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TECHNICAL MEMORANDUM 96/215
April 1996

POST-PROCESSED DIFFERENTIAL GPS FLIGHT TRIALS WITH A CP-140 AURORA AIRCRAFT

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Defence Research Establishment Atlantic

Centre de Recherches pour la Défense Atlantique

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ABSTRACT

In August of 1995, the Esquimalt Defence Research Detachment and the Maritime Proving & Evaluation Unit (MP&EU) used post-processed GPS data to yield highly accurate position estimates for a CP-140 AURORA flight. The results of this trial indicate an ability to determine the aircraft's position within 4 m when up to 400 km from the GPS reference station and within less than a metre when 20 km from the reference. These results are independent of aircraft altitude, attitude, and flight manoeuvres.

RÉSUMÉ

En août 1995, EDRD a employé des données post-traitées du Système mondial de positionnement afin de déterminer des positions très précises un CP-140 AURORA en vol. Les résultats de cet essai indiquent une capacité de situer l'aéronef uniformément dans la limite de 4 m au-dessus une ligne de base de 400 km et dans la limite de moins d'un mètre au-dessus des lignes de base de moins de 20 km.

EXECUTIVE SUMMARY

REPORT NO.: DREA TECHNICAL MEMORANDUM 96/215

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AUTHORS: MEAKIN, LT(N) MICHAEL and NELSON, J. BRADLEY

INTRODUCTION:

The DREA Esquimalt Defence Research Detachment and the Maritime Proving and Evaluation Unit (MP&EU) performed a trial to determine if the absolute position of a CP-140 aircraft could be measured to within a few metres using a differential Global Positioning System (GPS). The equipment used in this trial consisted of a PC-based receiver connected to the existing aircraft GPS receiver, and a second PC-based recording system at a ground station. Post-processing was carried out using commercial software.

PRINCIPAL RESULTS:

The differential GPS system yielded positional accuracies of better than 4 m when the aircraft was 400 km from the GPS reference station and better than 1 m when less than 20 km from the reference. These accuracies were achieved regardless of platform altitude, attitude or flight dynamics. These data are also being used by MP&EU to calibrate the existing CP-140 GPS receiver.

SIGNIFICANCE OF RESULTS:

This differential GPS installation can be used in future trials such as real-time MAD (magnetic anomaly detection) geological noise removal using a pre-recorded geological noise database, and submarine signature measurement trials. Calibration of the existing CP-140 GPS receiver may be important for prosecuting fishing violations in a court of law.

FUTURE PLANS:

If the Canadian Forces have other requirements for very accurate navigation, then the system used in this trial could be easily adapted for use on any aircraft. The portability and relatively cheap cost of the hardware involved would make the procurement of such systems attractive, but further market analysis would be necessary to find a more streamlined set of software for the processing, analysis, and display of the results.

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1. INTRODUCTION

On August 16, 1995 Esquimalt Defence Research Detachment and the Maritime Proving & Evaluation Unit carried out a trial at CFB Greenwood to demonstrate the feasibility of using a Global Positioning System to record an aircraft's position in flight and then apply differential corrections during post-processing to obtain positional accuracies on the order of one metre. Such accuracies are required for studies relating to real-time MAD geological noise removal using a pre-recorded geological noise database, submarine signature measurement trials, and CP-140 GPS calibration. The latter may be important for prosecuting fishing violations in a court of law.

The equipment used in this trial consisted of an on-board portable computer fitted with a NovAtel ten channel GPS receiver (GPS Card) running Premier logging software from Northern Survey Systems of Calgary. The computer was strapped into a rack just aft of the after bulkhead of the cockpit and the receiver was connected to a powered splitter coming from the aircraft's own Trimble GPS antenna. The configuration was documented and photographed by MP & EU to aid in future installations.

A ground station consisting of another portable computer fitted with a GPS Card, a GPS antenna, and a VHF antenna, was set up at CFB Greenwood. The VHF antenna was used to receive the differential corrections broadcast from the Western Head Coast Guard navigation beacon. These corrections were fed into the GPS Card where they were used to obtain a single fix accuracy on the order of 1-2 metres. This base station also ran the Premier logging software.

Premier GrafNav Post-Processing software was used to perform post-flight data analysis and Monarch data extraction software and MatLab were used for plotting the results.

