The Feasibility of Replacing Precise Levelling with GPS for Permafrost Deformation Monitoring

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Key words: GPS levelling, Arctic environment, satellite geometry, path delays, error analysis

SUMMARY

This paper describes experiments to determine the best field and processing strategies that can be employed in carrier-phase differential GPS levelling in the permafrost Arctic region of Canada (70° north). Errors in phase-centre correction and multipath effects are examined in common with other studies in engineering measurement applications. In addition, the balance between residual noise and poor geometry in this high latitude is investigated in periods of both high and low ionospheric activity. An external accuracy assessment is made of the results. Recommended field and processing strategies for DGPS levelling in Arctic Canada are given.

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1. INTRODUCTION

The advantages of carrier-phase Differential Global Positioning System (DGPS) in the analysis of subsidence in the Mackenzie Delta/ Beaufort Sea region (69° 20’ N and 135° 30’ W) of Canada were identified in a feasibility study (Tait and Moorman, 2003) into the most economic and effective ways of monitoring gas extraction in the area. The subsidence predicted in this area will occur over a 25-year production cycle, with little movement anticipated in the first 10 years due to glacial pre-stressing and associated rebound. A small annual subsidence (< 2-3cm) is therefore anticipated over a 15-year period. Precise levelling was less attractive in this case since a great deal of the area has large water bodies (>2km) over which to survey in addition to few, if any, stable locations for absolute benchmarks. This paper reports on the investigation into the use of DGPS in differential levelling as well as its potential in providing an adequate datum for such work.

2. BACKGROUND

Differential carrier phase techniques have allowed the estimation of deformation parameters at the centimetre level and at the millimetre-level in special cases (Beutler *et al*, 2001; Hartinger and Brunner, 1998). Phase-Centre-Variation (PCV) and multipath effects have been identified in the past as the major station-dependent causes of errors in precise engineering measurement using DGPS (Wübbena *et al*, 2000). However, the effects of ionospheric activity and relatively poor satellite geometry in the Arctic region might also contribute to the error budget over longer baselines, even when using an ionosphere-free solution during processing. Recent work on the effects of location dependent variables such as satellite geometry (Meng *et al*, 2004), tropospheric effects (Roberts and Rizos, 2004), and ionospheric effects (Janssen *et al*, 2001) have mitigated these errors by employing an optimised strategy for data capture and processing. Continuous GPS networks, which can average or accurately assess such errors over time, cannot be deployed in this remote area since the infrastructure required for permanent receivers is not currently available. The project described in this paper therefore investigated the location-dependent errors for this region, and the mitigation of these through different field and processing approaches, based on the expectation of an episodic campaign of DGPS measurements. Precise levelling was used to gather observations of the test points at a higher accuracy to provide ’ground truth’ with which to compare the DGPS results. The aim of the project was to find the most accurate DGPS levelling solution for this region.

3. DATA COLLECTION

Baselines were collected over 15km, 50km, and 130km lengths with the base receiver being the INVK IGS station, the closest IGS station available for the target area (http://igscb.jpl.nasa.gov). All available satellites were tracked. The 15km baselines were collected at the Geodetic Survey of Canada (GSD) survey monument test-bed in Inuvik, Northwest Territories. For a description of the test-bed see Tait *et al* (2004). In 2003, 21 monuments in this test-bed were occupied for 12 hours each with a sampling frequency of between 15-30 seconds dependent on the on-board memory of the receiver. Three of the monuments were re-occupied for similar periods of the day. For the 2004 campaign, a revised DGPS data collection regime was chosen as a result of the processing of the 2003 campaign. Only semi-codeless (Ashtech Z12) receivers were used (see section 4.2). In 2004, baselines from the INVK station were captured at 15km and 50km distances. The campaign recorded these baselines at different times of day, and with reoccupation of all baselines at the same time of day, to allow an analysis of the effect of satellite geometry in different parts of the day and to allow the analysis of multipath in this environment. Baselines of 130km were also observed using the TUKT IGS station at Tuktoyaktuk, Northwest Territories, which was established in August 2003. Observations of external accuracy were made of the heights of the stations using differential levelling for each of the 15km baseline campaigns. Table 1 summarises the data capture campaign.

