NEUTRAL ATMOSPHERE INDUCED GPS ERRORS CAUSED BY THE 2004 HALIFAX WEATHER BOMB

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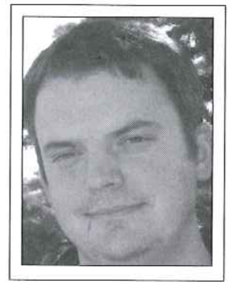
In February 2004 the city of Halifax was hit by a weather bomb. Weather bombs are the most intense and severe among all types of winter storms. This type of storm is typified by a strong low-pressure system with a central pressure that falls 24 hPa or more in a 24-hour period. Weather bombs are associated with heavy amount of precipitation, hurricane-force winds, beach erosion, and coastal flooding. A weather bomb is created when a low-pressure system develops over the Southern North Atlantic bringing moisture from relatively warm ocean water. This system is then brought up northwards by the Jet Stream provided it is plunging south enough, bringing cold air that combines with the warmer air from the Gulf Stream.

We have made use of GPS and meteorological data sets collected during the Princess of Acadia Project to analyse the impact of the 2004 Halifax Weather Bomb on positioning. The data were collected at stations located in Fredericton and Saint John, besides Halifax. The passing of the storm provoked huge variations in meteorological parameters. These variations are distinct for each one of the stations. Neutral atmospheric prediction models do not properly account for these variations. The analysis takes advantage of time series of coordinate differences of baseline solutions and also looks at the variations in the relative neutral atmospheric delay. Results indicate that variations in position of as much as a few centimetres are expected under similar severe storms, depending on the processing settings.

En février 2004, une « bombe » météorologique, c'est-à-dire un système dépressionnaire prenant rapidement de la force, a frappé la ville de Halifax. Les bombes météorologiques sont les tempêtes hivernales les plus intenses et les plus redoutables de tous les types de tempêtes hivernales. Ce type de tempête se caractérise par un système dépressionnaire intense dont la pression centrale chute de 24 hPa ou plus durant une période de 24 heures. Les bombes météorologiques sont associées à une quantité importante de précipitations, à des vents de la force d'un ouragan, à une érosion des plages et à des inondations côtières. Une bombe météorologique est créée lorsqu'un système dépressionnaire se développe au-dessus du secteur sud de l'Atlantique Nord, apportant de l'humidité de l'eau océanique relativement chaude. Ce système est ensuite poussé en direction du nord par le courant-jet, à la condition qu'il s'enfonce suffisamment vers le sud, apportant de l'air froid qui se combine à l'air plus chaud du Gulf Stream.

Au cours du projet Princess of Acadia, nous avons utilisé des jeux de données GPS et de données météorologiques pour analyser l'impact sur le positionnement qu'a eu la bombe météorologique de 2004 à Halifax. Les données ont été collectées dans les stations situées à Fredericton et à Saint John, près de Halifax. Le passage de la tempête a provoqué des variations énormes des paramètres météorologiques. Ces variations sont distinctes pour chacune des stations. Les modèles de prévision d'atmosphère neutre ne tiennent pas compte correctement de ces variations. L'analyse tire profit des séries chronologiques des différences de coordonnées pour les solutions des lignes de base et examine également les variations dans le retard relatif de l'atmosphère neutre. Les résultats indiquent que de telles variations au niveau de la position, pouvant parfois même atteindre quelques centimètres, sont prévues lors de tempêtes redoutables similaires, selon les paramètres établis pour le traitement.



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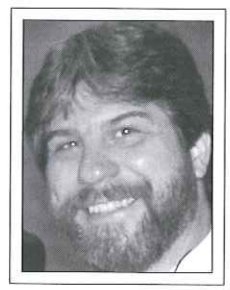

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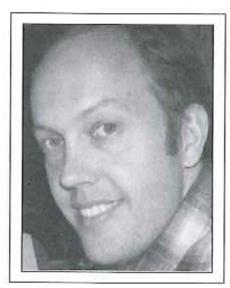

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1. Introduction

On February 18, 2004, Halifax was the primary target in the storm's path that devastated the Canadian Maritimes causing a complete cancellation of all activities and transportation movement in and around the area. The city was thumped with a vast amount of snow and violent high winds that made visibility virtually impossible. We have made use of Global Positioning System (GPS) data and meteorological information collected throughout the storm's duration by a Natural Resources Canada station in Halifax to analyse how positioning, especially vertical, was influenced by the passing of this weather storm.

All storm fronts have a tendency to rapidly alter the meteorological environment. Since the

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meteorological conditions that are being affected are very influential in many GPS atmospheric errors, it is expected that relative positioning should display some variations. This paper examines both positioning and meteorological variables to show which type of weather factors might have produced the greatest impact.

The importance of this research can be summed up in the widespread expectation of GPS being able to produce high precision results during all weather conditions. With the frequent occurrence of snowstorms in the Maritime regions, and in Canada as a whole, it should entice people to seek a better understanding of the expectations for GPS solutions during unfavourable weather conditions.

