sources can include any type of information, the original intention was for the streams to be comprised of RTCM DGNSS corrections.

For example, in the work carried out for this report, three NTRIP sources were employed:

1. A Trimble® NetR5 receiver was configured to output raw observations to a TCP/IP port for use with the CanSel® NTRIP caster.
2. The same Trimble® NetR5 was configured to output RTCM local DGNSS corrections to a TCP/IP port for use with the BKG caster (to be explained shortly).
3. A CDGPS receiver was configured to output RTCM local DGNSS corrections to an RS-232C serial port for use with the BKG caster.

Any device can be used as a source without any knowledge of NTRIP.

3.3 The NTRIP Server

An NTRIP server is a software program that acts as a liaison been an NTRIP Source and NTRIP caster. In software engineering terms, the server can be described as an abstraction layer. It allows devices that have no understanding of NTRIP to serve data into an NTRIP environment.

The NTRIP server must be prepared to communicate with the NTRIP source in a manner that the source understands. For our CDGPS receiver, this means RS-232C serial port communications. For our Trimble® NetR5 receiver, this means TCP/IP communications. Communications with the NTRIP caster is always via TCP/IP and uses a customized version of the Hypertext Transfer Protocol (HTTP) 1.1 protocol.

3.4 The NTRIP Caster

The NTRIP caster is the central block in the NTRIP architecture. All data streams are transmitted through this software program. NTRIP servers connect to the caster using HTTP 1.1 and register their respective data streams by means of a unique identifier known as a “mountpoint”. NTRIP clients may acquire access to data streams only through the caster. The caster is capable of serving many clients from the same data stream simultaneously, or serving many different streams simultaneously.

The simple design of the caster has many important features. It acts as a central warehouse for all information regarding data sources. Upon request, a caster can provide a client with a “source table”. This table contains an entry for every mountpoint available. For each, information regarding the type of data and the owner is provided.

The caster also serves a security role. It implements a simple username/password scheme that can provide a certain level of control to the system (though secure HTTP -- HTTPS -- is a more thorough solution). More importantly, the caster acts as an intermediary between sources and clients. This means that clients never have direct access to the actual source devices, which makes malicious activities much more difficult to initiate.

3.5 The NTRIP Client

The NTRIP client is a software program that essentially carries out the reverse roll of the NTRIP server. It is an abstraction layer that interfaces with the NTRIP caster to provide data streams to a user. Because of the client, a typical user does not need any knowledge of NTRIP.

The NTRIP client allows for username and password exchange, as well as the receipt of a source-table from the caster. Once a stream is initialized, data is transferred from the caster to a user.

3.8 NTRIP Administration

The NTRIP specification does not formally define the functions of an administration module. However, for large systems, this should be considered to be a essential feature. The administration functionality should include but not be limited to:

a) Maintaining usernames and passwords.

b) Maintaining source-tables and mountpoints.

c) Monitoring data streams. This includes recording when they start and stop, the rate of data transfer and the aggregate amounts of data transferred.

d) Providing notifications. These notifications should be sent to subscribed users when events that they have chosen to monitor occur. In our case, we received notifications from the BKG caster when either of our streams started or stopped.

e) Providing periodic statistics. This might include monthly availability rates for the caster and individual data streams, amounts of data transferred and number of client users.

3.9 Currently Available Resources

BKG provides a free set of utilities for NTRIP users [BKG, 2007]. These include NTRIP clients, NTRIP servers and various utilities for manipulating RTCM and RINEX data. Different versions of programs are available to support Windows®, Linux, Windows® CE and Palm® OS. BKG also maintains an exhaustive list of third-party vendors for various NTRIP products.

Trimble® has been involved with the design of the NTRIP specification along with BKG. To this end, much of their equipment supports NTRIP at a native level. The Trimble® NetR5 receiver that we used, for example, has an internal NTRIP server [Trimble, 2007b]. The Trimble® GeoXT we used to compute user positions had an NTRIP client embedded internally. Finally, Trimble®'s Virtual Reference System [Trimble, 2007c] appears to implement both an NTRIP caster and an administration model.

4.0 DATA COLLECTION AND ANALYSIS

4.1 The NTRIP Caster

The original intent for this work was to route all differential corrections through a single NTRIP caster maintained by CanSel®. By having all corrections travel through a single caster, routing effects should be similar and therefore a direct comparison of position solutions is possible. If some corrections travel through a caster located in Canada, for example, while others travel through a caster located in Germany, there is an additional concern that the difference in network routing paths will add latency to the corrections and thus add a bias between position solutions.

In practice, after many attempts, CanSel® was unable to route our CDGPS corrections through its caster. This is likely because NTRIP is constantly evolving, and the CanSel® caster was of an older vintage than the standard to which this report attempts to conform. It appears that the Cansel® software expects raw GNSS observations as inputs and then internally converts these to RTCM v2.3 for broadcast. In contrast, the NTRIP standard requires that we take our RTCM v2.3 CDGPS output and route it via an NTRIP server to the caster.

In the end, two casters were employed for our observations: The CanSel® caster routed corrections from our UNB-based Trimble® NetR5 and a similar receiver based in Halifax, Nova Scotia; and, a caster operated by BKG in Germany [BKG, 2007] routed corrections from our UNB-based Trimble® NetR5 and CDGPS receivers.

4.2 Setup of NTRIP Servers and Sources

4.2.1 The CanSel® Caster

The Trimble® NetR5 receiver [Trimble, 2007b] was connected to an antenna located on the roof of Head Hall. This receiver was configured by Rodrigo Leandro (a UNB PhD student) to stream raw observations to a local port that was accessible outside the UNB network. Cansel® then configured their NTRIP software to retrieve these observations through the Internet, convert them to RTCM v2.3, and assign the resulting differential correction stream to a NTRIP caster mountpoint.

Cansel® also already had a mountpoint defined for a Trimble® NetR5 receiver located in Halifax. This receiver was configured in the same manner as for the UNB-based receiver.

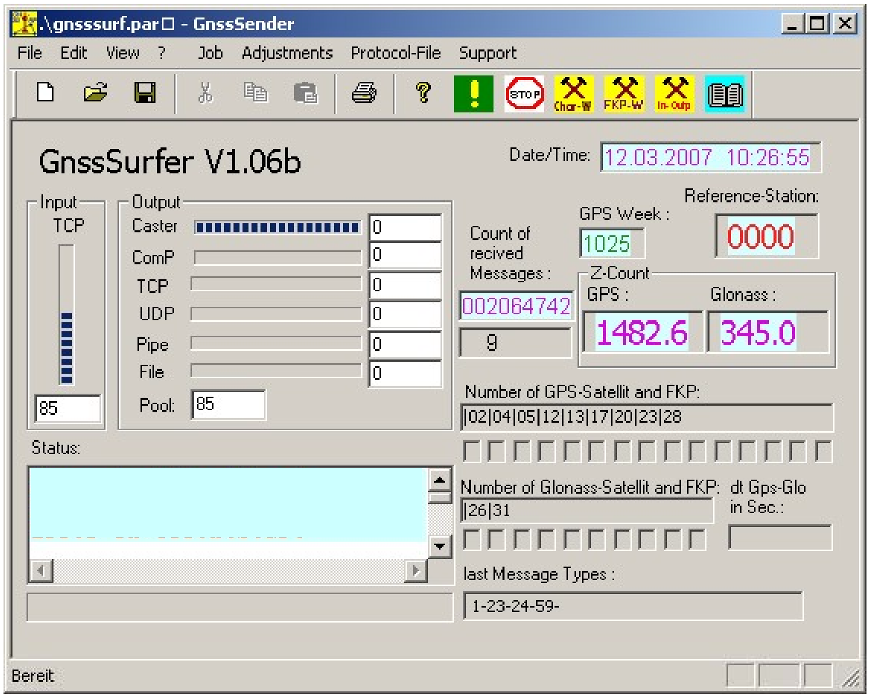
4.2.2 The BKG Caster

As already mentioned, it was not possible to use the Cansel® caster exclusively due to configuration problems. This left us with the option of either establishing our own NTRIP caster or piggybacking off an existing caster. Although caster software is available from BKG, it comes at a cost of 500€. We were thus, very happy when Christian Waese and his colleagues at BKG agreed to grant us access to their caster during the several weeks of our data collection.

The same UNB-based Trimble® NetR5 receiver discussed in §4.2.1 was configured to simultaneously stream RTCM v2.3 corrections to a local TCP/IP port.

These were captured and forwarded to the BKG caster via NTRIP server software. Several server programs are available from BKG at no cost [BKG, 2007]. We chose to use “GNSS Surfer Version 1.06b” since, through experimentation, we found that it also was able to work with our CDGPS solution (discussed below).

Figure 4.2.1 shows the main screen of the NTRIP server as it is receiving data via TCP/IP from the UNB Trimble® NetR5 receiver and transmitting to the NTRIP caster operated by BKG. Figure 4.2.2 shows the input settings to collect data from the receiver (outlined in red). Figure 4.2.3 shows the output settings to transmit data to the caster (outlined in red).



