Carrier Phase GPS Navigation to the North Pole

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Over the last few years, on-the-fly integer ambiguity resolution for GPS has proven to be successful over short baselines (< 20 km). However, the remaining challenge has been to extend the length of the baseline between the reference station and the mobile receiver, whilst still maintaining the capability of on-the-fly resolution and true carrier-based kinematic positioning. The goal has been to achieve centimetric level positioning at ranges of over 500 km. New techniques have been developed at the University of Nottingham to allow very long baseline integer ambiguity resolution, on-the-fly. A major problem with the use of carrier phase data is that posed by cycle slips. A technique for detecting and correcting cycle slips has been developed, and its use is discussed in this paper. The new technique has been proven through a series of trials, one of which included two flights to the North Pole, performing centimetric level positioning all the way to the pole. For many years, the GD Aero-Systems Course of the Air Warfare Centre based at RAF Cranwell executed a series of equipment flight trials to the North Pole, called the ARIES Flights. In May 1996, the authors were fortunate to take part in both flights, via Iceland and Greenland, to the North Pole. Based on reference stations at Thule Air Base, integer ambiguity resolution was accomplished, on-the-fly, and centimetric level navigation maintained throughout the flights. Earlier trials detailed in the paper demonstrate that the technique can resolve integer ambiguities on-the-fly within a few seconds over a baseline length of approximately 134 km, resulting in an accuracy of 12 cm. The majority of the residual error source for this being the ionosphere.

1. introduction. On-The-Fly (OTF) GPS has been shown to be useful over short baselines (< 20 km), (Hansen, 1996). This paper will show that it is also possible to use OTF GPS over much longer baseline lengths, in the order of hundreds of kilometres. Such a system would allow many more applications to use precise kinematic GPS. The applications that could benefit from long-range kinematic GPS include the offshore industry and precise navigation for civil and military aviation. These, and other applications, would not only require reliable positioning over such long distances, but also real-time OTF ambiguity resolution.

Research at the IESSG (Hansen, 1996; Walsh, 1994), has led to the development of in-house OTF software, known as the Nottingham OTF software (NOTF). The current software (Hansen, 1996) allows the use of multiple reference stations (MRS), which speeds up the ambiguity search and increases the permissible baseline length between the reference stations and the mobile receiver. Recent developments to the software have included reliable cycle slip detection algorithms for use in both static and dynamic situations (Roberts, 1997). Two sets of experiments that were carried out over long baselines, using the MRS technique, are described in this paper. The results from these trials were used to validate the algorithms and software before their

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subsequent use on the very long-range polar flight data. They are also used to illustrate the use of the new cycle slip detection algorithms.

The final section of the paper describes the experiments carried out over very long baselines during the ARIES 96 Polar Flights. Three reference stations were placed at the US Air Base at Thule in Greenland, whilst the roving receiver was located on an RAF Comet trials aircraft which flew from Thule to the North Pole and back again.

2. long baseline tests.

2.1. *Description of the Trials.* Before the Polar Flights, a series of trials were conducted on an airfield close to Nottingham. The tests were conducted using six Ashtech Z-XII dual frequency GPS receivers. Four static reference receivers were based near Oxford (ASH1, ASH2, ASH3, ASH4), approximately 134 km from the roving receiver. A fifth reference receiver was placed at Nottingham (NOTT) some 9 km from the rover (HUCK), this being the sixth receiver. The four receivers at Oxford had previously been positioned relative to NOTT over an 11-hour static occupation, using a precise ephemeris and ionospherically free, fixed, integer ambiguity observable. The relative accuracy of such a baseline length and positioning techniques has been shown to be in the order of 10–15 mm in height and sub-centimetre in plan (Beamson, 1995).