The neutral atmosphere is the non-ionized layer contained by the troposphere and the stratosphere, located from the earth's surface up to about 50 km above. It is the layer in which most of the earth's weather patterns are contained. Unlike the ionosphere, the delay caused when the signal crosses the neutral atmosphere cannot be eliminated by using dual frequency measurements. The neutral atmosphere is non-dispersive, which means the delay affects the signals in different frequencies by the same amount, which will require a different mitigation technique. All GPS signals will be affected by neutral atmospheric delay, but this effect is more prominent with satellites that are lower in the sky (thicker neutral atmospheric layer to travel through). Neutral atmospheric delay is broken into two types, the hydrostatic (sometimes also called dry) component that makes up about 90 percent of the total delay, and the non-hydrostatic (also called wet) component that makes the other 10 percent [*Langley* 1996]. The hydrostatic delay can be more accurately determined using *a priori* prediction models. Prediction models require information about the station's pressure and location on earth. The amount of wet delay is a function of water vapour present in the lower part of the neutral atmosphere. Surface humidity readings might be taken from the ground but are not a good indication of the amount of humidity contained in the layer above. This makes producing a precise wet delay *a priori* prediction model a difficult task.

Little has been investigated in terms of how much the passing of a weather front affects GPS positioning. The literature shows the work of *Blewit and Gregorius* [1998]; *Barlag et al.* [2002] and *Champollion et al.* [2004]. In this paper, we describe an investigation looking into a winter weather storm.

The scope of the project consists of performing a comparison on GPS baselines from Halifax to other GPS stations located in the municipalities of Saint John and Fredericton. Data was collected throughout the days of February 15-20, at 30-second intervals. For processing the baselines, GrafNav, from NovAtel's WayPoint Consulting was used. The results for different baselines should display similar behaviour with the passing of the storm. The meteorological data collected at the stations are also looked into and used to help explain why these effects are present in the solutions.

2. Weather Fronts

A weather front is defined as the boundary between air masses with different characteristics (e.g., temperature or humidity) [*AMS* 2000]. Weather fronts occur with variable frequency over a certain area leaving different amounts of precipitation along with it. At the latitude we are working on, the movement of these fronts is generally influenced by the Jet Stream, in which weather patterns move west to east. There are two basic types of fronts: cold and warm.

The arrival of a cold front occurs when a cold air mass approaches a warm air mass. As the two air masses approach each other, the cold air mass will go under the less dense warm air mass and overtake it, causing the atmosphere above it to be more turbulent. Cold fronts usually produce hard hitting, fast approaching storms such as snowstorms, thunderstorms and even tornadoes. These storm systems generally do not last long, since the jet stream moves them quickly out of the area. As for the warm fronts, they are produced from a warm air mass approaching a cold air mass, rising up above the cold air. The warm fronts usually bring about less severe weather, such as light snow or rain that can last longer [*AMS* 2000].

The error associated with oncoming storm systems is primary from neutral atmospheric delay that the GPS signal experiences. Storm systems bring rapid changes in the area's pressure, temperature, humidity, and precipitation. Therefore it is fair to expect that a massive snowstorm would cause variations in the position estimated with GPS, depending on the processing settings

3. The Halifax Weather Bomb

The storm that hit the Maritimes the night of February 18, 2004 was unlike any witnessed on the east coast of Canada for several decades. The northeaster storm traveled quickly through the middle of

Nova Scotia bringing with it a vast amount of snow in a short period of time. The "Weather Bomb," as meteorologists had called it, forced the Provinces of Nova Scotia and Prince Edward Island to declare their first ever state of emergency. This required anyone that was not an essential worker to stay off the roads and also allowed police officers permission to pull any traveling or parked cars from the snow-filled roads [*CTV* 2004]. Figure 1 shows a weather map of the snowstorm that hit the East coast of Canada on February 18, 2004 [*Santos et al.* 2005].

The most impacted area by the Weather Bomb was the City of Halifax, which was located right at the centre of the storm's path. Some areas of the city received over 90 cm of snow throughout the total duration of the storm. The amount of snow the City of Halifax received, broke the one-day record, which was previously set at 50.8 cm back in 1944. Along with a huge amount of snow, the storm had also produced 100 km per hour winds that knocked down many power lines and made visibility outdoors practically impossible. This storm left many people stuck in their homes without heat and electricity for many days [*CBC News* 2004].

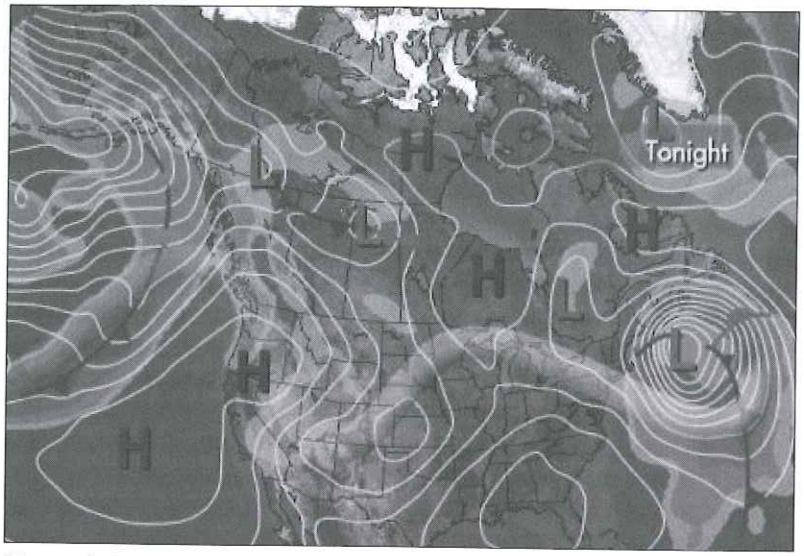

Figure 1: Weather Map of the February 2004 Snowstorm (courtesy of The Weather Network).