2. PREPARATION

Prior to the flight trial, an extensive electromagnetic interference test was performed by MP&EU to determine if the on-board GPS equipment was likely to interfere with the aircraft systems or vice-versa. The only serious problem encountered was with the transmission of cipher or plain voice at submultiples of the GPS L1 frequency on the upper VHF antenna only. This led to a complete loss of all satellites (lock had previously been held on ten satellites) immediately upon commencement of transmission. Transmitting on either the lower VHF antenna or on either antenna using CRAT (ciphered radio teletype) had little or no effect. As the transmitting VHF antenna is only 10 m away from the GPS antenna, it is not surprising that there is some interference on these particular frequencies. The EMI test was documented by MP & EU and will be promulgated to the CF through the usual channels.

3. SATELLITE AMBIGUITIES AND STATIC MODE DATA COLLECTION

GPS data are usually gathered in static (i.e. not moving) mode for several minutes prior to take-off. These data are used by the processing software to resolve the "satellite ambiguities", i.e. it determines the integral number of carrier frequency wavelengths (19 cm) between each satellite and the receiving station. Then during flight, as long as phase lock is maintained with at least four satellites, the post-processing software will yield highly accurate fixes. Should phase lock be held on less than four satellites at any time during the flight, then a second static mode data collection may be performed at the end of the flight and the data can be reverse processed. Alternatively, Kinematic Ambiguity Resolution processing can be applied to the flight data "as is" in hopes of solving for the satellite ambiguities. However, because the aircraft is moving at this time, the results of the KAR processing are usually not as good.

4. TRIAL

Fifteen minutes of static mode data were collected, then the CP-140 was taxied to the end of runway 26. The data collected during this slow-speed taxi were later compared to the surveyed height of runway 26 to estimate the vertical error in the differential GPS positions.

The aircraft then accelerated along the runway in preparation for take-off. During this acceleration the computer containing the GPS Card experienced a FAILURE TO WRITE TO C DRIVE error and the system crashed. Because repeated attempts to reboot the computer in-flight failed, we concluded that the vibration of the aircraft under full power was preventing the computer from accessing the C drive. Changing the propeller synchronization to move the vibrational nodes throughout the aircraft also failed to correct the problem, but it was found that the system would reboot when placed on a cushioned chair. The computer was remounted with additional padding to isolate it from the aircraft vibration, the system was re-booted, and the GPS Card and logging software restarted.

Re-acquisition of satellites and subsequent ambiguity resolution under the high dynamic conditions of flight required approximately 4-5 minutes. After that, lock was maintained on the required minimum of four satellites (typically 7-8) throughout the rest of the trial.

The flight trial consisted of flying a distance of approximately 400 km at an altitude of 6000 m and performing various dynamic manoeuvres such as figure-eights and a MAD trapping circle. The aircraft was then flown back towards CFB Greenwood, and similar manoeuvres were performed at an altitude of 150 m. The purpose of performing this second set was to ensure that low level effects such as surface reflection and multipath did not interfere with the GPS system. The CP-140 then returned to CFB Greenwood where no computer problems were experienced during the landing.

After landing, we allowed another fifteen minutes for static data collection. This enabled us to reverse process the flight data to obtain very accurate fixes even though we had lost the computer during take-off.

5. POST-PROCESSING: MANUFACTURER'S ESTIMATED ERRORS

The flight and ground station GPS data were re-processed using the Premier GPS software package "GrafNav" from Northern Survey Systems. The reliability of each recalculated fix is represented by a quality factor from 1 to 6. According to the manufacturer, these quality factors reflect a real error which is a function of the baseline length (the distance between the GPS reference base station and the aircraft). These qualities are represented on the graphical display as one of four colours corresponding to quality 1, quality 2, quality 3-4, and quality 5-6. A quality 1 represents 1-2 parts per million error, quality 2 2-8 ppm, etc. up to quality 6 which is >40 ppm. Each ppm translates into 1 mm error per kilometre of baseline plus, for baselines much longer than a few tens of kilometres, an additional 1 ppm error must be added to allow for path differences through the ionosphere from each satellite to each of the GPS stations. According to the manufacturer then, the error corresponding to each quality factor at 400 km from the reference station is:

Quality 1	0.8 - 1.2 m
Quality 2	1.2 - 3.6 m
Quality 3	3.6 - 6.8 m
Quality 4	6.8 - 11.6 m
Quality 5	11.6 - 16 m
Quality 6	>16 m

At ranges less than 400 km these errors are much less.