The kinematic data was collected at a rate of 2 Hz over a period of approximately 50 minutes. HUCK was placed upon a van, roving on an open runway at speeds of up to 110 kph (70 mph). On three occasions during the trial, the antenna was detached from the van and placed upon a previously fixed tripod for a number of minutes, hence establishing an absolute truth and repeatability criteria for the results. Table 1 illustrates the speeds and corresponding times during the trial, and the period

Table 1. Vehicle speeds during the trial

GPS time of week (s)	Comments	GPS time of week (s)	Comments
468660	Antenna on tripod	470029	Accelerate to 80 kph (50 mph)
468850	Antenna placed on vehicle	470084	Retard and turn through 180 degrees
468900	Travel at 30 kph (20 mph)	470154	Accelerate to 110 kph (70 mph)
469028	Turn through 180 degrees	470204	Retard and turn through 180 degrees
469156	Turn through 180 degrees	470269	Accelerate to 110 kph (70 mph)
469170	Accelerate to 80 kph (50 mph)	470654	Retard to 80 kph (50 mph)
469320	Accelerate to 110 kph (70 mph)	470729	Retard to 50 kph (30 mph)
469367	Retard and turn through 180 degrees	470814	Turn through 180 degrees
469375	Accelerate to 110 kph (70 mph)	470879	Accelerate to 65 kph (40 mph)
469427	Antenna on tripod	471035	Accelerate to 80 kph (50 mph) Antenna on tripod
469769	Antenna placed on vehicle	471147	Move antenna onto vehicle and
469829	Accelerate to 50 kph (30 mph)	471419	accelerate to 80 kph (50 mph)
469935	Turn through 180 degrees	471779	Stop

of data which was processed (highlighted). It is this period of data that is discussed during the following sections. The short and long baselines were processed independently using the NOTF software. The corresponding results were then compared with each other to test the validity of the long baseline OTF technique.

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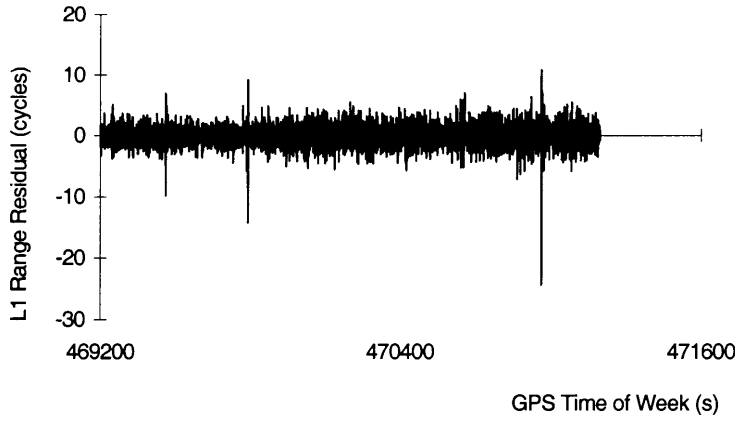


Figure 1. Satellite 7 – L1 Range Residual, showing spikes at high multi-path.

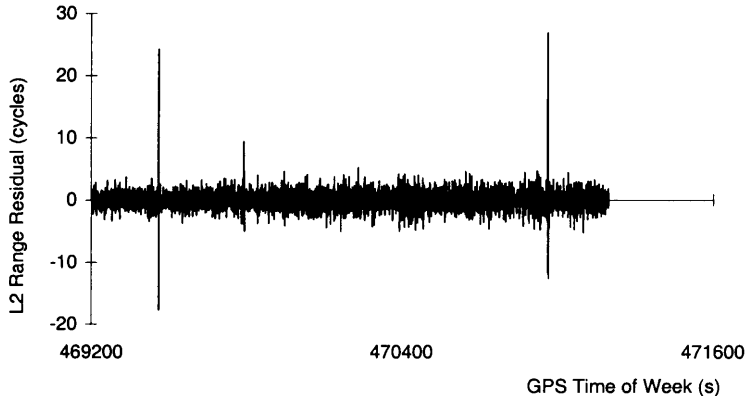


Figure 2. Satellite 7 – L2 Range Residual, showing spikes at high multi-path.