Date/Time: 12.03.2007 10:26:55

Input TCP: 85

Output
Caster: 0
ComP: 0
TCP: 0
UDP: 0
Pipe: 0
File: 0
Pool: 85

Count of recived Messages: 002064742
9

GPS Week: 1025

Reference-Station: 0000

Z-Count GPS: 1482.6
Z-Count Glonass: 345.0

Number of GPS-Satellit and FKP: |02|04|05|12|13|17|20|23|28

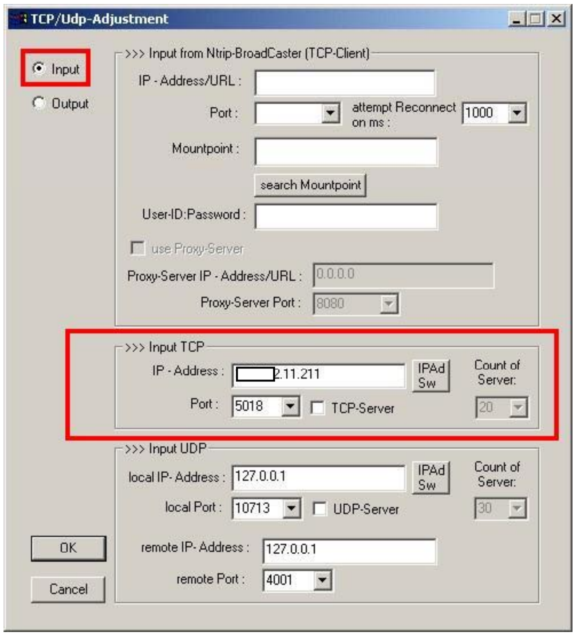
Number of Glonass-Satellit and FKP: |26|31

dt Gps-Glo in Sec.:

last Message Types: 1-23-24-59-

Bereit

Figure 4.2.1 – The main screen of the “GNSS Surfer” NTRIP server software as it transmits local differential corrections in RTCM v2.3 format from a TCP/IP port to an NTRIP caster located in Germany.



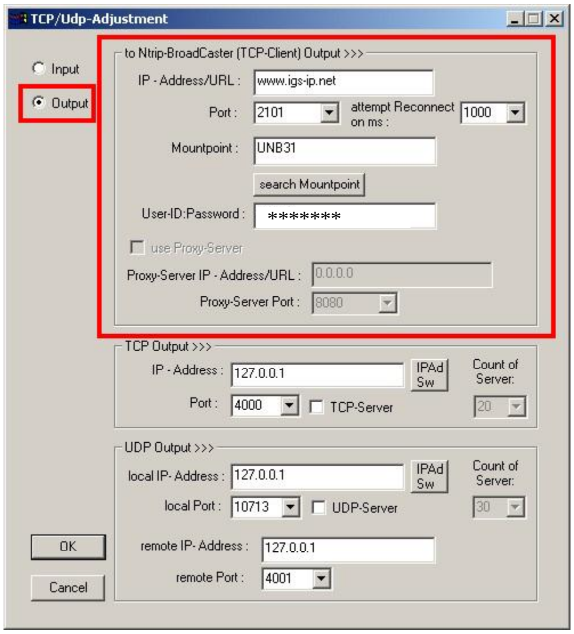
● Input
○ Output

>>> Input from Ntrip-BroadCaster (TCP-Client)
IP - Address/URL :
Port :
attempt Reconnect on ms : 1000
Mountpoint :
User-ID:Password :
☐ use Proxy-Server
Proxy-Server IP - Address/URL : 0.0.0.0
Proxy-Server Port : 8080

>>> Input TCP
IP - Address : [redacted]2.11.211
Port : 5018
☐ TCP-Server
Count of Server: 20

>>> Input UDP
local IP- Address : 127.0.0.1
local Port : 10713
☐ UDP-Server
Count of Server: 30
remote IP- Address : 127.0.0.1
remote Port : 4001

Figure 4.2.2 – The “GNSS Surfer” TCP/IP input configuration screen set to retrieve data from a Trimble® NetR5 receiver located at UNB.



○ Input
● Output

to Ntrip-BroadCaster (TCP-Client) Output >>>
IP - Address/URL : www.igs-ip.net
Port : 2101
attempt Reconnect on ms : 1000
Mountpoint : UNB31
User-ID:Password : *******
☐ use Proxy-Server
Proxy-Server IP - Address/URL : 0.0.0.0
Proxy-Server Port : 8080

TCP Output >>>
IP - Address : 127.0.0.1
Port : 4000
☐ TCP-Server
Count of Server: 20

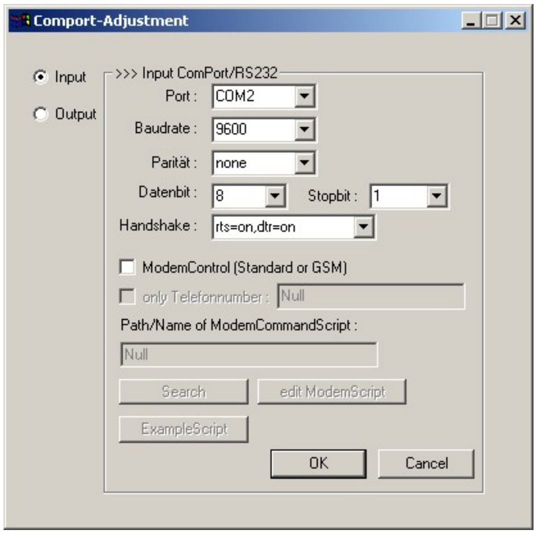
UDP Output >>>
local IP- Address : 127.0.0.1
local Port : 10713
☐ UDP-Server
Count of Server: 30
remote IP- Address : 127.0.0.1
remote Port : 4001

Figure 4.2.3 – The “GNSS Surfer” TCP/IP output configuration screen set to send data to an NTRIP caster operated by BKG in Germany.

CDGPS corrections were received via an existing antenna at UNB. These corrections are broadcast in a modified version of the RTCA format called MRTCA. As discussed in Chapter 2, RTCA corrections contain vector corrections that apply over a wide geographic region (in this case, over the entire country of Canada). These corrections must be converted into pseudorange corrections (PRCs) utilizing the user’s current location. This was accomplished using a “CDGPS Receiver” (also know as an “ePing” receiver) as shown in Figure 4.2.4. This unit uses an internal GPS receiver to determine its own location and outputs RTCM v2.3 via a RS-232C serial communications port.

Figure 4.2.4 – A CDGPS Receiver which receives modified RTCA corrections and converts them to RTCM v2.3 corrections. [CDGPS, 2003].

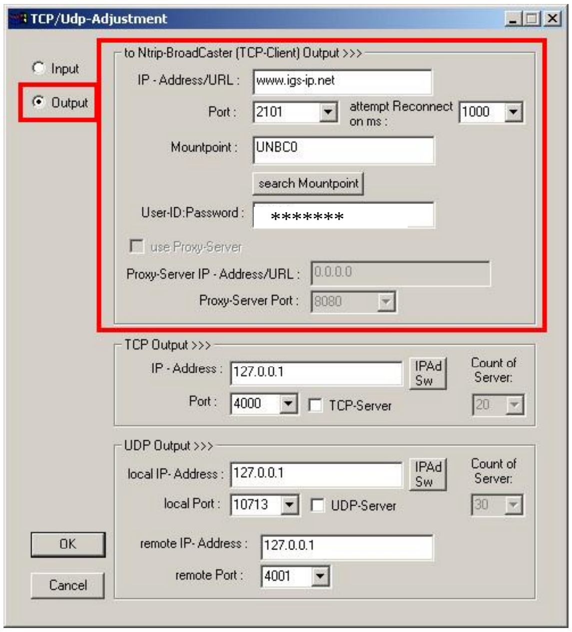
The ePing receiver was connected through a RS-232C serial cable to a Windows® computer running the GNSS Surfer software already mentioned. Figure 4.2.5 shows the COM port settings employed. Figure 4.2.6 shows the settings to transmit corrections to the BKG NTRIP caster.



Comport-Adjustment

● Input
○ Output

>>> Input ComPort/RS232
Port : COM2
Baudrate : 9600
Parität : none
Datenbit : 8
Stopbit : 1
Handshake : rts=on,dtr=on
☐ ModemControl (Standard or GSM)
☐ only Telefonnumber : Null
Path/Name of ModemCommandScript : Null



TCP/Udp-Adjustment

○ Input
● Output

to Ntrip-BroadCaster (TCP-Client) Output >>>
IP - Address/URL : www.igs-ip.net
Port : 2101
attempt Reconnect on ms : 1000
Mountpoint : UNBC0
User-ID:Password : *******
☐ use Proxy-Server
Proxy-Server IP - Address/URL : 0.0.0.0
Proxy-Server Port : 8080

TCP Output >>>
IP - Address : 127.0.0.1
Port : 4000
☐ TCP-Server
Count of Server: 20

UDP Output >>>
local IP- Address : 127.0.0.1
local Port : 10713
☐ UDP-Server
Count of Server: 30
remote IP- Address : 127.0.0.1
remote Port : 4001

Figure 4.2.5 – The "GNSS Surfer" COM input configuration screen set to retrieve data from a CDGPS ePing receiver located at UNB.