Table 1: Summary of 2003 / 2004 DGPS and external data collection

Length (km)	Rover co-ords	Rover type (s)	Choke ring	# of stations occupied	Occupation length (h) / sampling frequency (s)	# re-occupied	External comparison
15 (2003)	68°23’ 31” -133° 45’ 29 “	Ashtech Z12 Trimble 400SSI	N	21	12 / 15-30	3	Differential levelling (Reduced level estimated accuracy 0.02mm 1σ)
15 (2004)	68°23’ 31” -133° 45’ 29 “	Ashtech Z12	N	6 (twice)	12 / 30	6 (twice)	Differential levelling (RL 1.1mm 1σ)
50	68° 41' 35" -134° 07' 35"	Ashtech Z12	N	4	6 / 15	4	None
130	69°26’17” -132° 59’ 39”	Ashtech UZ12	Y	2	12 / 30 (Data from CDDIS)	N/A	IGS weekly average coordinates

4. ANALYSIS

4.1 Initial Processing

Data collected from the 2003 Inuvik campaign was first processed using Bernese 4.2, using a standard processing strategy (Mode 1, Table 2) and then processed by changing one of the options (Mode 2-3). All the other options were kept the same, including cut-off angle which was kept at 15°. The final results are all given with ionosphere-free fixed solution, since this gave the best results compared to the levelling values. The standard deviation in differential height compared to levelled values are show in Table 2 for 24 baselines of 15km.

Table 2: Effects of various error sources on the standard processing strategy for the 15km baselines measured in 2003

Processing Mode	**Standard deviation in differential height compared to levelled values (mm)**
Mode 1. Standard Processing Strategy: • Including PCV correction (from IGS tables) • Using IGS precise orbit • 12 hours time span • Saastamoinen model and cosz mapping function	13.0
Mode 2. Set antenna PCV corrections to zero	28.3
Mode 3. Processing using Broadcast orbit	13.8

The effect of PCV correction is significant as expected, and errors using broadcast orbital ephemeris display the insignificant affect anticipated in theory. The data was also processed using different tropospheric delay estimation methods in Bernese to investigate their influence on GPS height estimation. The tested strategies were as shown in the Table 3:

Table 3: Tested tropospheric delay estimation strategies

Processing Mode / **Options**	1	2	3	4	5	6	7	8
A priori tropospheric model	Saas	Saas	Saas	No	No	Saas	Saas	Saas
Mapping function	cosZ	cosZ	cosZ	Neill	Neill	cosZ	Neill	cosZ
Estimate residual zenith delay every	2 h	2 h	2 h	2 h	2 h	1 h	2 h	2 h
A priori sigma for absolute/relative zenith delay	1m/5 m	1m/0. 012m	1m/0. 012m	1m/0. 012m	1m/0. 012m	1m/0. 012m	1m/0. 012m	1m/0. 012m
Estimate residual tropospheric zenith delay parameter for base station	No	No	Yes	No	Yes	Yes	Yes	No
Estimate residual tropospheric zenith delay parameter for rover station	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No
Elevation Dependent Weighting	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

The results show that there was no significant difference between Saastamonien model combined with cosZ mapping function, and no *a priori* model with the Neill mapping function (with only 1 mm difference in the estimated station height). The *a priori* sigma value for absolute/relative zenith delay had no influence on the height estimates. Estimating residual zenith delay on both base and rover station gave better results, especially when using the no *a priori* model with Neill mapping function. High resolution (for example every half an hour) for residual zenith delay parameters is not recommended, since this may introduce additional error into the height estimation, with 1-2 hours recommended in most cases. In all cases for this project 2-hours resolution was used, except in the case of the 1-hour session in Section 5 where a 1-hour resolution was employed. The most appropriate stategy was determined to be tropospheric estimation mode 3 in all cases (15, 50, and 130km baselines). The results were compared to differential levelling for the 15km baselines and IGS weekly published height coordinate for the 130km baselines (Table 4). The differences in standard deviation between the 2003 / 2004 15km baselines can be explained by the use of different antenna configurations in each campaign (Sections 4.2 and 4.3). The 130km baselines only account for variation in one of the stations, hence the better result in this case than the differential comparisons.