2.2. *Short Baseline Results*. To enable the long baseline (approximately 134 km) results to be compared to those from the short baseline (approximately 9 km), it was first necessary to establish the accuracy of the short baseline. Fast static processing was carried out during the three periods the HUCK receiver was placed upon the tripod. The resulting solution for the three occupations was used to compare the short baseline results. The RMS radial difference between the fast static and short-range OTF solution was calculated at 0·025 m. Over 900 OTF positions were taken into account.

2.3. *Cycle Slip Detection and Correction*. The new cycle slip detection techniques worked successfully on all the data sets (Roberts, 1997). Four independent approaches are used that jointly identify cycle slips. These are the Range Residual, Ionospheric Residual, Doppler Residual and the Four Observable techniques. The Range Residual technique compares the change in pseudo-range to the change in carrier phase over consecutive epochs of data. The reliability of this technique is of the order of 5 cycles in low multi-path and is ideal for detecting multiple cycle slips. The Ionospheric Residual technique compares the change in the ionospheric effect on the L1 and L2 carrier phase observables; this technique can identify single cycle slips.

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The Doppler Residual technique compares the change in carrier phase with that of the doppler value; again, this technique can be accurate to the single cycle value. The Four Observables technique compares the change in four observables (Melbourne, 1985) from epoch to epoch; this technique can resolve wide lane cycle slips to the order of a couple of cycles. Each technique has its advantages and disadvantages. However, their combination results in an unmitigated cycle slip detection and correction technique.

2.4. *Long Baseline Results.* The cycle slip detection technique implements the four methods described above, which jointly identify and confirm cycle slips. The data sets processed are referred to as HUCK, NOTT and ASH1 to 4, as described above. The following illustrates some of the results for HUCK. Figures 1 and 2 show the L1 and L2 Range Residuals, respectively, for satellite 7. It can be seen that the residuals are of the order of ± 4 cycles as would be expected, but there are one or two peaks during periods of high multi-path. Figures 3 and 4 illustrate the L1 and L2 Doppler

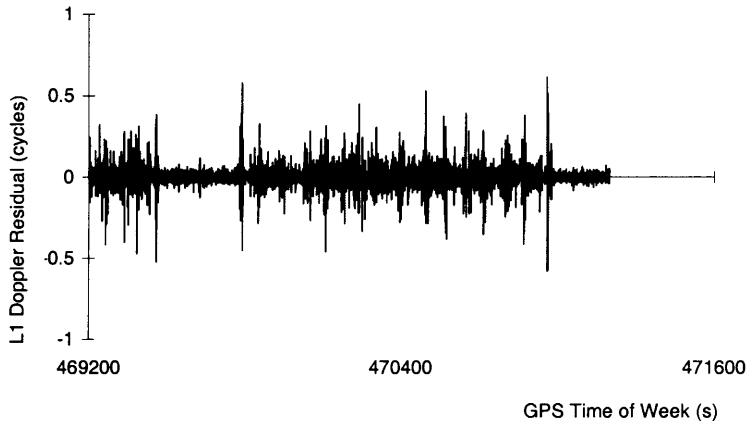


Figure 3. Satellite 7 – L1 Doppler Residual, showing higher resolution at constant velocities.

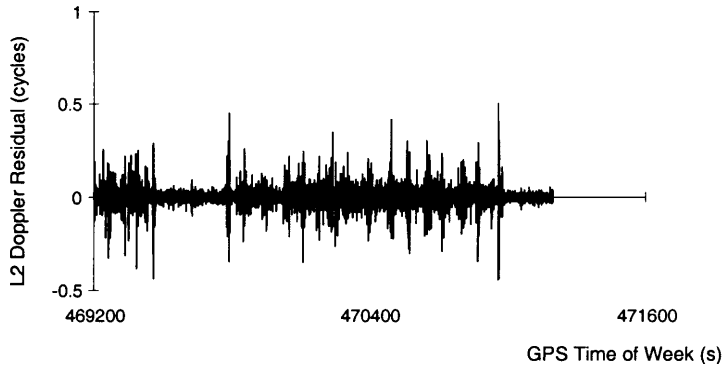


Figure 4. Satellite 7 – L2 Doppler Residual, showing increased accuracies at constant velocities.