4. Type and Location of Sensors

An important aspect that helps to understand the damage caused by the storm is the amount of snow that fell during the storm's duration. As the GPS station in Halifax does not have a precipitation sensor located near the site, data collected from Environment Canada's Halifax International Airport sensor was used. Even though they are 15 km apart, the information is useful to show the general intensity of the snowstorm. The precipitation sensor utilized by Environment Canada to monitor snow and rainfall for Halifax is a Nipher gauge, shown in Figure 2. It is essentially a bucket; in the opening of the bucket, snow is gathered and turned into liquid by an antifreeze agent. Precipitated water collected is weighted and converted into the actual measured readings. As the Nipher gauge measurements are in rainfall amounts (not actual snowfall), a conversion stated by Environment Canada was applied. Snow amounts are calculated by multiplying the rain amount collected by ten to get snow amount (accuracy of ± 0.5 mm) [*Environment Canada* 2006].

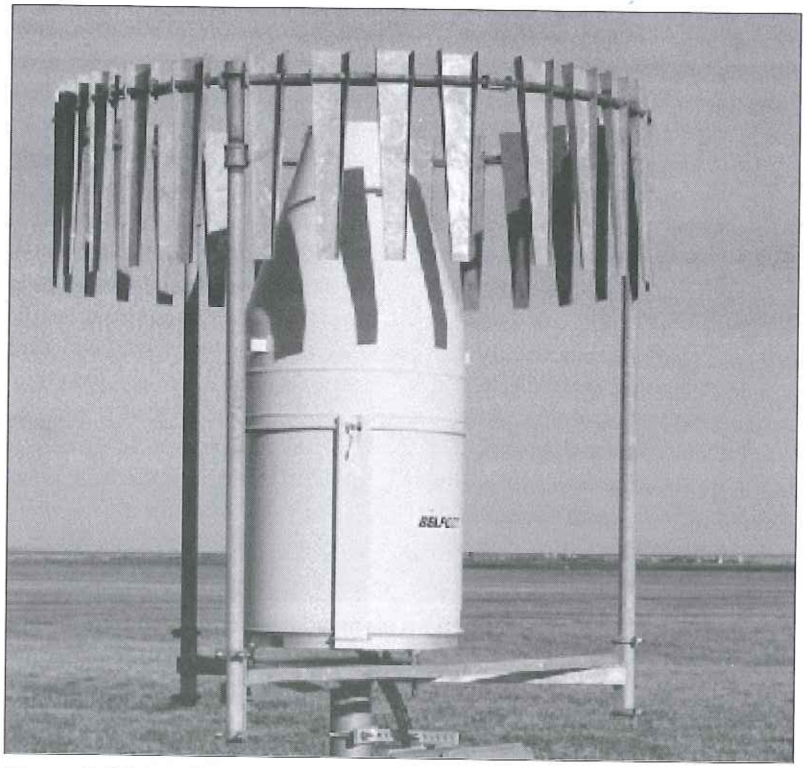

Figure 2: Nipher Gauge.

Figure 3 displays the snowfall amounts according to the dates it was collected. Precipitation data was recorded every 15 minutes for the Halifax station throughout the course of each day. As the figure shows, the snowstorm that struck Halifax late on the 18th to early 19th of February produced 300 millimetres of snow. This information will prove to be important to determine time of arrival and explaining some of the results.

A number of GPS stations were in operation in and around Halifax before, during and after the storm. Beside the two GPS stations in Saint John (CGSJ) and in Digby (DRHS), which were part of

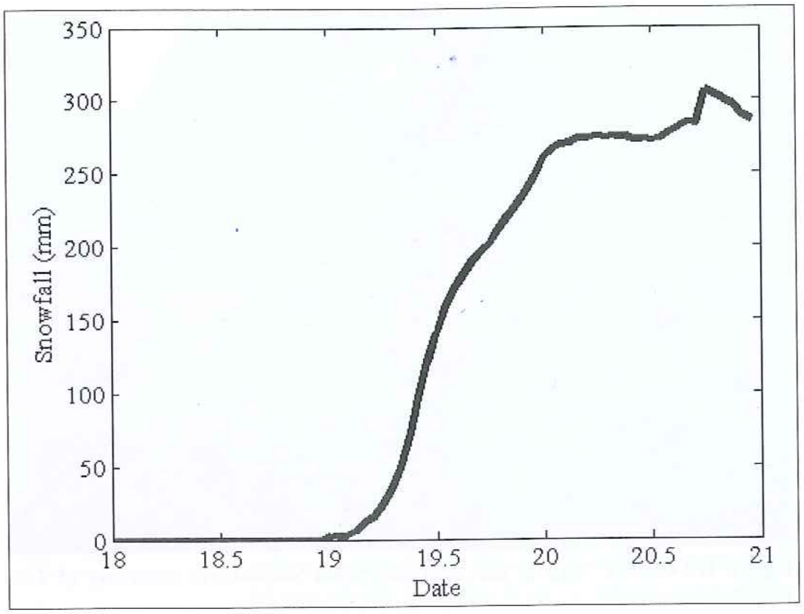

Figure 3: Amount of snowfall in Halifax.