Table 4: Results of the mode 3 processing of 15km baselines

Observation set	**# of baselines**	**External accuracy measures**	**Difference with external accuracy measures**	
			Mean (mm)	**Standard deviation (mm)**
2003 (15km)	26	Differential levelling (Reduced level estimated accuracy 0.02mm 1σ)	0.7	13.5
2004 (15km)	24	Differential levelling (RL 1.1mm 1σ)	2.0	8.5
2004 (130km)	2	IGS weekly average coordinates	1.5	3.5

4.2 Phase Centre Variation Errors

In 2003 several stations were re-occupied with a different antenna (Trimble TRM22020.00+GP and Ashtech 700718 antennas), as well as with the same type. On examination of the repeatability of station height estimation, those stations occupied by the same types of antenna gave agreement within 2 mm, while the stations occupied by the different types of antenna was around 3 cm. The bias in the differential heights was presumed to come from uncorrected PCV. The processing was repeated in Trimble Total Control with similar results, indicating that a residual error in PCV correction is a common occurrence. An experiment was undertaken to investigate these conclusions, with the aim of isolating the effect of PCV error from other noise errors such as multipath, troposphere, and ionosphere.

Three sessions of data were captured, each of 12-hour period and with the start and end at the same time of the day, so that the effects of multipath were approximately the same in each data set. Two monumented, force-centring, pillars (Figure 1) were used as the stations. To exclude the possible influence of errors in antenna height measurement, all GPS antennas were mounted directly onto the pillars and the antenna height set to zero during processing. In the first session, two Ashtech antennas were set up on the pillars. In the second session, two Trimble antennas were set up on the pillars. In the third session, one Ashtech and one Trimble antenna were set up on the pillars respectively. The coordinates of pillar N4 were held fixed for all scenarios. The baselines were processed with Bernese using both L1 and ionosphere-free (L3) frequency combinations. The results given in Table 5 show a disagreement in relative height estimations between scenarios of 1.5mm to 12mm. In the absence of other noise (the RMS of residuals was 3-4mm in each case) this was assumed to stem from un-calibrated PCV effects, especially in the mixed antenna case. Use of similar antennas in 2004 is believed partly the reason for the observed increase in precision seen in Table 4, but also partly from the use of codeless receivers (Section 4.2), all other errors (including multipath) presumed equal for the two observation periods since they were recorded at exactly the same locations.

The L3 solution gives the biggest differences, which is in agreement with previous work that shows this frequency combination to exacerbate the effects of an incorrect PCV model (Wübbena *et al*, 2000). Although it does not make sense to process such a short baseline with L3, the project baselines were all processed this way, and so the effects were of interest.