Figure 4.2.6 – The "GNSS Surfer" TCP/IP output configuration screen set to send CDGPS corrections to an NTRIP caster located in Germany.

4.2.3 CDGPS Issues Encountered

4.2.3.1 ePing Receivers Are No Longer Manufactured

Two important factors should be mentioned here. Firstly, the ePing receiver as a stande-alone unit is no longer commercially available. In the past, a CDGPS user needed to carry an ePing receiver to generate corrections which would then be fed into a GPS receiver for application. Although cumbersome, this had the advantage of the user being able to choose from a wide variety of GPS receivers that had no native support for CDGPS themselves.

CDGPS receivers are now integrated with GPS receivers built by NovAtel® [NovAtel, 2007]. (At this time, NovAtel® is the only vendor listed as an “integrator” on the CDGPS website. A limited number of third-party vendors incorporate NovAtel solutions into their own receivers.) From a positive point of view, this is much less cumbersome than the traditional ePing unit solution. From a negative point of view, this severely limits the number of users who will be able to employ CDGPS solutions, since mainstream vendors such as Trimble® and Magellan® have not chosen to integrate (yet).

NTRIP could move CDGPS into the mainstream since more and more mapping-grade GNSS units support digital communications. However, it is not clear how one would obtain CDGPS corrections to disseminate using NTRIP in the absence of an ePing receiver. Likely such a solution would require the participation of CDGPS as an entity.

4.2.3.2 Intermittent Problems Encountered with the ePing receiver

After the NTRIP server streams were configured, the intention was to let them run continuously for the duration of the project. However, we found that the ePing receiver intermittently ceased functioning every two or three days. In its default mode, the receiver would power off when certain error conditions arose. This required restarting both the receiver and the GNSS Surfer NTRIP server software. This also resulted in a “Notice Advisory Broadcaster Users (NABU)” email being sent to all subscribed users of the stream noting that the stream was unavailable.

The “CDGPS Receiver Configuration Utility” program [CDGPS, 2007] was downloaded and used to reconfigure the ePing receiver to stay powered on in the event of a problem. While this did provide more stability in our streams, it did not deal with the issue that the ePing receiver apparently fails to work at arbitrary times.

It is noted that another ePing receiver working nearby does not appear to have such frequent problems. It may be that this particular receiver has hardware problems.

4.3 Data Collection Procedures

4.3.1 GNSS Receiver Selection

From the outset, we were interested in comparing differential corrections disseminated using the NTRIP protocol. To this end, we looked for a receiver with an integrated NTRIP client. Cansel® was very gracious in its offer to lend us such a unit and supplied us with a Trimble® GeoXT handheld as shown in Figure 4.3.1. This is a single-frequency receiver with a Windows® Mobile PC operating system. Although the unit has an embedded antenna, we chose to use an existing geodetic quality antenna at UNB because the GeoXT did not work well in –20C weather.

Figure 4.3.1 – The Trimble® GeoXT Series Handheld. [Trimble, 2007a].

4.3.2 Collecting Data with the Trimble® GeoXT

4.3.2.1 Establishing A Bluetooh® "Bond" With a GSM Mobile Phone

Since the GeoXT that we were using did not have either an integrated GSM data services or a wireless connection we used a Sony Ericsson T616 GSM-enabled mobile phone with Bluetooth® connectivity (This phone, with service, was graciously provided by CanSel®). GSM (Global System for Mobile Communications) is a standard for cellular phone communications on digital networks. It is arguably the most widely used cellular standard in the world [GSM, 2007] and is supported in New Brunswick by Rogers® [Rogers, 2007]. Using this technology, a TCP/IP Internet connection could be established.

The costs for this service vary based on the amount of data transferred. In March 2007, for example, 200MB of data per month costs approximately C$110. Using our CDGPS data rate of 0.5 kB/s, 200MB is equivalent to approximately 114 hours of continual use. It is unlikely that even a daily user would exceed this quantity of data.

Bluetooth® [Bluetooth, 2007] is a standard that allows for wireless data and voice communications over short distances (under 10 metres). Both the Trimble® GeoXT and the Sony T616 units support this standard. Once the devices are “bonded” or “paired”, the GeoXT can seamlessly communicate with the mobile phone to establish a TCP/IP internet connection.

“Bonding” is a procedure carried out only once between any two Bluetooth® devices. In our case, the GeoXT (“client” device) scans the Bluetooth® radio frequencies looking for available “hosts” (our GSM phone). Once discovered, a user enters identical passwords into both devices and a permanent bond is established. Passwords guarantee that both users intend a bond to be formed [Trimble®, 2004].

To complete connectivity, a “dial-up network” connection is configured on the GeoXT. This process tells the receiver to use the Bluetooth® connection as a modem, includes the GSM dialing sequence required by the mobile phone to connect to the Internet, and includes the username and account password required to log onto the mobile service.

4.3.2.2 Configuring COM ports for NMEA

Position solutions can be logged on the GeoXT by either storing them on the local media or by emitting them in the NMEA-0183 format [NMEA, 2007] through a serial port and logging them remotely. For normal operations, a user would likely choose to store solutions locally. However, for this work we specifically want information regarding the latency of differential corrections. Since we were unable to extract this information from the locally stored solutions, we elected to capture emitted NMEA strings.

To enable RS-232C serial output, the Windows® Mobile PC operating system onboard the GeoXT must be used to enable the serial port. Once this is done, the TerraSync® software installed on the GeoXT must be configured to output NMEA strings. In our case, we were interested in receiving NMEA “GGA” messages, which contain time, position, latency and other relevant data.

TerraSync® [Trimble, 2006] is a user program provided by Trimble® which runs under the Windows® Mobile PC operating system on the GeoXT. It is through this software that all GPS data collection operations are carried out. Aside from the system configurations discussed above, all further GeoXT work is carried out inside TerraSync®

4.3.2.3 Configuring the NTRIP client.

When collecting data using differential corrections, we configured the GeoXT using the TerraSync® software. This software contains an NTRIP client. Selection of the data stream (mountpoint) is a two step process. First, the client requests a source-table containing available mountpoints from the NTRIP caster and then the user selects the mounpoint they wish to use. Before starting configuration, the GeoXT must already be connected to the Internet as discussed above.

Although we were able to connect to all desired data sources from both the Cansel® caster and the BKG caster, we did find nuances with the BKG caster. In particular, one attribute that NTRIP assigns to a mountpoint is the “Station Number”. The GeoXT client allows a number to be entered, or the selection “Any” to be chosen. For the Cansel® caster, “Any” always worked. For the BKG caster “Any” worked only for our CDGPS stream while a value of zero was required for our NetR5 stream. We could find no obvious reason for this issue.

In general, once configured correctly, the GeoXT was able to connect to a caster and establish a differential correction stream in approximately one minute.

4.3.2.4 Starting data collection.

Because we were capturing NMEA strings, very little configuration was needed to collect data. **We chose 5 second epochs** since we intended to collect data over long periods. In addition, when differential corrections were to be applied, we configured the GeoXT so that it would emit no data at all during epochs when corrections were not available.

4.3.2.5 Capturing NMEA with Hyperterminal®

NMEA strings were captured to a text file using the Microsoft® Hyperterminal® program integrated with the Windows® operating system.

4.3.2.6 Problems Encountered with the Trimble® GeoXT

Several problems were encountered while collecting data with the GeoXT. The most serious of these was the inability to collect data for long periods of time while differential corrections were being applied. A number of different scenarios arose which resulted in data sets from the order of one-half hour to eleven hours. It was difficult to determine the cause of the problem, so the states in which the equipment was found are described:

1. The GeoXT is still in data collection mode, but the dial-up network connection is lost.
2. The GeoXT is still powered on but it appears that the GPS unit is disconnected. That is, it appears that TerraSync® can no longer communicate with the internal GPS unit.
3. The GeoXT is powered off.

Near the end of our observations, the second problem became dominant. It became increasingly hard to acquire data for more than one half hour.

A second problem was with regard to NMEA output. Although the NMEA standard specifies that 4,800 baud is to be used, it was found that data overruns occurred occasionally. As an experiment the baud rate was changed to 38,400. It was found that at this setting the Windows® Mobile PC operating system crashed. In order to recover, a system reset was required. Although no data was lost, all settings were lost, including Bluetooth® bonding, dial-up networking and NTRIP-related data.

Finally, early on it was found that the screen on the unit became faded and sluggish in temperatures of -10ºC or lower. Since observations were made in the month of February when temperatures were routinely lower than this, we were not able to use the unit outside. This meant that we had to use an external antenna. The Trimble® GeoXT Datasheet [Trimble, 2007a] says that this unit has a lower limit of -10ºC, thus, users should beware if they intend to use this unit outdoors during the Canadian winter.