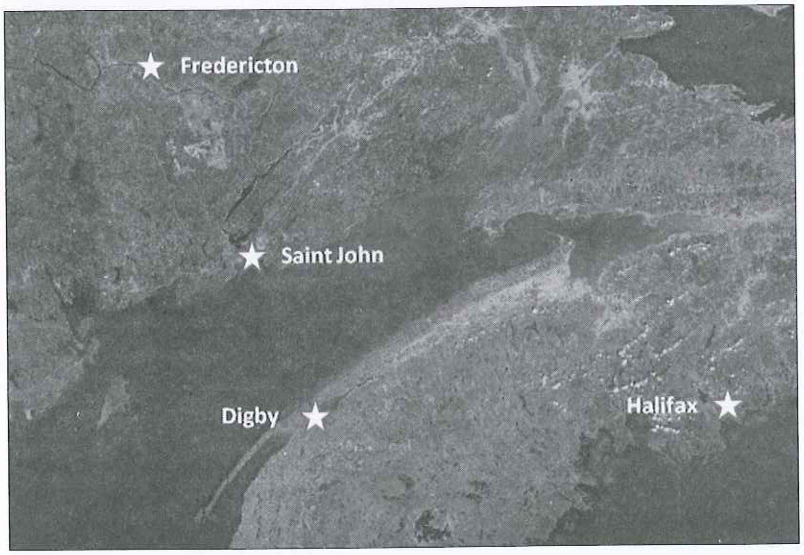

Figure 4: Distribution of GPS Stations (as mentioned in the text, Digby could not be used).

the Princess of Acadia Project [*Santos et al.* 2005], there were other two permanent stations, one located in Fredericton (FRDN) and the other in Halifax (HLFX). The GPS data was continuously recorded at 30-second intervals throughout the course of the day. Meteorological sensors were set up near each GPS unit to monitor temperature, pressure and humidity (unfortunately, the met sensor in Digby mal-functioned during that week and could not be used). The met data was collected at 15-minute intervals throughout the dates of February 16 to the 20. The Saint John station was situated on the top of the Coast Guard building. The two other GPS stations (Halifax and Fredericton) are part of the Canadian Active Control System. The location of these stations is as follows: Halifax—roof of the Bedford Institute of Oceanography; Fredericton—by the lawn of the Hugh John Flemming Forestry Complex. The actual coordinates for each station were very accurately determined previously in ITRF2000 and all analysis was done in this reference frame.

The baselines from Saint John and Fredericton to Halifax are all quite long for purposes of GPS kinematic positioning (202 km and 310 km, respectively). The farther the station is from Halifax, the less similar will be the atmospheric effects on the signals originating from the same satellite to the two stations. Figure 4 shows the location of the stations. During the storm, each station was affected differently, what would translate into differences in the data. Starting with Halifax that was definitely hit the hardest and moving west, the storm became gradually less severe. For example, in Fredericton, the farthest station to the west, the storm produced some unfavourable weather conditions but nothing comparable to Halifax.

5. *Effects on the Meteorological Data*

An important aspect of testing the effects of weather fronts on GPS positioning is to determine the kind of atmospheric conditions the site was experiencing at that time. Using the meteorological data collected at Halifax and Fredericton stations, an analysis was made to determine which atmospheric factor had the greatest effect on the GPS data.

Temperature is the most easily noticeable weather parameter. Before the arrival of a storm system, usually temperature will steadily increase until the storm hits. Once the storm has arrived, the temperature will remain reasonably constant (for snowstorms, around zero degrees Celsius) for the duration of the storm [*Blewitt and Gregorius* 1998]. As shown in Figure 5, these same common traits also exist in the temperature data collected for the Halifax and Fredericton stations. On February 16th through to late on the 18th, the temperature varied from relative highs in the afternoons to relative lows during the night. However, as the winter storm system approached, the Halifax station readings showed the temperature had increased until it reached about –2 degrees Celsius about the time of the arrival of the system, and then remained steady.

Humidity is a measure of water vapour content in the air. Surface humidity observations are measured using a hygrometer; it is important to bear in mind, though, that surface conditions are not necessarily representative of the actual humidity for areas higher up in the atmosphere [*AMS* 2000]. Since the hygrometer at the Halifax station at the time of observation was experiencing mechanical problems, humidity data from the Halifax International Airport, the closest Environment Canada station, was used. These two sites are 15-km apart, so the humidity shown in Figure 6 may not be exactly the humidity experienced at the GPS station. From the observations that were obtained, humidity for the region took a sharp increase to close to 100 percent around the time of the storm's arrival. This drastic increase in the water vapour can be explained by the simple fact that the storm brought with it large amount of water vapour and probably dissipated into precipitation. Since the wet part of the neutral atmospheric error depends on the water vapour in the atmosphere, its increase suggests (but not guarantees, since conditions on the ground and surface may differ) an increase in the amount of neutral atmospheric delay. As for the City of Fredericton, the result shown in Figure 6 displays the same increase in humidity, but at a smaller scale. In fact, the real danger for relative GPS positioning lies not at the large humidity readings in Halifax, but at the large difference in humidity between Halifax and Fredericton; these large differences will not be cancelled out by the double-differencing technique employed in relative positioning.

Measuring air pressure is usually conducted by a barometer. During situations in that an oncoming weather storm is traveling through an area, the air pressure will make a significant drop from its normal level. Once the storm has begun to exit, air pressure will start increasing back to its normal levels [*Blewitt and Gregorius* 1998]. Figure 7 indicates the Halifax snowstorm started affecting the city around late February 18, with a sudden decrease in pressure. The pressure continued to drop throughout the entire next day, until it started to stabilize with the passing of the system. These pressure changes should produce variations in the amount of neutral atmosphere delay that will be impacting the observations. Fredericton station data can be observed in conjunction with Halifax's, in Figure 7.