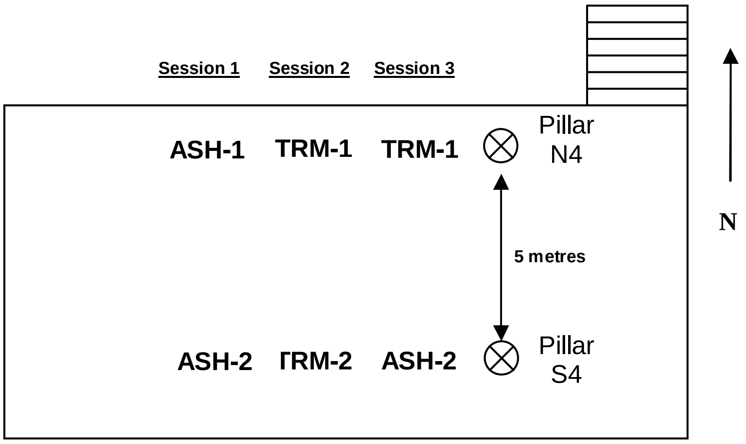


Figure 1: Experimental set-up for PCV correction error analysis

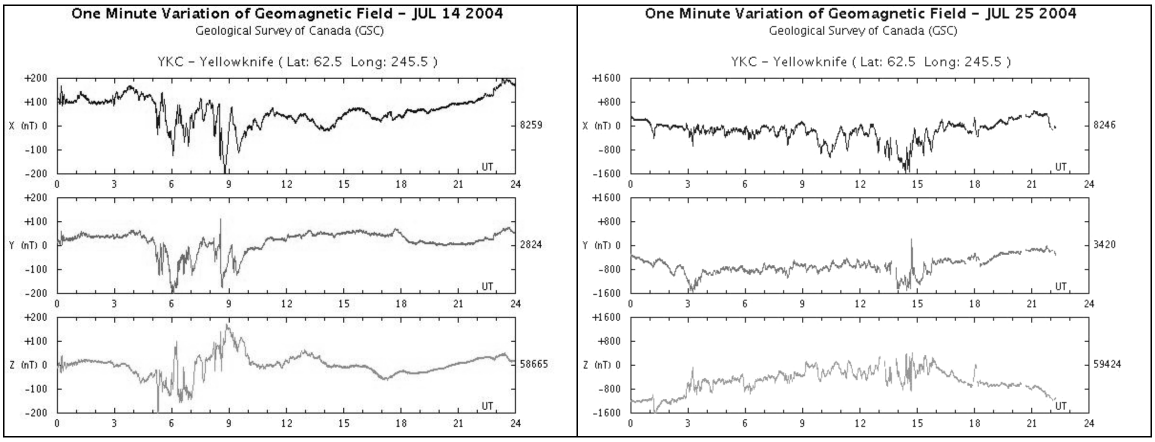
Table :5: Differences in height between pillars (m) estimated with three different antenna configurations using L1 and L3 processing strategies

	L3 Processing			**L1 Processing**		
	Session 1	Session 2	Session 3	Session 1	Session 2	Session 3
Session 1	-	-0.0033	-0.0119	-	-0.0019	-0.0014
Session 2	-	-	-0.0086	-	-	-0.0033

4.3 Ionosphere and Satellite Geometry

In the 2003 campaign, significant loss-of-track (almost exclusively due to the loss of L2) was noted (100 events / 12-hour period for the codeless Trimble receivers and around 30 events for the semi-codeless Ashtech receivers). This led to substantial loss of ambiguity resolution from the Trimble receiver data. For this reason, only the semi-codeless Ashtech Z12 receivers were used in the 2004 campaign. The use of semi-codeless receivers for the 2004 15km, 50km, and 130km baselines gave approximately 30-40 cycle-slips per 12-hour session at 15° elevations. These data were used in all the following analyses. This section examines whether or not the most effective processing of the baselines observed using the L3 solution, together with the usual elevation dependent weighting (EDW) measures associated with path delay correction, are effective during an ionospheric event. The balance between reducing errors in longer paths and maintaining the best satellite geometry was also of interest.

In order to assess the most appropriate strategy for processing data observed during an ionospheric event, two 15km baselines were chosen from the 2004 campaign that each had 12-hour observations in both a quiet ionospheric period and during an ionospheric event. These periods were assessed using the one-minute variation of geomagnetic field for the Yellowknife station, the closest station to the test area (approximately 1100km). The dates chosen were the 14 and 25 July, the assessments of which are shown in Figures 2a and 2b. The figures show a quiet day (July 14 2004) and a day of significant ionospheric disturbance (July 25 2004). An event of such magnitude has a frequency of approximately 10-12 times per year and duration of around 24 hours.



(a) (b)

Figure 2: Plots of ionospheric activity from Yellowknife recording station for (a) July 14 and (b) July 25 2004 (Natural Resources Canada website)

The baselines were processed at different cut-off angles to determine whether there was a ‘best’ configuration of processing in these conditions. The 2004 15km baselines were processed for both days with EDW both activated and switched off. The results demonstrated no major advantages gained through the application of EDW during the 14 July dataset, and a worsening of the result using EDW during the 25 July session. In terms of path length versus geometry, external accuracy assessments displayed an increasing accuracy from 0° until the 15° cut-off was reached, followed by a reduction in accuracy. In the longer baselines (130km), with larger expected differences in atmospheric delays at the stations, the same trend was evident (Table 6). No 50km baselines were observed during the ionospheric event.

Table 6: The effect of the variation in cut-off angle, and the use of the EDW corrections, for two 130km baselines observed on July 14 and July 25 2004. Estimates of height and the mean and standard deviations between these and weekly IGS averages results are shown.