The data from both the airborne system and the ground station were downloaded into the same computer. For the first part of the trial, from the static initialization through to the system failure on take-off, forward processing was used. For the remainder of the trial two different methods of processing were attempted; forward processing using Kinematic Ambiguity Resolution; and reverse processing utilizing the 15 minutes of static data obtained at the end of the flight to determine satellite ambiguities.

The forward processing of the first part of the trial resulted in fixes of qualities 1 and 2, predominantly quality 2. As the baseline was about 2 km long, this corresponds to errors of 2-4 mm for quality 1 and 4-16 mm for quality 2. According to the manufacturer then, the vertical profile of runway 26 measured during the slow-speed taxi should be accurate to within 4-16 mm.

For the second part of the trial, reverse processing of the data resulted in a majority of the fixes having a quality factor of 2 and KAR forward processing resulted in quality factors of 3 and 4. According to the manufacturer then, using reverse processing resulted in errors of less than 4 m even at the range of 400 km from the ground station.

Due to the limitations of the GrafNav software (including the inability to obtain a printout of the processed ground track or to display altitude), further manipulation of the data required exporting the information to Monarch data extraction software. Using this tool, each individual variable (i.e. latitude, longitude, altitude, quality and time) was extracted. Also, the latitudes and longitudes were converted from degrees/ minutes/ seconds to decimal degrees. This information was then input to MatLab where it could be graphed in two or three dimensions, broken up into segments for more detailed analysis of specific events or rotated for different cross sectional views of the flight.

6. DATA ANALYSIS AND COMPARISON TO MANUFACTURER'S ESTIMATED ERRORS

The results of re-processing the data from slow-speed taxi along runway 26 are shown in Figures 1 and 2. The runway appears to have both a grade to the south and a small hump of approximately 1 m in height near the north end. Examination of the contour maps of the airport confirm that both of these phenomenon are real. In fact the size of these features in the surveyed and DGPS data agree to within the manufacturer's error estimate of 16 mm (based on quality factor =2 and a baseline of 2 km). This confirms that, at least at low speed, the DGPS system is extremely accurate and the manufacturer's error estimates are valid.

To determine the DGPS performance at high-speed we re-processed the landing data from the second part of the trial. Figure 3 is a plot of latitude vs. longitude during the landing. Figure 4 is a plot of the antenna height during the landing. Figure 4 also shows the gradual grade and the 1 m hump found in the slow-speed taxi results. Comparison of the two ground tracks (Figure 5) shows a very close correlation in latitude and longitude (as would be expected). Figure 6 compares the antenna heights measured during the slow-speed taxi and the landing. The difference between the two profiles is about 10 cm and is probably due to the crowning of runway 26. Both profiles are very smooth and show the same size of hump and grade as found in the contoured survey data. This illustrates the excellent reproducibility of the DGPS results, irrespective of speed.

A three dimensional representation of the entire flight (Figure 7) demonstrates the power of this analysis tool in comparison to a simple ground track (Figure 8). However, a ground track is the more useful of the two for displaying quality factors throughout the entire flight (Figure 9). This plot shows the overwhelming predominance of quality factors 1 and 2. It should be noted that the extended interval of quality 3/4 fixes between point A and point B in Figure 9 correspond to the period when the GPS system was restarted and was in the process of re-acquiring satellites. It could therefore be surmised that, had the system not experienced a failure during take-off, this interval would not have been as extensive if, indeed, it had occurred at all. Even including this period of poor fixes, however, the number of solutions which fall into quality 1 or 2 is 26252 of 29993, or 88% of the total solutions.

Finally, any section of the flight may be examined in more detail for post-mission analysis and, combined with the quality factors and the platform's position (to give the baseline), a probable error in position can be assigned to any portion of the flight. As stated earlier, this was less than four metres for almost the entire flight. Examination of the manoeuvres performed by the aircraft at both high-altitude (Figure 10) and low-altitude (Figure 11) show that the quality factor (and therefore the positional accuracy) does not appear to be a function of platform attitude, altitude or speed. Although occasional degradation of accuracy is experienced, it is very infrequent, short term (less than a few seconds) and not noticeably related to platform dynamics.