4.4 Solution Comparisons

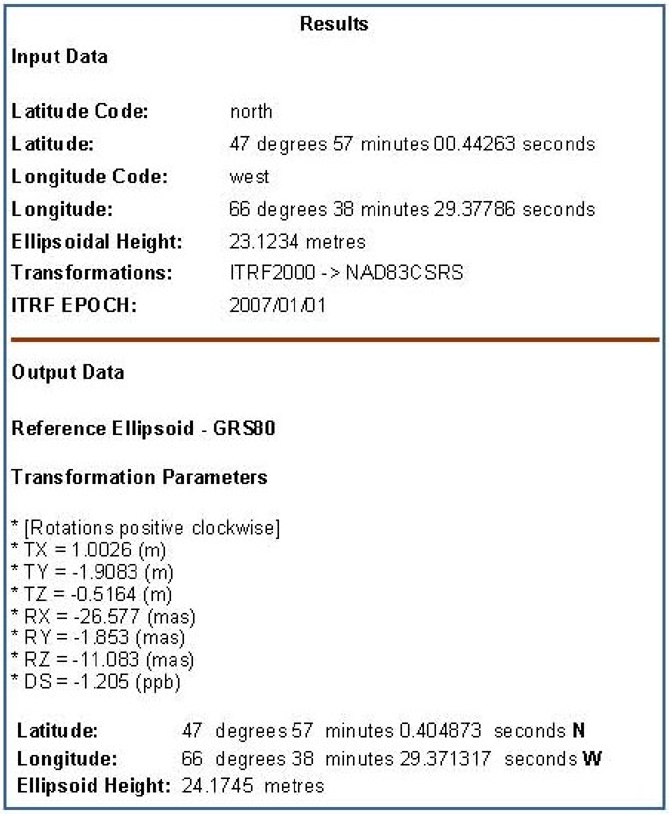
Although GPS solutions are generally carried out in the WGS-84 datum, RTCM corrections can be used to translate the final solution to a different datum (see Appendix E of [RTCM, 2001]). In our case, final solutions are in WGS-84 for uncorrected GPS, NAD83 (CSRS) for CDGPS and the NetR5 located at Halifax, and ITRF2005 (epoch 2007.0) for the NetR5 located at UNB. Section 4.4.1 will show how solutions were transformed into ITRF2005 (epoch 2007.0). It is noted that the uncorrected GPS solutions were left in WGS-84 because it is so close to ITRF [Langley, 2007].

GPS solutions were obtained in geodetic coordinates (latitude, longitude, ellipsoid height). Since most people have a better feeling for position differences in metres rather than degrees or seconds, all differences were converted to metres. Section 4.4.2 describes the formulae used for these conversions.

4.4.1 Datum Changes

Solutions derived using differential corrections from CDGPS and the Trimble® NetR5 located in Halifax were in NAD83 (CSRS). These were converted to ITRF2005 (epoch 2007.0) using the TRNOBS 3D coordinate transformation online application provided by Natural Resources Canada [NRCan, 2007c].

Established ITRF coordinates for the UNBN antenna [Leandro, 2007] were entered into the application and subsequently transformed into NAD83 (CSRS). The difference between these geodetic coordinate values was used to shift all observations. This operation was valid since our observations were static. Figure 4.4.1 shows the TRNOBS program screen after execution.



```
                         Results
Input Data

Latitude Code:          north
Latitude:               47 degrees 57 minutes 00.44263 seconds
Longitude Code:         west
Longitude:              66 degrees 38 minutes 29.37786 seconds
Ellipsoidal Height:     23.1234 metres
Transformations:        ITRF2000 -> NAD83CSRS
ITRF EPOCH:             2007/01/01

Output Data

Reference Ellipsoid - GRS80

Transformation Parameters

* [Rotations positive clockwise]
* TX = 1.0026 (m)
* TY = -1.9083 (m)
* TZ = -0.5164 (m)
* RX = -26.577 (mas)
* RY = -1.853 (mas)
* RZ = -11.083 (mas)
* DS = -1.205 (ppb)

 Latitude:          47  degrees 57  minutes 0.404873  seconds N
 Longitude:         66  degrees 38  minutes 29.371317  seconds W
 Ellipsoid Height:  24.1745  metres
```

Figure 4.4.1: Output of the TRNOBS 3D coordinate transformation program [NRCan, 2007c].

4.4.2 Conversion From Degrees To Metres

Two-dimensional results shown in this report were computed as follows starting with geodetic (latitude ϕ, longitude λ) values [Santos, 2006]:

Step 1: Compute the difference from a known point

$$\Delta\phi = \phi_{observed} - \phi_{known} \tag{4.1}$$

$$\Delta\lambda = \lambda_{observed} - \lambda_{known} \tag{4.2}$$

Step 2: Convert degree differences to distances

$$M = \frac{a\left(1-e^2\right)}{\left(1-e^2\sin^2\phi\right)^{3/2}} \tag{4.3}$$

$$N = \frac{a^2}{\sqrt{a^2\cos^2\phi + b^2\sin^2\phi}} \tag{4.4}$$

$$\delta\phi = \frac{\pi}{180°}\Delta\phi\left(M+h\right) \text{ (metres)} \tag{4.5}$$

$$\delta\lambda = \frac{\pi}{180°}\Delta\lambda\left(N+h\right)\cos\phi \quad \text{(metres)} \tag{4.6}$$

Step 3: Compute the 2DRMS difference

$$2DRMS = \sqrt{\delta\phi^2 + \delta\lambda^2} \text{ (metres)} \tag{4.7}$$

4.4.3 2D Position Scatter Plot

Figure 4.4.2 shows the NMEA position solutions collected between February 2, 2007 and February 12, 2007. It should be noted that, due to equipment problems, data sets were of different lengths. As will be discussed in Section 4.5, both accuracy and precision are correlated with collection time. Although all of our data sets are of sufficient length that the uncertainties have converged to their smallest values, one should be careful when attempting a direct comparison of the uncertainties shown in this graph.

In general, the scatter plot is not surprising. Uncorrected GPS solutions were at the few metre level while all corrected solutions were of an improved quality. Local differential corrections provided the best result: a bias of 20 cm and an uncertainty of

30 cm at 95% confidence. (In this report, “accuracy” or “bias” refers to the horizontal root-mean-square (RMS) distance of a solution from its known point. “Uncertainty” or “uncertainty at 95% a confidence level” was determined by computing the RMS distance of an observation from the mean of the entire set and then ordering these from smallest to largest and choosing the value 95% into the list. These are presented as $\Delta = \mathit{accuracy} \pm \mathit{uncertainty}$).

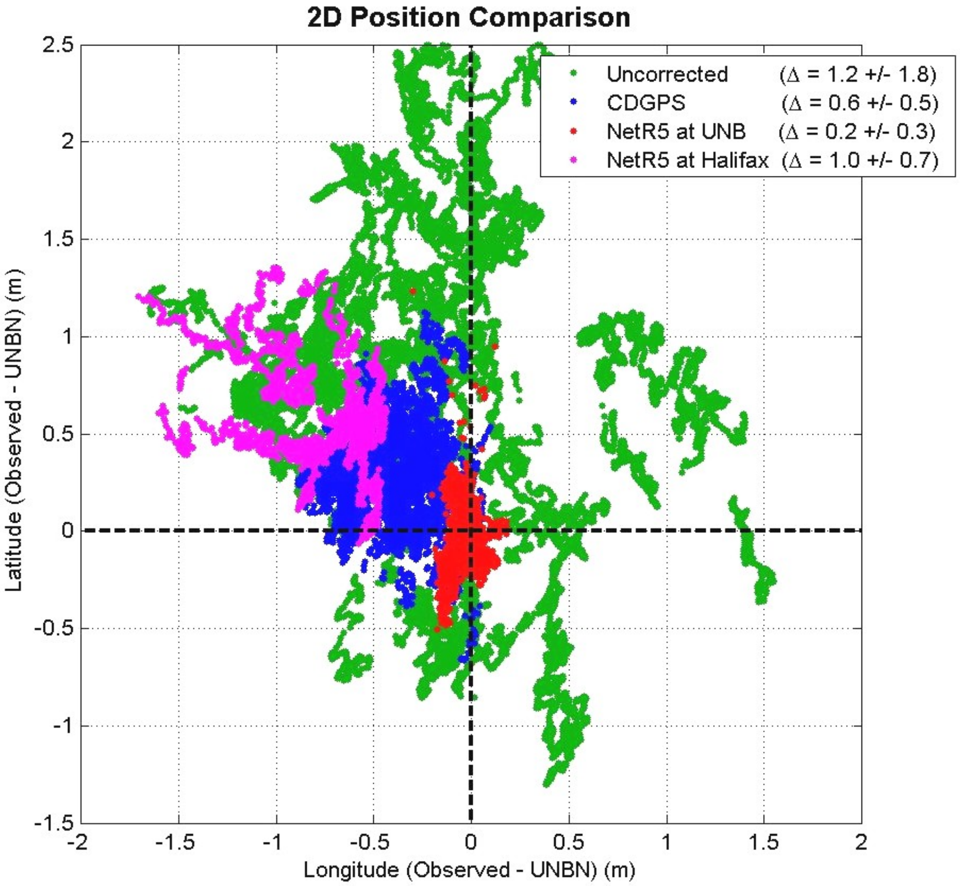


Figure 4.4.2: 2D position solutions with uncertainties at 95% confidence.