Residuals, again for satellite 7. These are of the order of $\pm 0{\cdot}1$ cycles whilst the vehicle is static. However, these soon increase when the vehicle accelerates, but are still around $\pm 0{\cdot}5$ cycles. Figure 5 illustrates the Ionospheric Residual plot for the main

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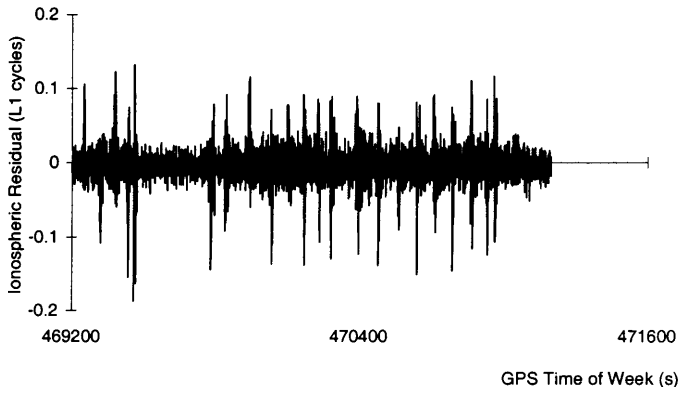


Figure 5. Satellite 7 – Ionospheric Residuals.

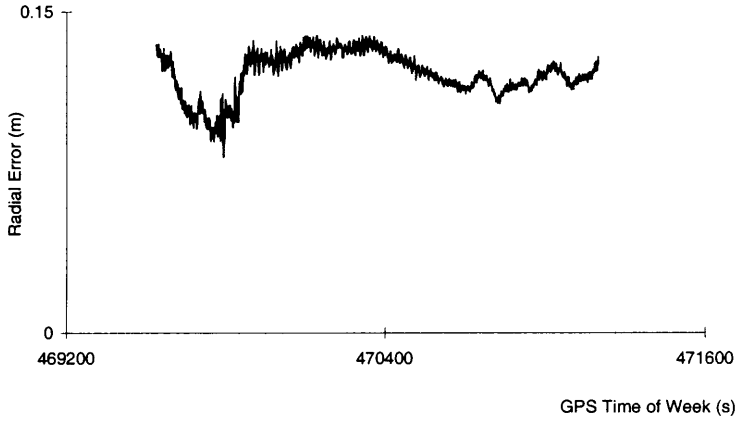


Figure 6. Short baseline L1 minus long baseline L1 radial error for the kinematic trial.

period of data, for the same satellite. This plot suggests that the Ionospheric Residual is by far the most reliable means of detecting cycle slips, although it does suffer from spikes during periods of high acceleration.

Figure 6 illustrates the radial difference between the long and short baseline L1 solution results for a sample of the data, with the mobile receiver travelling at speeds of up to 110 kph (70 mph). Figure 7 illustrates the difference between the L1 short baseline results and the long baseline wide lane results for the same data.

The RMS errors for the L1 and wide lane solutions are 0·121 m and 0·378 m respectively. The radial errors in Figures 6 and 7 appear to be offset from the truth. This offset may be due to the relative positioning accuracy of ASH1-4 and NOTT, carried out through an 11-hour static carrier phase occupation processed using a precise ephemeris. The relative accuracy, however, has previously been shown (Beamson, 1995) to be in the order of a centimetre for such a static positioning technique. The ionospheric noise in the resulting L1 OTF solution is more likely to be the cause of the offset. OTF positioning using an ionospherically-free observable rather than L1 would increase the positioning accuracy.