6. *Effect on GPS Relative Positioning*

The first criteria for determining if passing weather fronts have any effect on GPS relative kinematic positioning is to verify the existence of trends in the processed results during the time of the storm's arrival. All the baselines were processed using *GrafNav* [2004], from NovAtel WayPoint Consulting, version 7.4. Stations Fredericton and Saint John were constrained. Solution for Halifax was processed in kinematic mode. Dual frequency was utilized so that the results would not be overly contaminated by the ionospheric delay. The processing package also has a neutral atmospheric model that can be used to eliminate some of the zenith delay. During the processing, the option to correct for neutral atmospheric delay using an a priori model was left enabled, since this is the most

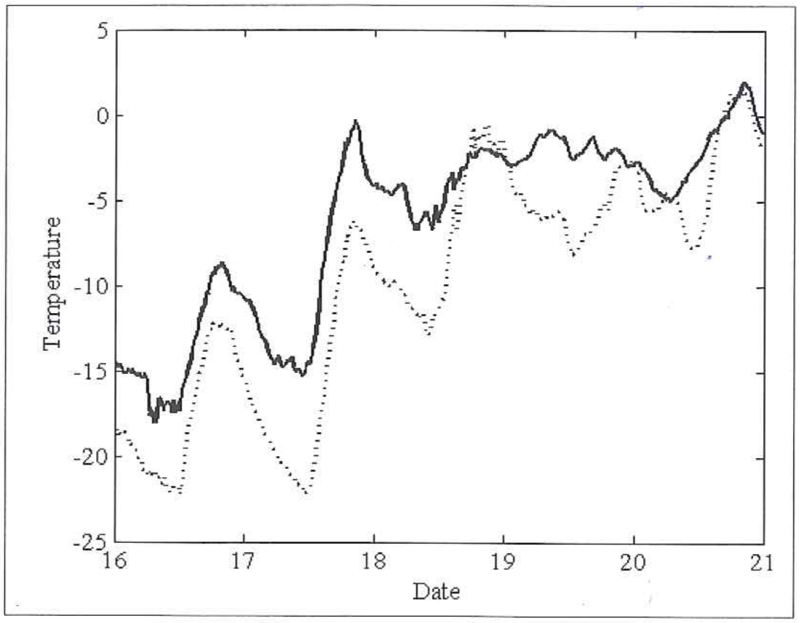

Figure 5: Temperature in Halifax (continuous line) and Fredericton (dotted line).

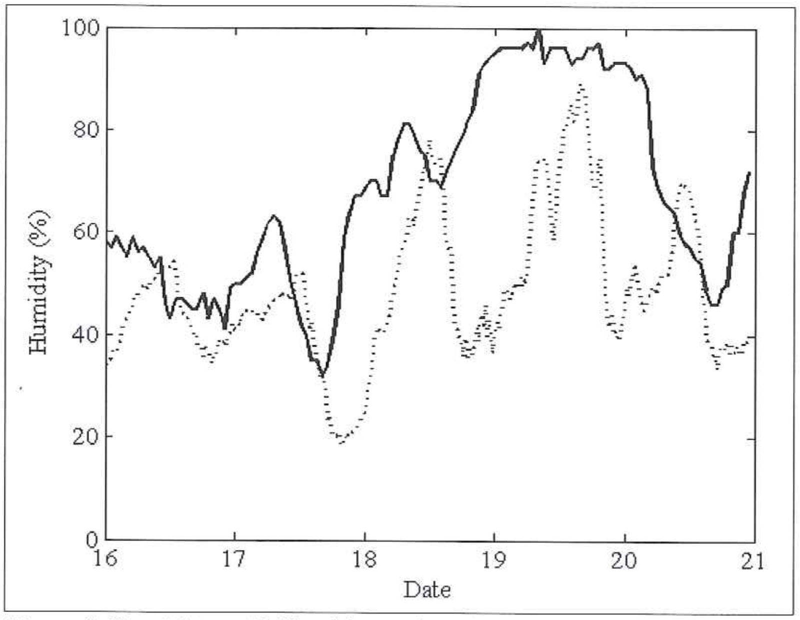

Figure 6: Humidity at Halifax Airport (continuous line) and in Fredericton (dotted line).

common approach in GPS processing; no residual delay was estimated because of the danger of causing a bias in the estimated phase ambiguities.

6.1 Vertical Positioning

Figures 8 and 9 show the difference between the estimated coordinates of Halifax and their mean value, as reckoned from Saint John and Fredericton, respectively. We expect results from the longer baseline solution (Halifax-Fredericton) to be more severely affected by the storm. As the