CDGPS generated the next best solution with a bias of 60 cm and an uncertainty of 50 cm at 95% confidence. However, is clear from the scatter plot that there is a northwesterly bias present. It is possible that this is due to datum issues. Appendix E of the RTCM v2.3 specification allows for a datum change in user position to be made through the addition of pseudorange corrections [RTCM, 2001]. Normally a GPS receiver carries out its computations in the WGS-84 datum, and thus solutions obtained are also relative to this datum. If a reference station generating differential corrections computes PRCs based on its known position in the WGS-84 datum, then resulting solutions will continue to be in the same datum. However, if the user computes PRCs based on its known position in a local datum, then the resulting receiver solutions will be in the local datum. However, Appendix E warns that this datum transformation brings with it an error that is proportional to the shift between the local datum and WGS-84. This error will grow linearly as the user moves away from the reference station. With CDGPS, reference stations are located throughout Canada. It is possible that the bias we are seeing is an artifact of this datum change.

The only local corrections that were not statistically equivalent to the known value of the antenna at a 95% confidence level were generated by the Trimble® NetR5 receiver located in Halifax (approximately 430km from where the solutions were computed). In this case, two major considerations come into play: the validity of local differential corrections at such a distance, and the effects of a datum shift, since this unit's position was specified in NAD83 (CSRS).

In the work carried out by Monteiro et al., it was found that at this distance from a DGPS reference station (430 km), the 95% uncertainty was approximately 1.5m [Monteiro et al., 2004, Figure 7a]. In our case, we have an error of 1.0 m ± 0.7 m at 95% confidence. Even though we have different equipment and observation times, we can see that our bias is well within the bounds of expectation. To explore this more fully, intermediate reference stations should be set up, perhaps every 100 km and in various directions.

Again, with the Halifax NetR5, a datum shift comes into play. Although we did not oversee the implementation of this receiver ourselves, the vendor states that the coordinates of this station were computed through both a three-day set of observations processed with the “CSRS – PPP” program provided by Natural Resources Canada [NRCan, 2007b] and through baseline observations with nearby Canadian Active Control Stations [NRCan, 2007a]. Resulting coordinates were entered into the unit in NAD83 (CSRS) and thus, receiver solutions were in this datum also.

Knowing this information, it is interesting to note that before the datum shift from NAD83 to ITRF (described in §4.4.1) was applied, the solution set statistically agreed with the known coordinate values. Once the shift was applied, the solution no longer agreed. This would lead one to question the configuration of the receiver in Halifax. However, as will be seen in the next section, the height solutions exhibited the opposite behaviour.

4.4.4 Height Time Series Plot

Figure 4.4.3 shows the height solutions extracted from the NMEA observations. As with the 2D solutions, we see a clear improvement in quality between different techniques. Uncorrected GPS was the worst, wide area was significantly improved, and local differential corrections were the best. Unlike the horizontal case, all solutions were in statistical agreement with the known height of the antenna at a 95% confidence level.

It is observed that height uncertainties were about 50% greater than the corresponding horizontal certainties for uncorrected solutions. This follows the general rule of thumb that horizontal positions are more accurate than heights because geometrically satellites are always above the user, whereas, horizontally they virtually surround the user. For corrected solutions, the uncertainties remained constant. This would imply that differential corrections also account for the geometrical weakness in the satellite constellation.

With the height solutions, we see the opposite behaviour seen with the 2D position solutions with the NetR5 receiver located in Halifax. In this case, after performing the datum shift from NAD83 (CSRS) to ITRF, a bias of only 50 cm remained. If this shift was not made, the bias increases to 80 cm. Though both solutions are within the confidence region computed, it seems that applying the shift is better than not applying it. Thus, whereas the 2D solution indicated that reference receiver configuration issues might be present, the height solution indicates that the configuration is correct.

From this data, we also see that although the Halifax corrections result in solutions centred on the correct value, both the bias and the uncertainty have increased five-fold from the local corrections generated at UNB. As discussed in Chapter 2, this decrease in accuracy and precision with increasing receiver separation is exactly the behaviour expected.

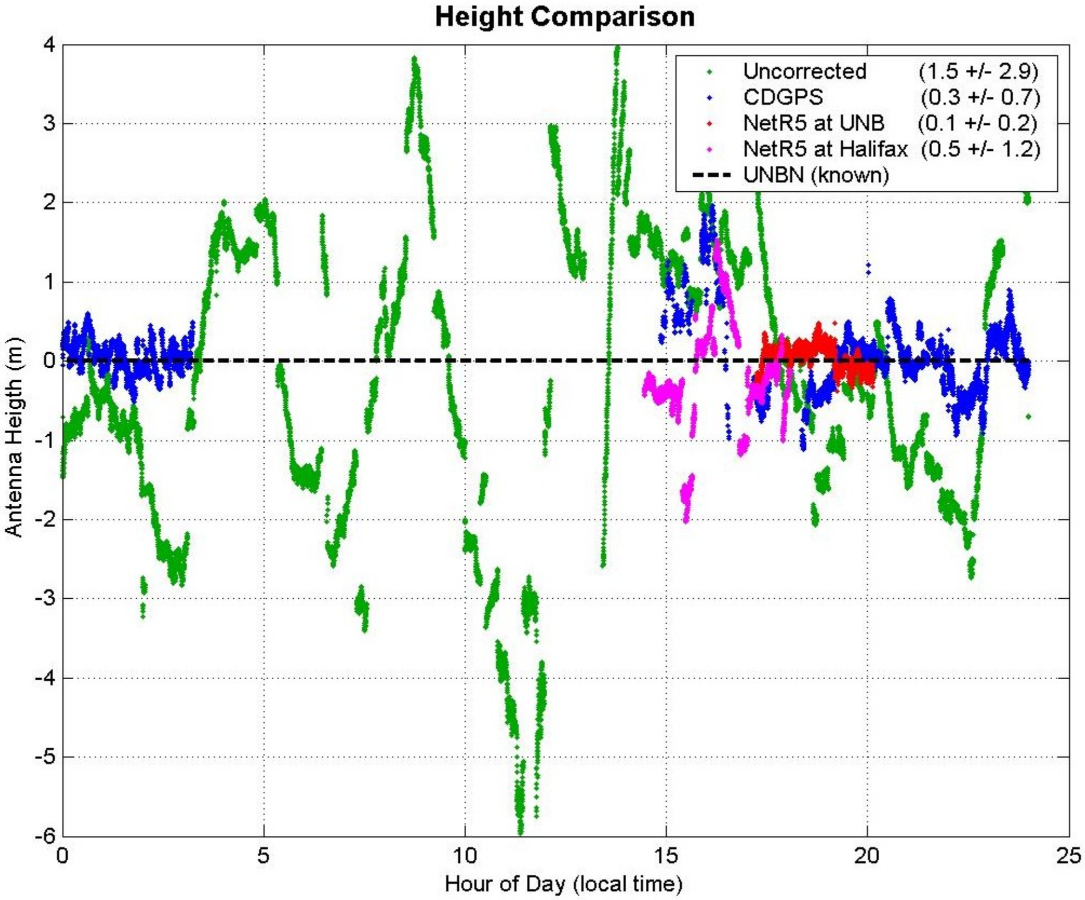
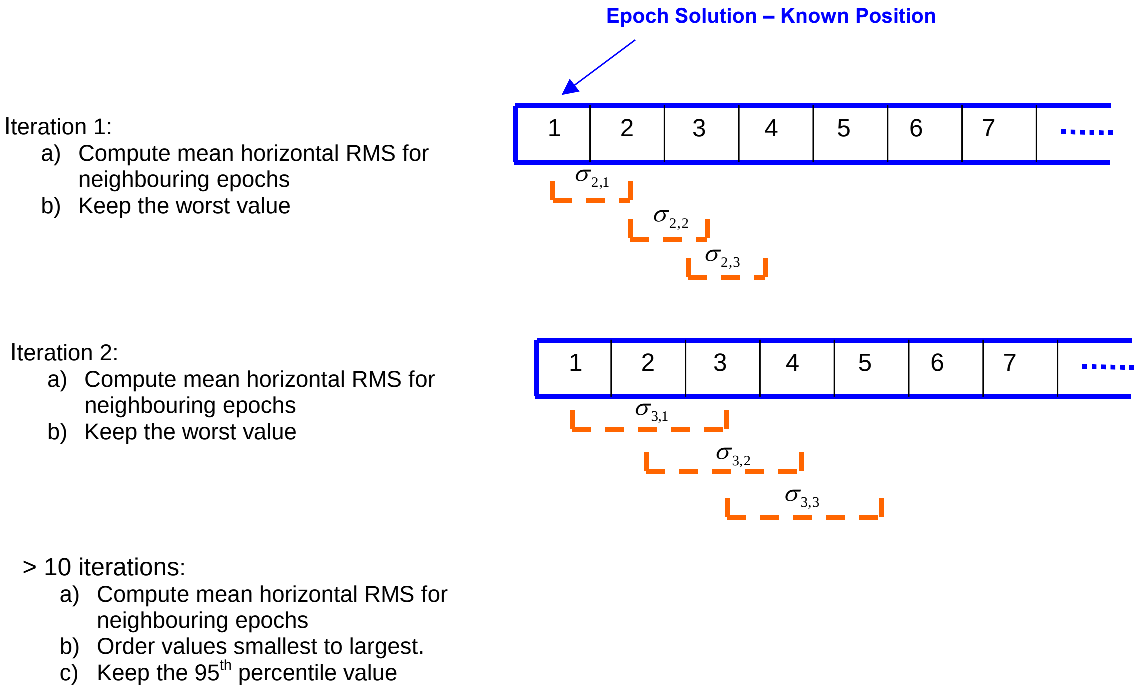


Figure 4.4.3: Ellipsoid height solutions with uncertainties at 95% confidence.