Cut-off angle (degrees)	**Estimated heights (GPS) in metres**				**12 hour session height TUKT– weekly average (m)**	
	July 14 EDW on	July 14 EDW off	July 25 EDW on	July 25 EDW off	**mean**	**1σ**
0	-1.5313	-1.5348	-1.5440	-1.5357	-0.0074	0.0070
5	-1.5461	-1.5363	-1.5494	-1.5357	-0.0129	0.0074
10	-1.5415	-1.5339	-1.5358	-1.5299	-0.0063	0.0040
15	-1.5321	-1.5283	-1.5249	-1.5253	0.0014	0.0018
20	-1.5228	-1.5220	-1.5233	-1.5230	0.0062	0.0025
Average height estimated (IGS height difference = -1.5308m for July 14 and -1.5272m for July 25)	-1.5348	-1.5311	-1.5355	-1.5300		

4.4 Multipath

There were two environments analysed for multipath effects. These are representative of the Mackenzie River basin above Inuvik (68° 18’ N). The first is just within the tree-line (68° 23’ N), and consists of small trees (3-4m) and low shrubs (0-1m) with tundra beneath (moss-covered peat). The second is the tundra only, above the tree-line (68° 41’ N). Figure 3 shows plots of residuals from the same satellite-pair during four 12-hour sessions on one of the benchmarks within the tree-line; these have been smoothed to reduce noise using a 3-epoch moving-average filter that improved the correlation statistics (shown in Figure 4). Day-to-day correlation was found to be in the range 0.5 – 0.7 at around 4 minutes (a sample rate of 30 seconds was necessary since that is the rate of the IGS base-station). The tundra-only areas showed a higher day-to-day correlation (average 0.6) with similar offset.