The curve in Figure 6 exhibits two distinct features. Firstly there is an offset of approximately 0·12 m from the truth, and secondly there is a fluctuating bias within

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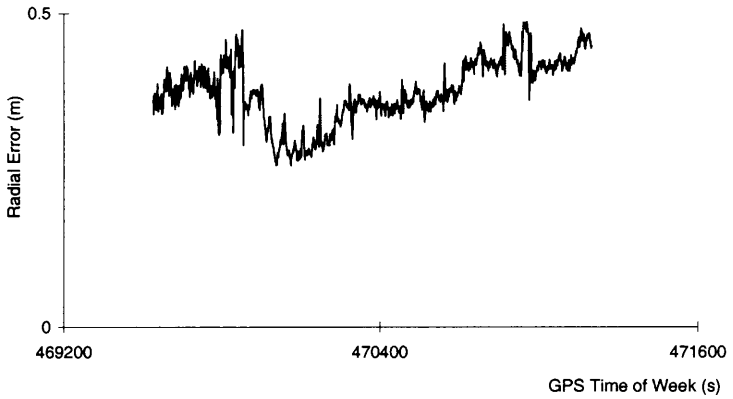


Figure 7. Short baseline L1 minus long baseline Lw radial error for the kinematic trial.

Table 2. Baseline differences due to ionospheric activity

Frequency	Integer	Dx from truth (m)	Dy from truth (m)	Dz from truth (m)	Radial error (m)
L1	Free	−0·260	−0·720	−0·440	0·883
L0	Free	−0·112	−0·005	−0·127	0·169

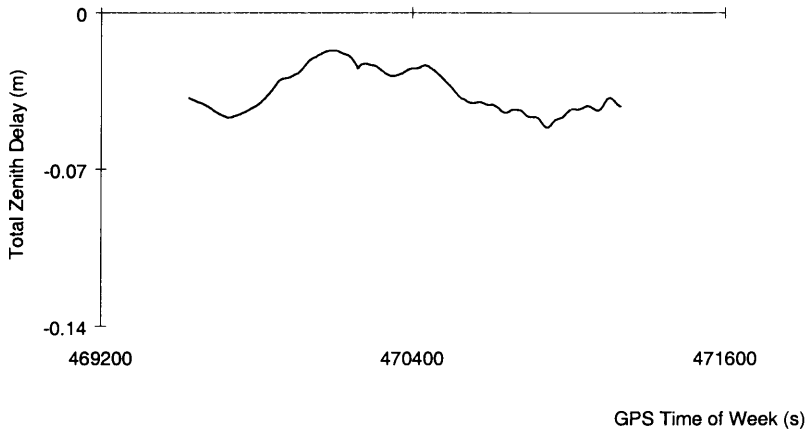


Figure 8. Total trophospheric zenith delay for kinematic trial.

the graph. The offset of the curve in Figure 6 may be a result of the ionospheric activity, whilst the shape of the curve may be due to the tropospheric delay.

The data was processed through a second technique from ASH1 to NOTT in a static mode during the 50-minute kinematic trial, using L1 and ionospherically-free (L0) frequencies. The results from the two frequency tests, Table 2, show the effects the ionosphere can have on the coordinate differences.

The results in Table 2 suggest that the ionospherically-free observable is closer to the truth than when using L1 only.

As a means of quantifying the effect of the troposphere on the results, a second test was performed. The coordinates of both stations were fixed to the truth, and the data was processed solving only for the troposphere. Figure 8 illustrates the total zenith

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delay for the kinematic data set during the trial. It can be seen that there is a correlation between the shape of the graph presented in Figure 6 and that presented in Figure 8. Both the ionospheric activity and tropospheric delay are the limiting factors for this technique at present. They are both the subject of research at the IESSG, and their effect on OTF is under investigation.

The time to resolution is an important factor for OTF. It has previously been demonstrated that the Nottingham OTF technique can resolve wide lane integer ambiguities over minimum baseline lengths of 130 km within approximately 3 epochs (Ashkenazi *et al*. 1996). Tests carried out on the long-range data showed that 7 seconds, or 14 half-second epoch intervals were taken to resolve the L1 ambiguities.