4.5 Precision Versus Observation Time

Up to this point we have examined position and height solutions that resulted from long observation periods. A more pragmatic question pertains to the amount of time required to achieve a particular accuracy with and without differential corrections.

To address this question, data sets were submitted to a moving average window process. In the first iteration, the observation with the largest horizontal RMS error was found and stored. In the second iteration, each neighbouring set of epochs was averaged and the worst average epoch was stored. With each successive iteration, the window-size was increased by one epoch. When window sizes increased past 10 epochs in length (that is, for the majority of the processing), the RMS values for each window were ordered, and the 95th-percentile value was stored. Figure 4.5.1 illustrates this process.



Iteration 1:
a) Compute mean horizontal RMS for neighbouring epochs
b) Keep the worst value

Iteration 2:
a) Compute mean horizontal RMS for neighbouring epochs
b) Keep the worst value

> 10 iterations:
a) Compute mean horizontal RMS for neighbouring epochs
b) Order values smallest to largest.
c) Keep the 95th percentile value

Figure 4.5.1: Moving average-window algorithm used to compare uncertainty with collection time.

4.5.1 Horizontal Positioning

Figure 4.5.2 illustrates the convergence of corrected and uncorrected solutions as collection time increases. It should be recalled that the data sets were not of uniform length. This means that the complete set of horizontal error values for uncorrected solutions came from an 11-hour sample, while data sets for corrected positions came from samples of only a few hours in length. As will be discussed shortly, this should not cause much concern because corrected solutions appeared to converge on their best values at a faster rate than the uncorrected solutions.

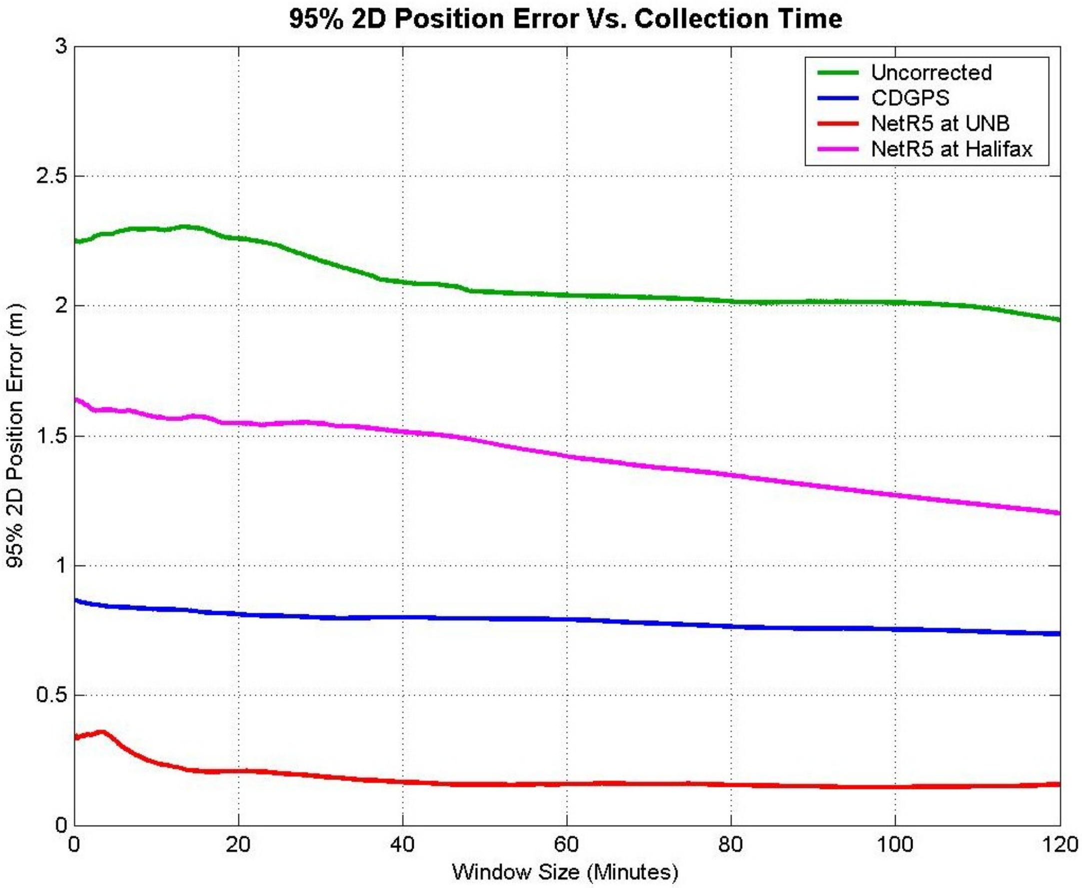


Figure 4.5.2: 2D position uncertainties versus observation time at 95% confidence.

The uncorrected solution actually worsens in accuracy over the first 20 minutes of observation. In fact, it is only after about 40 minutes that the solutions approach the 2-metre level and begin to slowly but steadily decrease with time. The solutions augmented with differential corrections generated at UNB show a similar behaviour, however, they achieve a stable 30 cm-level after only about 10 minutes.

CDGPS and the solutions augmented with corrections generated 430 km away in Halifax, show a different behaviour. The Halifax-corrected solutions start at a 1.7-metre level of accuracy and then increase in accuracy approximately linearly over the next two hours until they reach a 1.3-metre level. Conversely, CDGPS immediately achieves an 80 cm-level accuracy, which it maintains throughout the data collection period with very little improvement.

4.5.2 Height Positioning

Figure 4.5.3 shows the 95-percentile height uncertainties from the corrected and uncorrected observations. As can be seen, the situation with heights is dramatically different than that with horizontal positions.

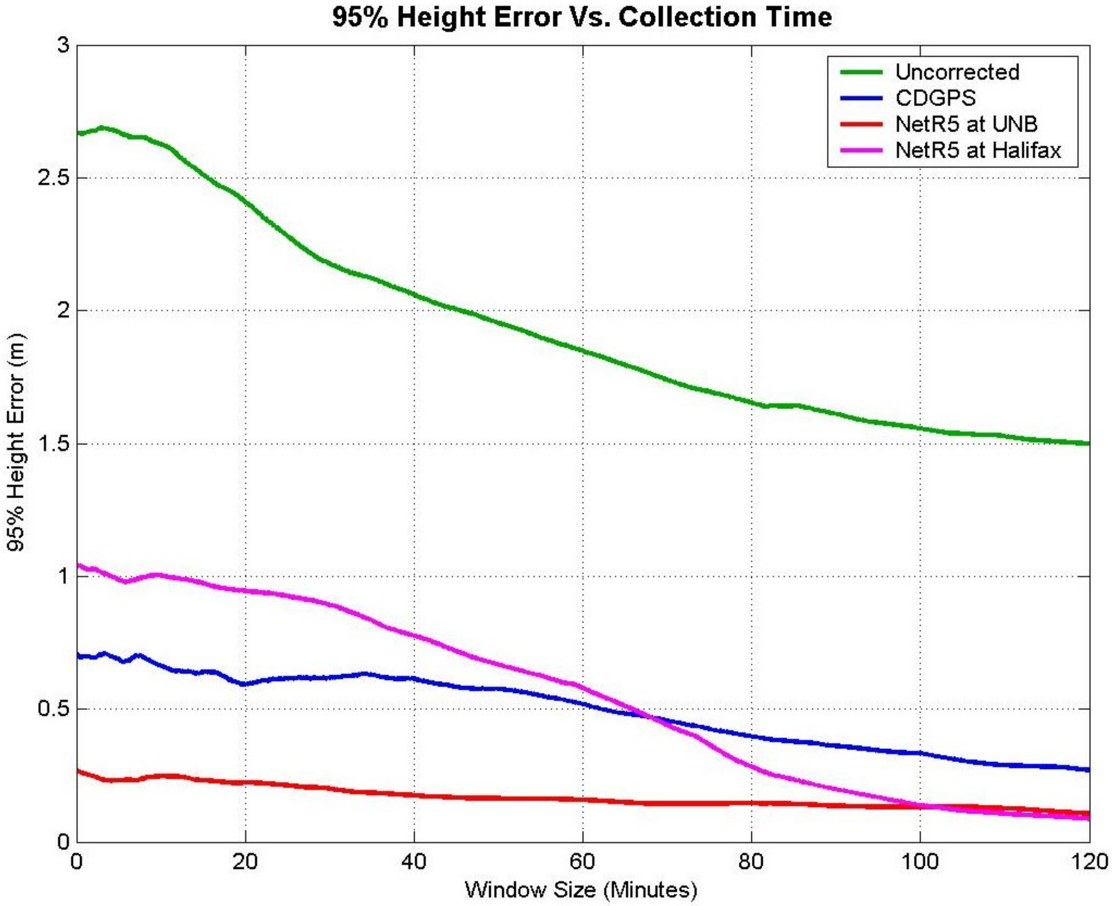


Figure 4.5.3: Height uncertainties at 95% confidence.