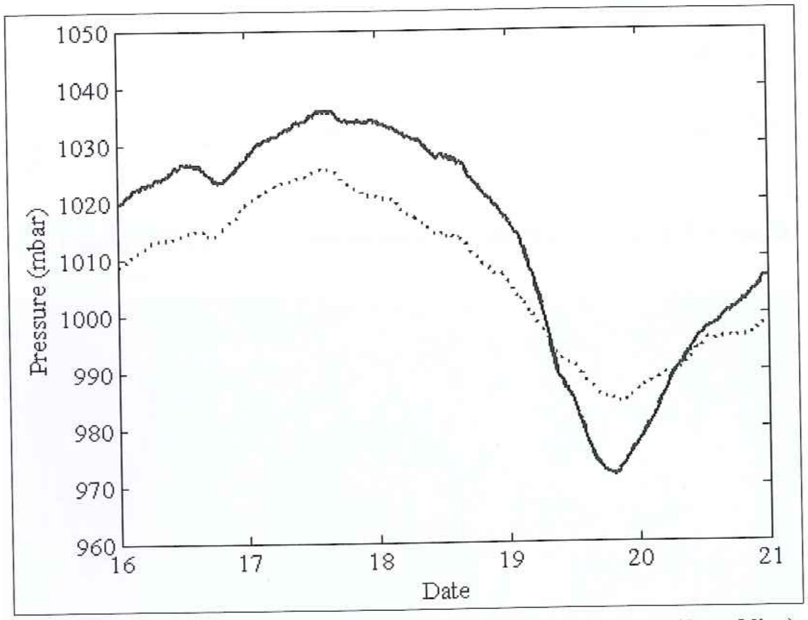

Figure 7: Pressure in Halifax (continuous line) and in Fredericton (dotted line).

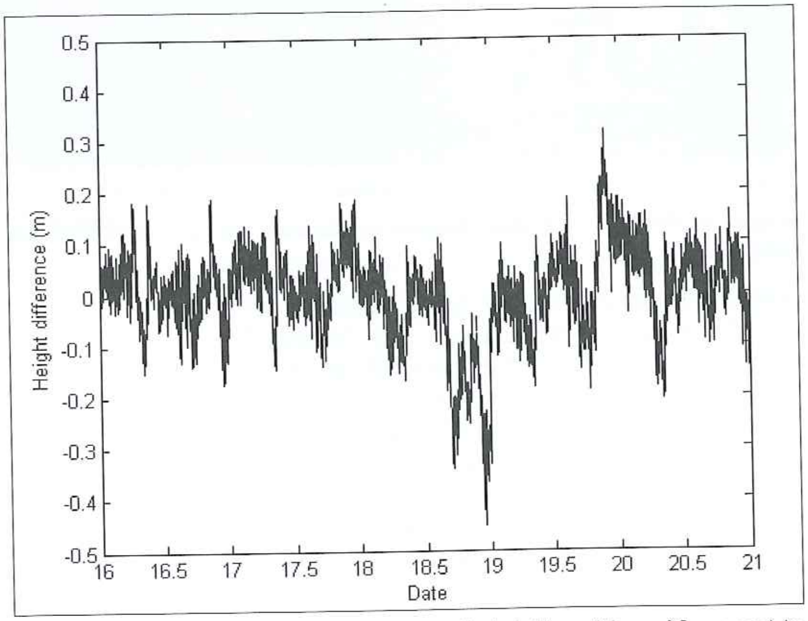

Figure 8: Saint John to Halifax: difference in height position with respect to average (m).

storm system passed over the area (late February 18) the positioning of Halifax produced a height variation that made these positions fall well below the average. Once the system left the area (around early 20th), the height positioning suddenly starts to increase above the average of the data set, returning to a value close to its mean at the end of the period.

To look at the same effect from a different perspective, the mean root mean squared (RMS) value for every 6 hours was computed. In Figure 10, the Fredericton to Halifax baseline's RMS values reach their highest about the time that the storm system was first traveling through the area. Both the positional and RMS results display strong discrepancies around the arrival of the storm. From this evidence we conclude that neutral atmospheric delay was very influential on data that was collected and detrimental to the vertical positioning results. A Similar result was obtained from the Halifax-Saint John baseline.

The experimental results presented in Figure 10 confirm the theoretical expectation explained in section 5, in relation to Figure 6: that the real danger for relative GPS positioning lies not at the large humidity readings in Halifax, but at the large difference in humidity between Halifax and Fredericton. Notice that soon after 19.5 h the height RMS decreases, even though humidity in Halifax remains relatively stable at its maximum during the weather bomb; the key is that around 19.5 h the humidity in Fredericton increased to a level comparable to that experienced in Halifax, thus decreasing the residual wet delay left over in double-differenced observations.

6.2 Observation Residuals

Satellite residuals can provide a better understanding of possible errors that are occurring in the travel of the signal. It is expected that satellite residuals should be larger whenever the satellites are rising or setting, when more multipath, poor antenna gain, and – what we are interested – atmospheric delays tend to occur. Figure 11 shows the sky plot of satellite 29 used as an example of the amount of residual with elevation angle. This satellite was observed during the time of the storm arrival. The satellite first appeared to the south of Halifax about 9 pm and traveled in a northeast direction until leaving visibility at about 3 am. Figure 12 shows the residuals over time for February 15, a calm day, and Figure 13 shows the residuals for February 18, the stormy day. It can be seen that there is an increase in the residuals for the 18th, as compared to the 15th. Residuals rise up to 2 centimetres around 23.5 h of the stormy day. Therefore, satellite residuals do show variations as the storm system approached the area, as expected. The large residuals before 22.5 h are unrelated to the storm; they are caused by ambiguities being still float soon after the satellite rise.

7. Possible Error Sources

The effects from the passing weather front on GPS positioning were shown from the time series of the relative solutions. Many different errors combined together by the storm's conditions to contribute to these major discrepancies. Among them, the main error is due to wet delay. The neutral atmospheric wet delay is very dependent on water vapour that is contained in the lower part of the atmosphere. This type of delay is the most difficult to model, since humidity readings that are taken on the ground may not represent the actual atmosphere humidity aloft. Halifax's surface humidity does indicate that the storm contained a great deal of water vapour that moved into the area, as shown in Figure 6. From a similar study [*Blewitt and Gregorius* 1998] it was noticed a very important contribution from the wet delay. The baseline that was monitored in their project illustrated that during warm fronts, the neutral atmospheric delay can increase to about 8 centimetres in 11 hours. As the cold front passed through, the delay would decrease to about the same amount.