7. CONCLUSIONS AND RECOMMENDATIONS

The conclusion which may be drawn from this experiment is that post-processed differential GPS is a reliable and cost effective means of accurately determining the position of a CP-140 regardless of the attitude, altitude, or flight dynamics. This degree of navigational accuracy would be very useful in a variety of missions, including real-time MAD geological noise removal using a pre-recorded geological noise database, submarine signature measurement trials, and CP-140 GPS calibration. For instance, this system could be used to provide navigational accuracies of 20 cm for MAD trials at the Canadian Forces Maritime Experimental and Test Range (assuming a baseline of 10 km and a quality factor of 2).

It should also be noted that this technique can be used in the absence of a dedicated ground station so long as data can be obtained from a local differential correction beacon. Such data are available through several computer bulletin boards (such as the Canadian Active Control System) and can be used in the same manner as the dedicated system with the location of the beacon transmitter substituting as the ground station location. This may also be useful if the flight takes place closer to the beacon than to the ground station as the shorter baseline would result in increasing the absolute accuracy of the fixes. However, there are very few beacons (at best every few hundred nautical miles) and not all beacons have their data carried on the bulletin boards (e.g. the only CACS station on the east coast is St. John's Nfld).

Finally, this system could be installed on any CP-140 with mission requirements for highly-accurate navigation anywhere in the world. The system would be low-cost and reliable. Should this be considered, however, a more streamlined method of performing the analysis would be required. The Premier software, while very good for post-processing, is severely limited in its ability to analyze and display the data. A post-processing package which is capable of displaying altitude, latitude, and longitude, and able to generate colour printouts of the results would be necessary before widespread introduction of such a system.