As in the horizontal case, for early periods height accuracy actually worsens for the uncorrected solutions. However, after approximately 10 minutes, the accuracy improves in an exponential manner, reaching the 1.5-metre level after two hours of observation.

Solutions augmented by local corrections generated at UNB do not share this behaviour. They appear to immediately achieve the 30 cm level and make only slight improvements over the next two hours.

CDGPS height solutions improve in accuracy by 0.5 metres over a two-hour observation period. This is in contrast to the horizontal situation, where a steady error level was maintained throughout the observation period.

Finally, solutions augmented by corrections generated in Halifax start at the metre-level and actually reach the same 30 cm level of accuracy achieved by the UNB corrections after two hours of observations.

4.6 Latency Comparisons

Latency is the elapsed time between when a PRC initially becomes valid and the time when it is actually applied to observations. Range-rate corrections (RRCs), supplied by the source of differential corrections, may be generated to account for the change in PRC during the latent period. In our case, RRCs were generated for NetR5 corrections but not for CDGPS corrections. Latencies are included in the GGA sentence of NMEA output. These are plotted in Figure 4.6.1. (Note that our receiver was programmed to cease computing solutions if corrections were unavailable for greater than four minutes.)

As can be seen, latencies were generally under 10 seconds. The CDGPS corrections had uniformly higher latencies than either of the other solutions. The NetR5 receiver located in Halifax had the lowest latencies, in the order of 3 seconds. Using packet-watching software owned by CanSel® it was determined that the UNB network contributed approximately 3 seconds to the latency values.

We see also that the mean of the CDGPS latencies is only 0.4s larger than the mean of the NetR5 at UNB. However, the CDGPS uncertainty spread is almost double that of the local NetR5.

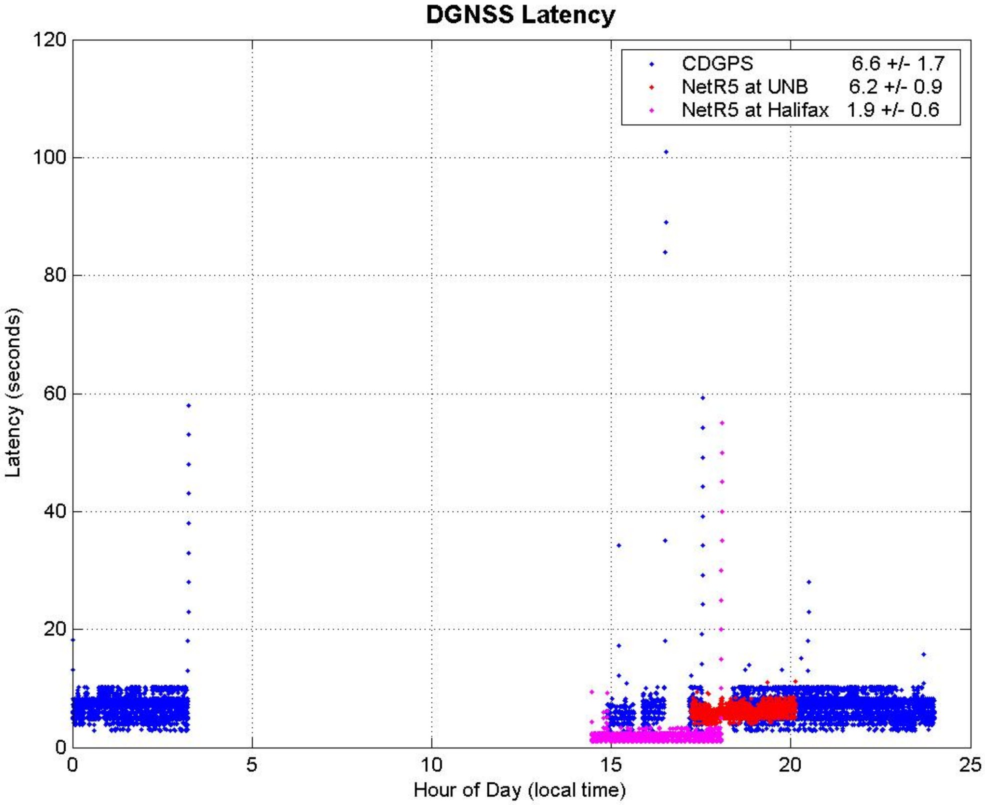


Figure 4.6.1: Latency comparison of differential corrections.

Spikes on the latency graph denote points in time where corrections were disrupted. CDGPS had the worst problem with this issue. Figure 4.6.2 shows the correlation between latency and position solutions. From this we can see that there were three occasions during the data collection where corrections ceased for more than 4 minutes, each causing the unit to stop producing position solutions. The reasons for these disruptions were unclear but were due either to the ePing receiver itself or to the CDGPS system.

During the data collection we saw 3 periods where the Halifax data was latent by approximately 10 seconds. The final spike shown in Figure 4.6.1, however, was caused by a loss of Bluetooth® connection between the GNSS receiver and the mobile phone.

Figure 4.6.2 compares latency with 2D position solutions.

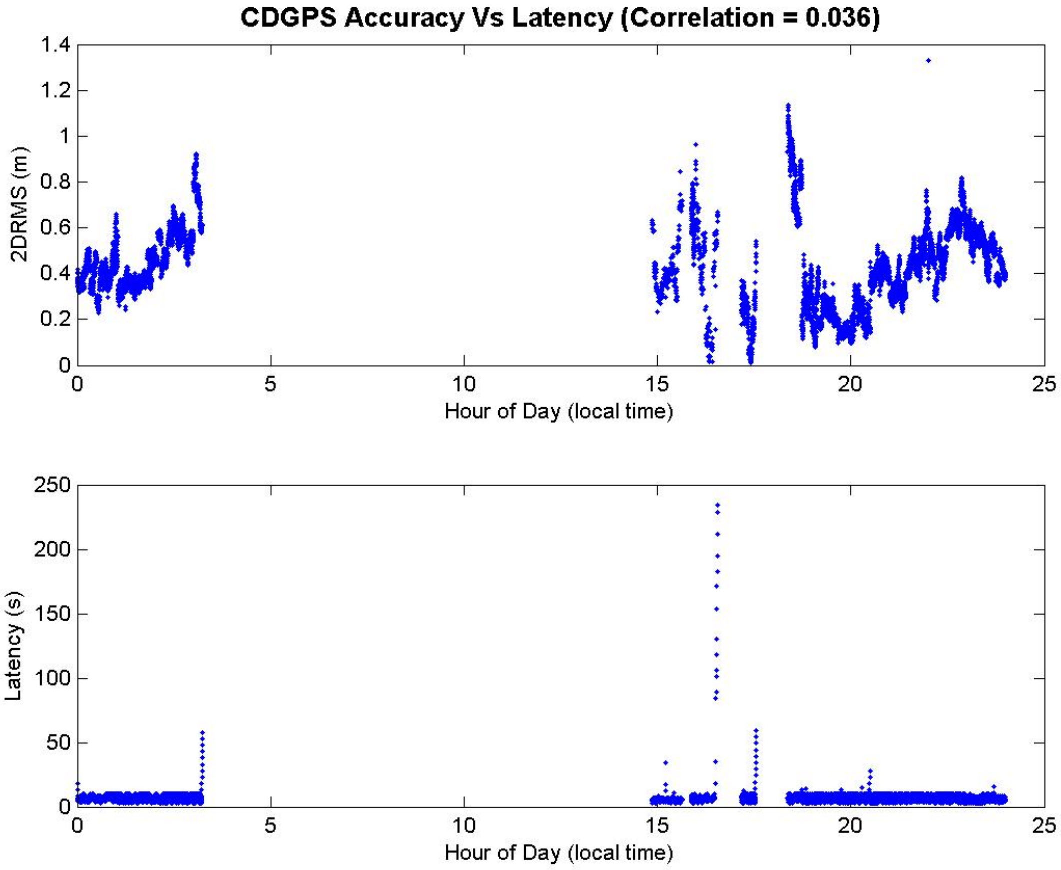


Figure 4.6.2: Correlation of CDGPS 2DRMS with correction latency.

The cross-correlation was computed using the standard formula [Wolf and Dewitt, 2000, Eq. 15-1]:

$$c = \frac{\sum_i \sum_j \left(A_i - \overline{A}\right)\left(B_j - \overline{B}\right)}{\sqrt{\sum_i \left(A_i - \overline{A}\right)^2 \sum_j \left(B_j - \overline{B}\right)^2}} \tag{4.8}$$

Where:

A and B	Are the two vectors being compared
$\overline{A}$ and $\overline{B}$	Are the mean values of these two vectors.

For all data sets, the cross-correlation between latency and accuracy was very nearly zero, indicating that under normal conditions the position solutions were not significantly affected by latency. However, as shown in Figure 4.6.3, the solution accuracy can quickly degrade once corrections stop arriving.