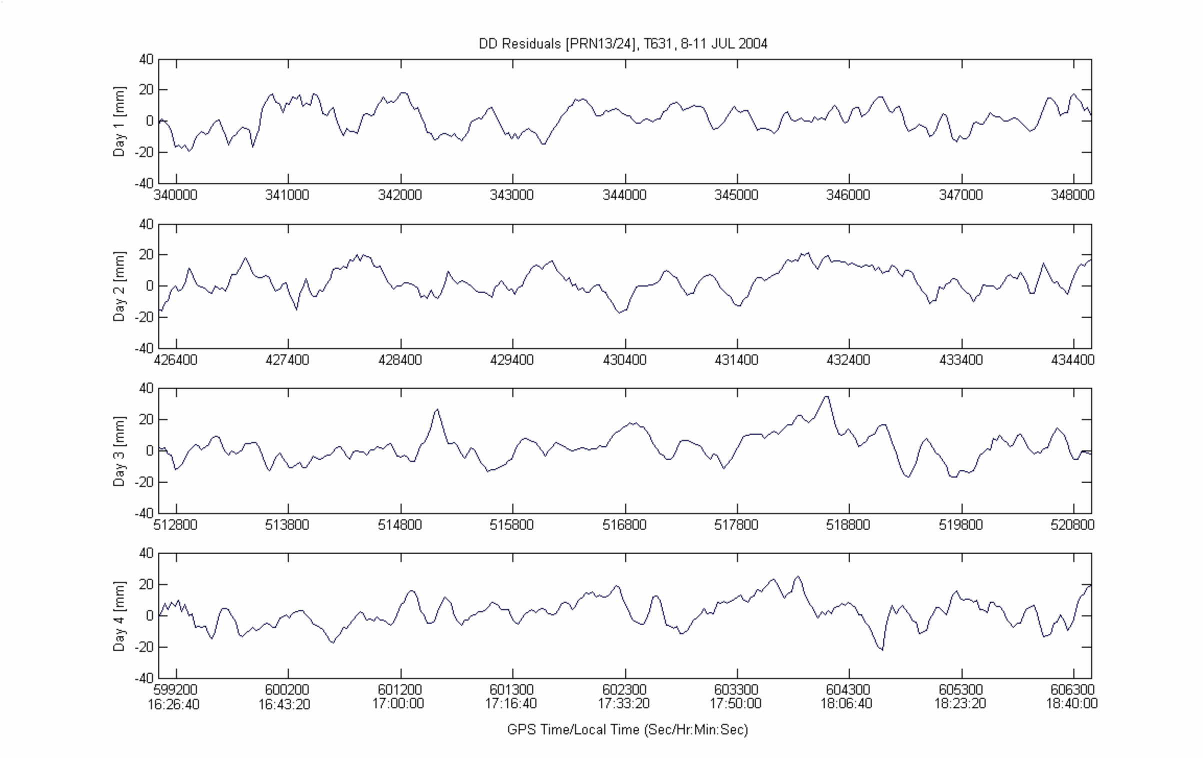


Figure 3: Smoothed residuals for four 12-hour sessions on one station within the tree-line environment

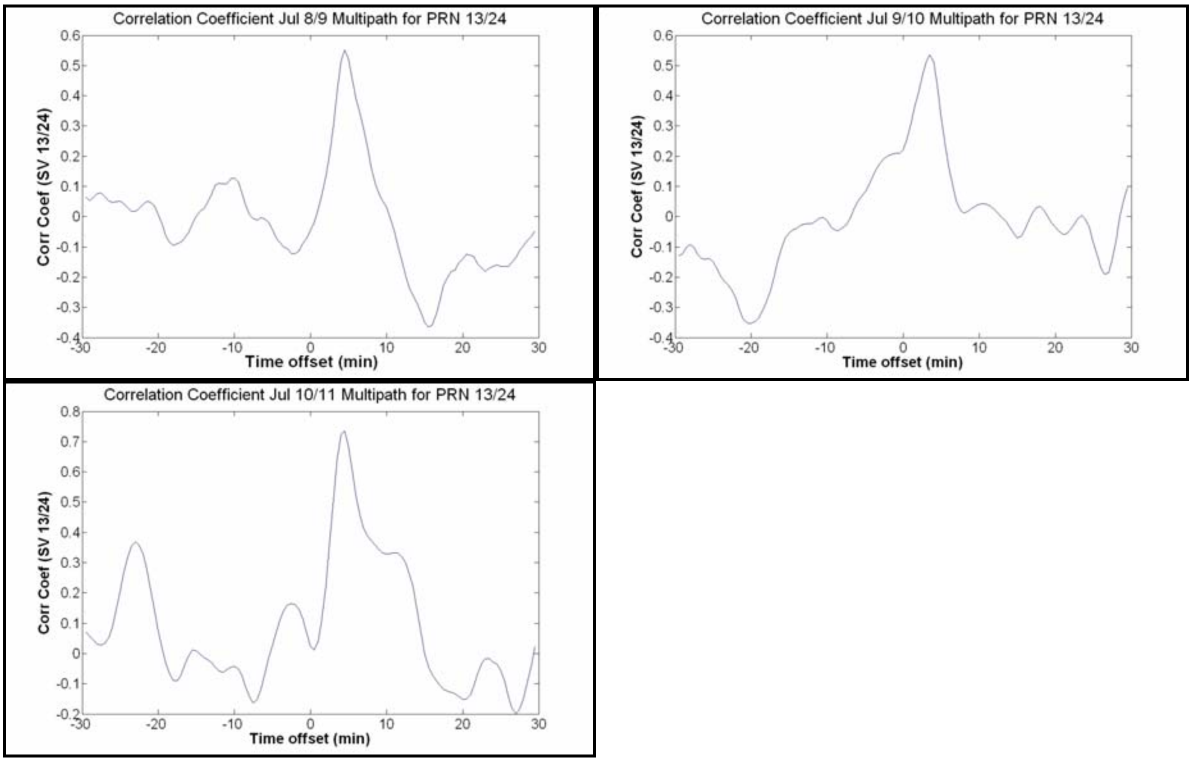


Figure 4: Day-to-day correlation from the residuals shown in Figure 4.

5. DEVELOPING THE BEST STRATEGY

From the foregoing results and analysis the proposed strategy would be:

- Processing mode 3 (Table 3)
- Using the same type of rover antenna throughout the campaign to avoid uncorrected PCV effects,
- Using a 15° cut-off angle, which gave the best balance between satellite geometry and errors due to different path lengths for both 15km and 130km baselines on days of both low- and high- ionospheric activity,
- EDW correction switched off, since it was found to have insignificant or even deleterious effects on the levelling results.