3. aries 96 polar flight results. The authors were invited to take part in the Royal Air Force ARIES 96 Polar Flights which were part of the flight trials training syllabus of the GD Aero-Systems Course run by the Air Warfare Centre based at RAF Cranwell. All the students on this military post-graduate course take part in these trials, involving two flights between the United Kingdom and the geographic North Pole, during which they operate the various navigation systems on board a specially configured aircraft and collect data for later analysis. Figure 9



Figure 9. The Comet aircraft at Thule AFB.

illustrates the Comet aircraft used during the ARIES 96 flights. The systems included both military and civilian GPS receivers, as well as inertial navigation systems (INS), combined INS and GPS systems and gyro compass systems. Amongst these systems was one of the IESSG's Ashtech Z-XII GPS receivers.

During the flights between the United Kingdom and Greenland, there was no reference station data available. The data recorded by the Z-XII during these periods was processed at the IESSG, after completion of the flights, using pseudo-range positioning, carrier phase smoothed pseudo-range positioning and a precise ephemeris. During the flights from Greenland to the pole and back to Greenland,

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three reference receivers were located at the US Air Force Base at Thule. The data recorded by the IESSG's Z-XII receivers on the ground and in the air during these flights was processed to assess the suitability of OTF GPS techniques for a flight of such extensive duration and range. The maximum amount of usable data was included in this analysis.

The processed Z-XII data from all the flights was also supplied to the students on the GD Aero-Systems course at RAF Cranwell for them to examine and analyse against the other navigation systems on the aircraft.

The positions of the reference stations were coordinated from the IGS station, also at Thule, using over eight hours of static data and a precise ephemeris. Figure 10



Figure 10. The GPS receivers located at Thule, Greenland.

illustrates the three reference GPS receivers located at Thule, as well as a Trimble GPS receiver used by Trimble Navigation Europe Ltd, who were also carrying out trials on the same aircraft.

The kinematic data was recorded with an interval of 2·5 seconds due to limited data storage on the receivers. One of the reference stations recorded data at only 5-second intervals, as this receiver had very limited storage space. During subsequent data processing, only two of the reference receivers were used, as the third had recorded little useful data. The flights took approximately 4·5 hours to complete. During the flights, there were no visible problems with cycle slips or loss of lock. Whilst flying over the North Pole (approximately 1500 km from the reference station at Thule), data from 12 satellites was being recorded, with none of these satellites having an elevation of more than 45°.

3.1. *Cycle Slip Analysis.* The data was analysed using the software and techniques described previously. All the data from the reference receivers was found to be clean of cycle slips, and the data from the aircraft was found to have only a very few cycle slips. The cycle slip detection technique, however, did manage satisfactorily to detect all the cycle slips, and to show that the remainder of the data was clean.

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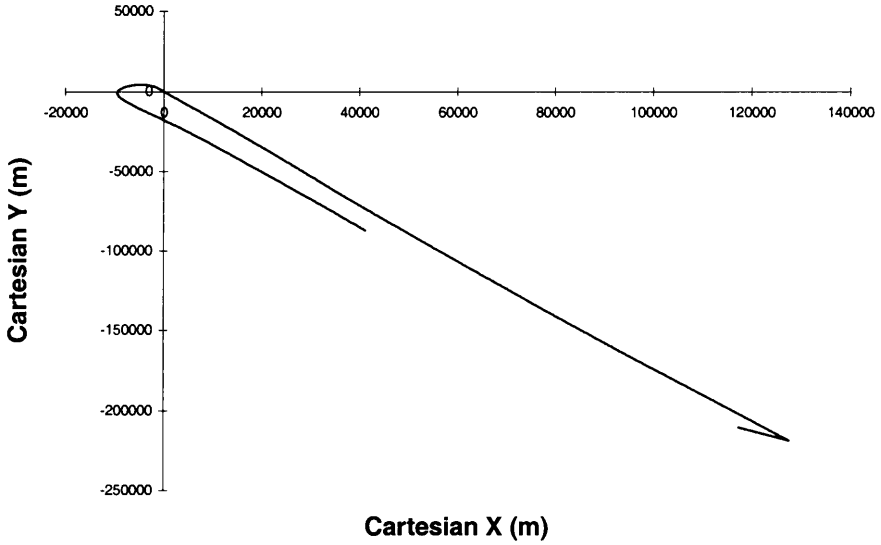


Figure 11. The resulting L1 integer fixed position.