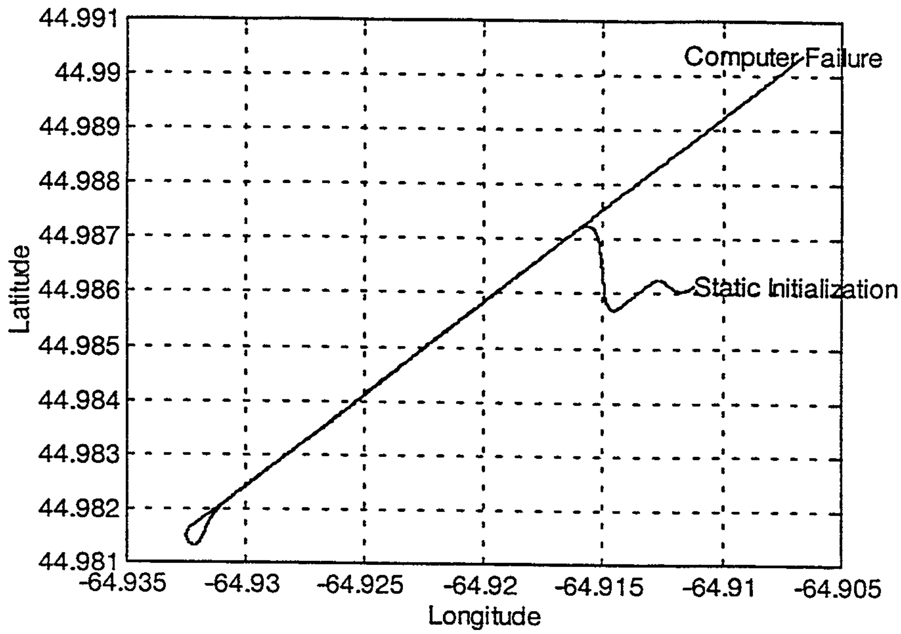

Figure 1: Profile Obtained for Runway 26

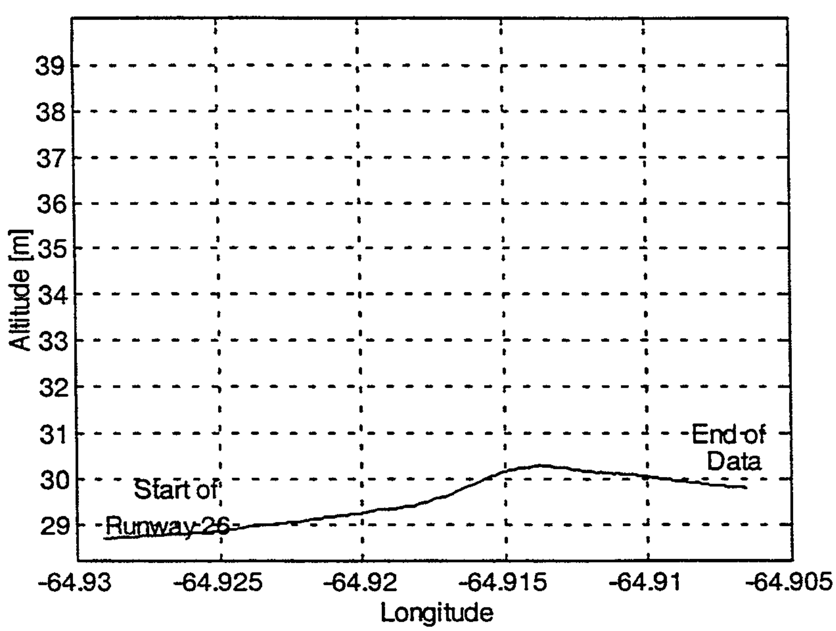

Figure 2: Initial Slow Speed Survey of Runway 26

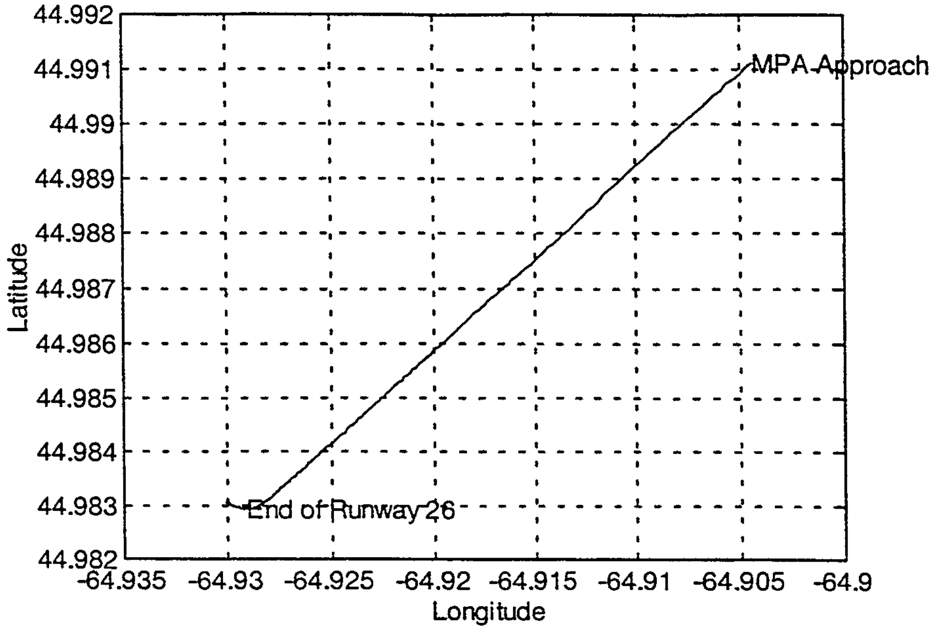

Figure 3: Landing and Taxi Along Runway 26