Monteiro et al., note that most GNSS receivers are configured to cease using PRCs and their associated RRCs after a latency period of 4 minutes [Monteiro et al., 2004]. They propose that this limit was chosen in an era when Selective Availability was in place and that in the common era, a 4 minute cap on PRCs is unwarranted. However, here we see that error doubled during this 4 minute period. It would be interesting to see how much more the solution would degrade with time. If the observed trend were to continue as shown in our figure, errors would likely meet the uncorrected GNSS levels at a latency of approximately 10 minutes.

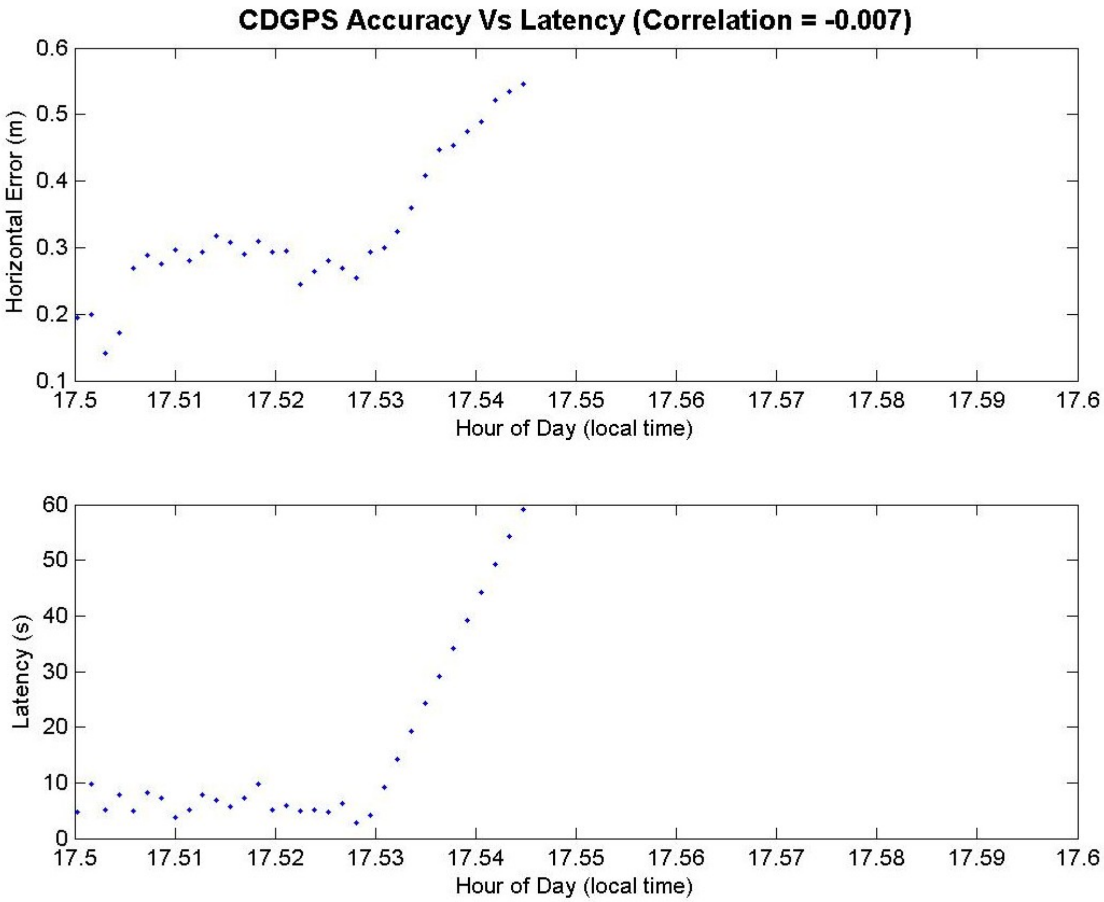


Figure 4.6.3: Close-up of correlation of CDGPS 2DRMS with correction latency at a correction outage.

5.0 CONCLUSIONS

In this report, an examination of the dissemination of pseudorange corrections (PRCs) using the NTRIP specification over the Internet has been carried out. Of interest have been both the comparison of wide area corrections versus local corrections and the ability of NTRIP to facilitate the transport of corrections into the field for real-time application.

Although NTRIP is also able to carry real-time kinematic (RTK) corrections, it is felt that PRCs still maintain a significant relevance in modern work due to their significantly cheaper cost and ease of application. Many applications, such as establishing ground control for satellite imagery and positioning for hydrographic surveys require only sub-metre-level accuracies. These accuracies were realized in this work using differential corrections and NTRIP.

In the following sections, comments will be made regarding NTRIP, CDGPS and local DGNSS.

5.1 NTRIP

NTRIP is still in its formative stage. Due to this, we encountered problems such as the inability to connect our NTRIP server to the CanSel® network, and difficulty in configuring freeware NTRIP server software to accept corrections from a local serial port. However, the specification itself seems strong and the fact that the open-ended design allows dissemination of any type of binary stream, and not simply RTCM, will ensure its relevance in the future.

In the current market, the biggest obstacle is connectivity. The availability of GSM in Canada is a relatively recent advent and the cost is still fairly high. The Rogers® GSM service used for this work is available on the order of $110/month or $1320/year plus phone equipment. In addition to this cost, the expense of either producing differential corrections or subscribing to a commercial service must be considered.

This report did not explore the current geographical coverage for mobile phone connectivity in New Brunswick. However, before one committed to this technology, one would want to ensure that cell phone coverage was available in the intended regions of use. To date, one can be confident of coverage in the corridor occupied by the Trans Canada Highway, while more remote regions may not provide sufficient signal.

The future for NTRIP and other Internet-based services is bright. The last twenty years has seen a rapid rise of the Internet. The last ten years has seen cell phone technology gain popularity to the stage where we now see elementary school children with mobile phones. Today, we are seeing a rapid merging of the two technologies as the entertainment industry strives to provide music and movies through the mobile network. In addition, wireless Internet is coming into age. Projects such as the Fredericton eZone [City of Fredericton, 2007] allow free Internet access from many public places within the city limits. As time passes, Internet access will become ubiquitous in our environment. Under these circumstances, NTRIP will flourish.

5.2 CDGPS

Currently CDGPS is of limited use to the general population of Canada because it is not supported by the mainstream GNSS receiver market. In the past, users have had to purchase an external ePing receiver, which could receive satellite broadcasts and forward them in RTCM format to a GNSS receiver. Today, ePing receivers are no longer in production, and so new users must typically buy a NovAtel®-based GNSS receiver solution. When one compares this to the FAA's Wide Area Augmentation System (WAAS), which is integrated into virtually every receiver solution now on the market, one sees why the general public has never heard of CDGPS.

NTRIP could be the technology to bring CDGPS to the mass population, since virtually all GNSS receivers do accept RTCM PRC corrections. Such a solution would still be cumbersome for receiver units that do not support NTRIP natively. One could envision two scenarios for implementation. In the first, CDGPS would stream raw wide area (that is, GPS*C) corrections over the Internet via NTRIP. Clients would need a mobile PC unit with an NTRIP client embedded and a software program to localize these corrections to RTCM and forward them to the GNSS receiver. In the second scenario, CDGPS would set up a full NTRIP caster system. In requesting a mountpoint, NTRIP clients would transmit their own approximate location. The CDGPS caster would then localize the corrections and transmit RTCM. The latter scenario might be what is required to encourage more users to employ the system.

Another issue that should be addressed for CDGPS to become a mainstream solution is its interaction with the public. The CDGPS website [CDGPS, 2007] appears to have not been updated in quite some time. It still appears to promote the ePing receiver, though this avenue has been terminated. In addition, there are apparently software toolkits available for end-users to support CDGPS, but there is no mention of them on the website. CDGPS needs to provide an environment where the general public can interact.

Finally, CDGPS needs to provide more analysis of performance on their website. Currently, the most recent document is dated in 2003 and provides an indication of initial performance of the system. The types of questions that most potential end-users will have are more of the form addressed in this report: what accuracy can be expected, what observation times are required, and how can various types of equipment can be configured to accept corrections? Some comment on the datum shift from WGS-84 to NAD83 (CSRS) should also be made, along with the variation effects across the country.

5.3 Local DGPS

Local DGPS vastly outperformed all other solutions tested in this report. Partly, this was due to the fact that our corrections were generated at the same location as the position solutions were obtained. This does not give a true sense of the accuracy of corrections, as is seen by the Halifax results. The effects of increasing distance on corrections have been examined by Monteiro et al., but should be examined by any user intending to make use of local corrections.

NTRIP provides an interesting opportunity in the Canadian and New Brunswick context. Canada currently operates 46 active control stations [NRCan, 2007a]. New Brunswick also operates a more densified network of several active control stations [SNB NRCan, 2007a]. Each of these stations consists of a dual-frequency GNSS receiver and is connected to the Internet such that users can obtain observation files on an hourly or daily basis. By simply forwarding the raw observations through a NTRIP caster, users would be able to generate their own RTK or PRC corrections. Alternatively, RTCM streams could be generated by the stations and streamed through an NTRIP caster, further simplifying the user experience. Given that the infrastructure is already in place in both jurisdictions, a huge gain could be made for very little cost. Extra effort should be made by a service organization to provide studies to guide end-users regarding accuracy expectations and observation time requirements.

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