3.2. *Positioning through OTF GPS.* IESSG's NOTF processing package (Hansen, 1996) allows the use of Multiple Reference Stations (MRS), which, as noted previously, assists with the search procedure and also permits the use of longer baselines between reference stations and the mobile receiver. NOTF allows the user to position the mobile receiver using a combination of techniques, which includes pseudo-range DGPS, wide-lane carrier phase positioning, L1 and L2 positioning, as well as narrow-lane positioning. The data was processed using the MRS option, as if operated in 'real time'. The 'real time' processing was carried out by allowing the program to run through the data once, as it would be in a true real-time situation. All usable data was processed, demonstrating that the NOTF software could be used for such long baseline distances (1500 km). However, it is unfortunate that the accuracy of the results could not be established, as there was no other positioning system on the aircraft of a corresponding accuracy.

Figures 11 and 12 show plots of positioning data from one of the two flights completed. Figure 11 illustrates the WGS84 Cartesian X and Y components for the resulting L1 position. Only X and Y are shown as Z depends, at these high latitudes of course, on the altitude or flight level of the aircraft and therefore has little meaning when related to the position of the pole. Figure 12 shows an expanded view of the resulting L1 integer fixed solution close to the pole, indicating that the antenna passed within a few metres of the WGS84 geographic North Pole.

4. conclusions. The results for the 134 km trial have shown that the MRS technique can be used over long ranges to fix the L1 integer ambiguities quickly and reliably, resulting in coordinates with a precision of 12 cm. The ionosphere and troposphere, however, affect the resulting L1 solution, which are not currently modelled in the NOTF software.

The polar flights have shown that NOTF may be used over very long distances (up to 1500 km), but as no means of absolute comparison was available, it is not possible to quote an accuracy figure. A future trial could include more than one roving GPS

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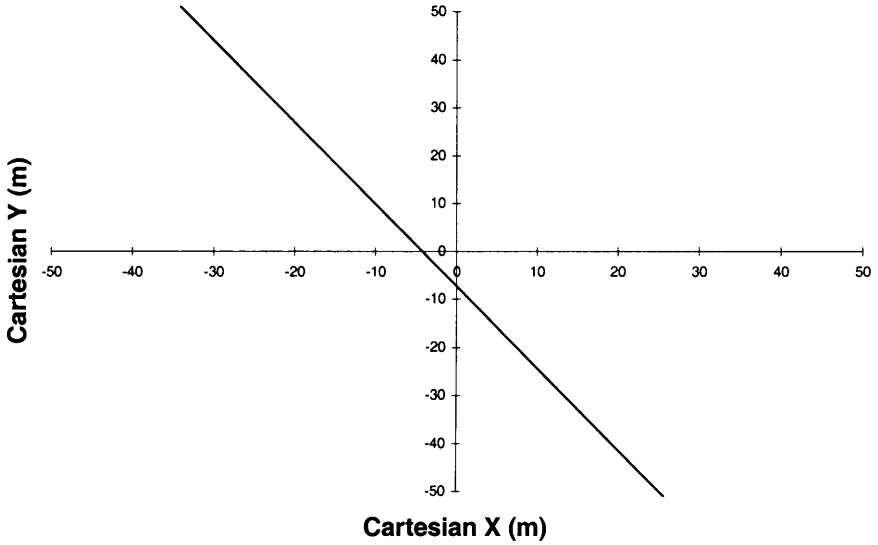


Figure 12. The L1 integer fixed solution at the North Pole.

receiver on the aircraft, which would allow the comparison of the positioning of two independent receivers.

acknowledgements

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