With this strategy applied, there might still be a balance to be struck between the length of occupation (and processing period), the time required to average the residual path effects that exist, and the accuracy of levelling. Table 7 shows the results of processing using the recommended strategy for 15km and 130km baseline data from days of low and high ionospheric activity. Columns under each baseline length show the mean and standard deviation difference compared to differential levelled results (15km) and weekly average IGS height coordinates (130km).

Table 7: Variation in accuracy (and standard deviation of grouped baselines) with occupation length for days of low and high ionospheric activity. 15km baselines compared to differential levelling, 130km baselines compared to weekly IGS coordinates

Occupation length (hours)	**15 km (low)**		**15km (high)**		**130km (low)**		**130km (high)**	
	Mean (mm)	Sd (mm)	Mean (mm)	Sd (mm)	Mean (mm)	Sd (mm)	Mean (mm)	Sd (mm)
12	1.7	-	-1.9	-	2.2	-	2.7	-
6	2.4	2.2	-2.7	2.6	-2.1	0.4	2.6	7.7
4	2.7	2.7	-2.3	2.3	-2.0	1.2	2.6	5.2
3	1.9	2.7	-3.1	3.1	-2.7	1.4	2.3	6.2
2	2.0	2.9	-3.2	5.1	-1.9	2.3	2.4	6.2
1	-11.6	25.1	-24.0	46.8	-4.4	13.6	-6.8	20.5

These results are for only two baselines for each distance, and the variations in standard deviation for the 15km baselines should be seen in the context of the reported differences in Table 4 that represent the results from multiple baseline sets. So, for the standard deviation of 8.5 mm given in Table 4, the standard deviation can be expected to increase marginally with decreasing occupation length up until the 1-hour session, when large increases in standard deviation are evident. The results for the 130km baselines incorporate the estimation of only one parameter, so the standard deviations would be expected to be better than in the 15km differential case where two rover stations are varying. With the chosen strategy, the effect of high ionospheric activity is minimal until 2 hours for the 15km baselines, but the effect on the 130km baseline is evident throughout. So, for baselines of this length it is recommended that the survey be planned on a day of relative inactivity according to on-line data at the Geological Survey Canada.

6. CONCLUSIONS AND RECOMMENDATIONS

A field and processing strategy has been developed for carrier-phase DGPS levelling in the Arctic region of Canada at 70° North. A field strategy has been recommended for differential levelling based on semi-codeless receivers, utilising the same antennas to reduce PCV error effects, with occupation lengths of 2 hours or more (30 second sampling) being sufficient to average residual noise effects, even on days of high ionospheric activity for the shorter (15km) baselines. Since this project presumes that an episodic campaign strategy will be employed in practice, day-to-day correlation was examined but mitigation strategies not implemented. The best processing strategy used an ionosphere-free solution, a typical *a priori* model and mapping function for troposphere, together with additional zenith delay parameter estimation for both base and rover. A 15-degree cut-off angle was found to give the optimum balance between satellite / receiver geometry and low-elevation path-length noise for all baselines. However, for the 130km baselines even the optimum 15° cut-off could not prevent a marked decrease in precision during an ionospheric event. It is recommended that for this length of baseline, surveys are planned on days of low ionospheric activity as judged by the one-minute geomagnetic field data available online.

The project was looking for a standard deviation in levelling of around 9mm or better to perform an annual campaign of measurement on the gas extraction areas of the Mackenzie Delta. Differential levelling results for 15km baselines, compared to highly accurate conventional levelling data, were in the order of 8-9mm (1σ) for a 12-hour occupation with only slightly decreasing precision found with shorter observation periods down to 2 hours. It is unlikely, therefore, that the longer baselines needed for the gas lease (100km) will improve on these figures. A campaign every two years may be the best that can be expected using this method. The 130km baseline results are encouraging but, without an external accuracy assessment, the comparison is only to the IGS weekly average of height.

Further work will examine the effects of multipath mitigation through day-to-day correlation, and the improvement that may thus occur from re-occupation of the stations, and whether schemas for ‘correcting’ the over-optimistic estimated parameter variances are applicable in this work.

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