The hydrostatic delay can be more easily mathematically modelled and eliminated during the GPS processing stage. This procedure is performed by the majority of the GPS processing packages that are in use today and for that matter does not constitute a major contributing error source.

Other possible errors, such as precipitation and snow cover, would account for some of the delay, but it is believed that they do not produce as much zenith delay as wet neutral atmospheric delay [*Solheim et al* 1999]. The passing snowstorm only affects GPS positioning for a relatively short time span (usually a day maximum). "A potential more serious effect of heavy snow precipitation is the accumulation of snow on the top of the GPS antenna and on its surrounding" [*Jaldehag et al.* 1996]. The built-up snow accumulation on the antenna adds an extra medium that the GPS signal will need to pass through. As the signal hits this medium, the direction of the signal gets refracted from its original path causing a small time discrepancy in its arrival time. The amount of signal refraction produced from the snow cover depends on many factors that include the amount of snow, size and shape of the antenna and packing density of the snow. Snow built-up on top of the antenna can remain there for days, weeks and even months at a time and from accounted reports have varied vertical positioning an estimate of about 0.4 metres when the antenna is buried under 2.5 m of snow [*Webb et al.* 1995].

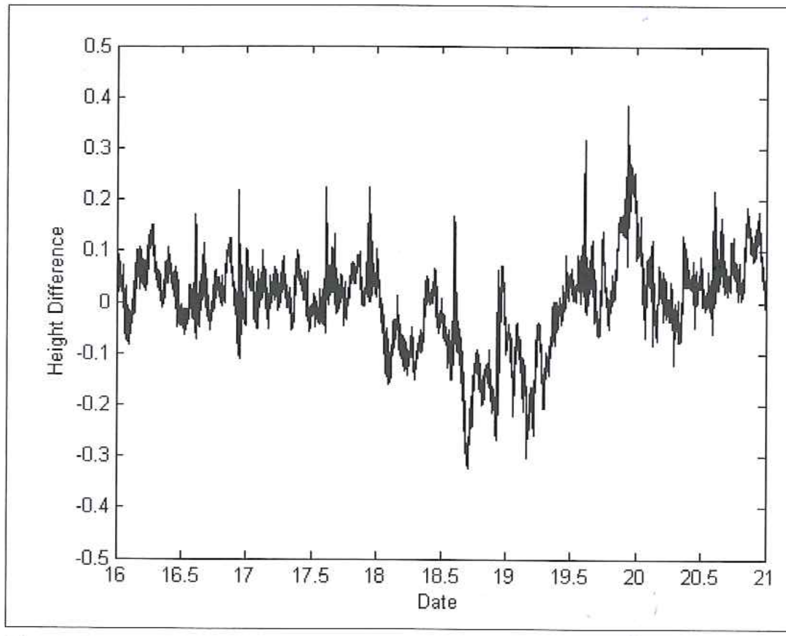

Figure 9: Fredericton to Halifax: difference in height position with respect to average (m).

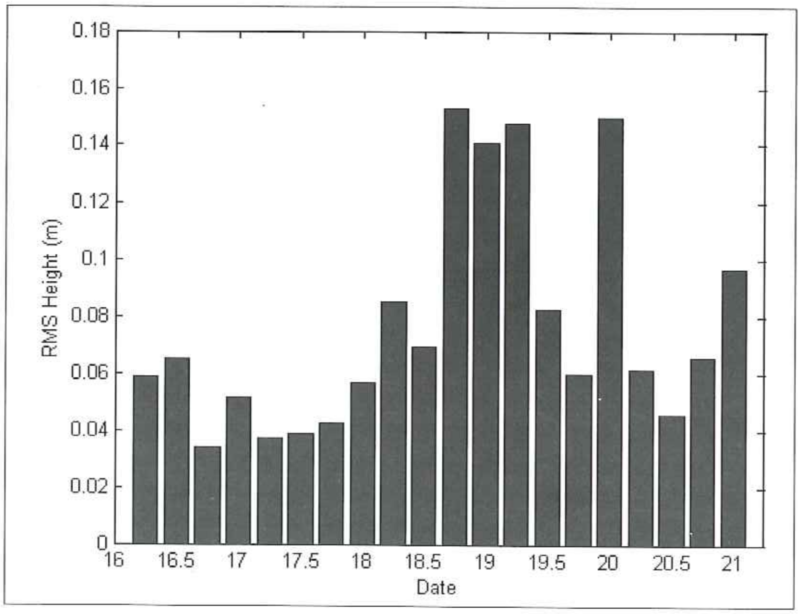

Figure 10: RMS height values for baseline Halifax to Fredericton.

8. Concluding Remarks

The storm that devastated Canada's eastern coast had a pronounced effect on GPS positioning in that area. From the results shown, it was quite clear the positional variations of station Halifax during the

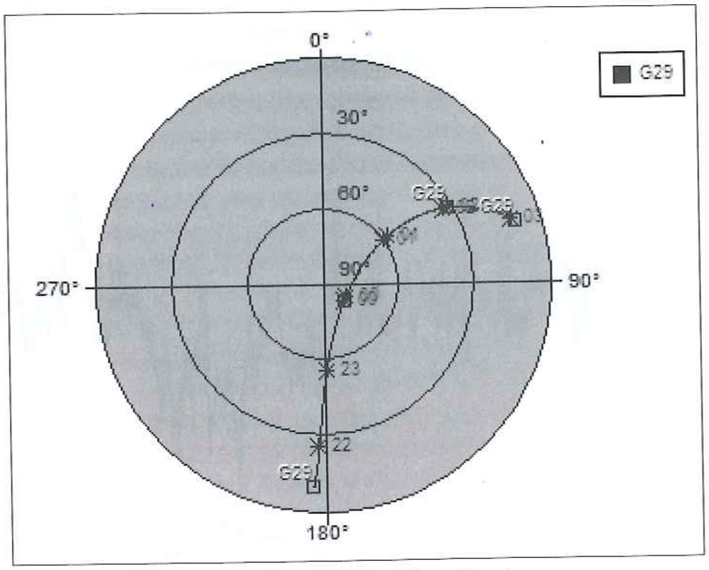

Figure 11: Traveling path of satellite 29 on the sky.

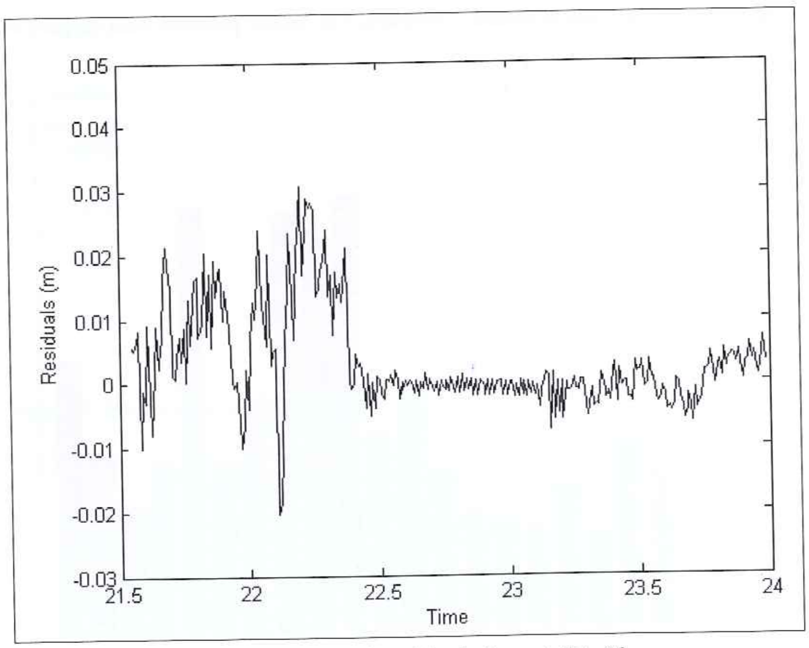

Figure 12: February 15, (calm day) residuals for satellite 29.

passing of the storm. In having used data from days before the storm's appearance, constant daily systematic errors cannot be blamed for the cause of the error trends. Any constant daily factors would have been present in each of the day's results.

Typical GPS errors are well known, but little has been researched about positioning during passing weather disturbances. Many GPS users utilize the system 24 hours a day, 7 days a week in all kinds of weather conditions for positioning. If height precision is the up most importance in the survey, collecting long baseline GPS positions during passing weather front should be used with great care. The zenith delay errors might be at its maximum amount during such conditions and any processing corrections may not account for all the delay error. With further analysis and modeling, height discrepancies from storm fronts may be able to be eliminated, but for now the best survey practices is to realize that GPS positioning during oncoming storms will not be as accurate as in calm days.

Acknowledgements

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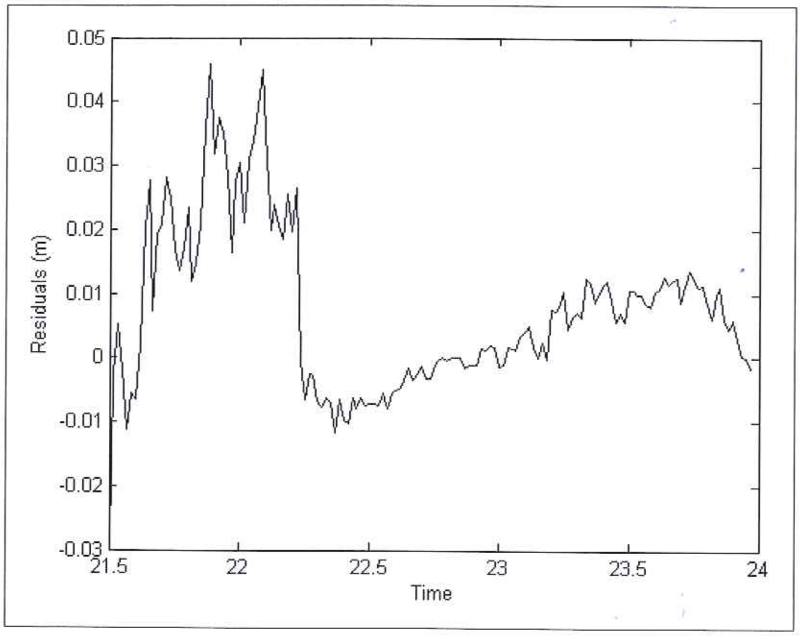

Figure 13: February 18, (stormy day) residuals for satellite 29.

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