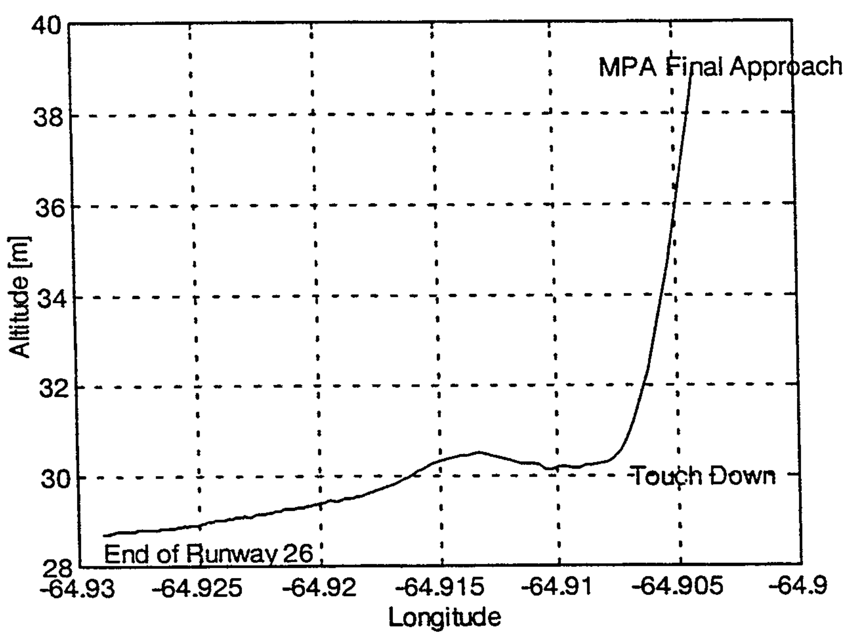

Figure 4: 3D MPA Approach, Landing & Taxi Along Runway 26

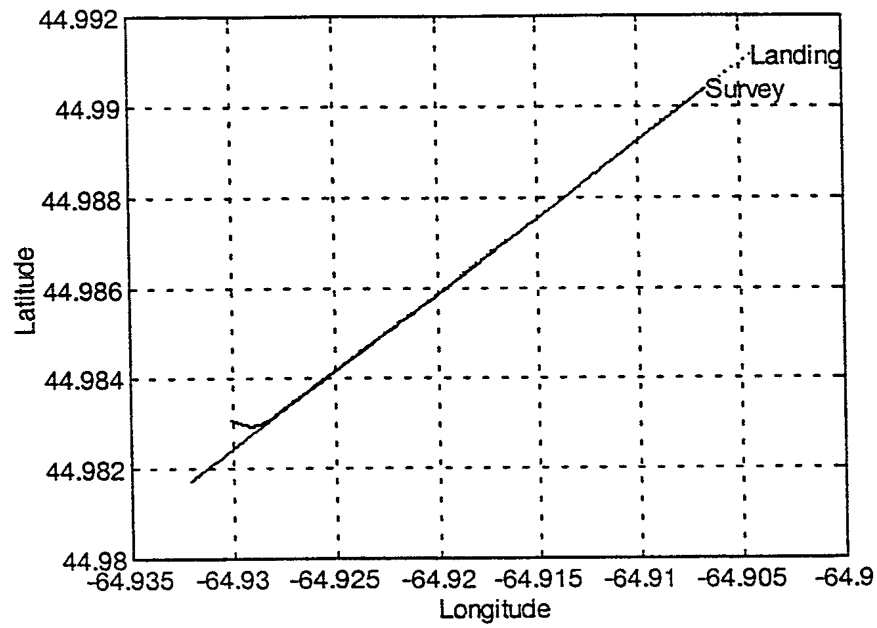

Figure 5: Ground Track of Landing vs Survey

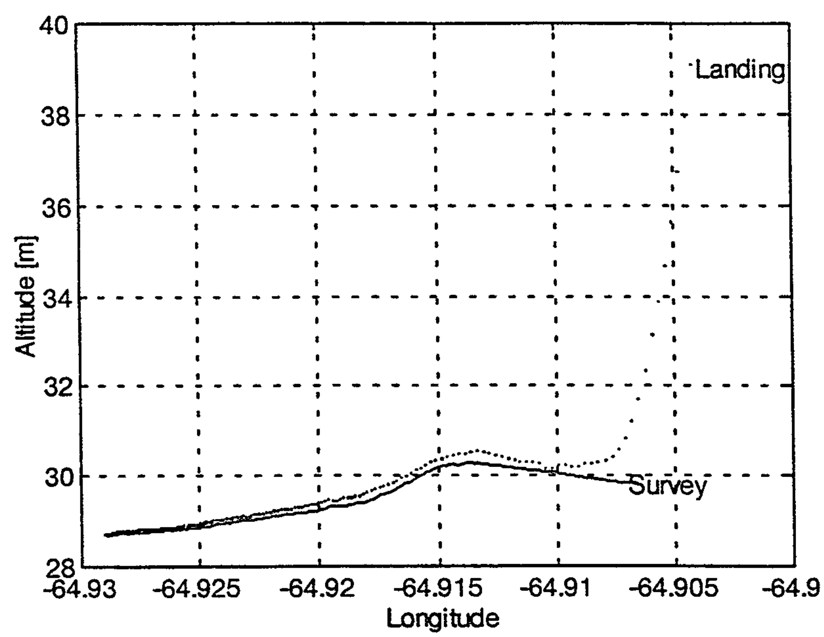

Figure 6: Comparison of Slow Speed Runway Survey with Landing Track

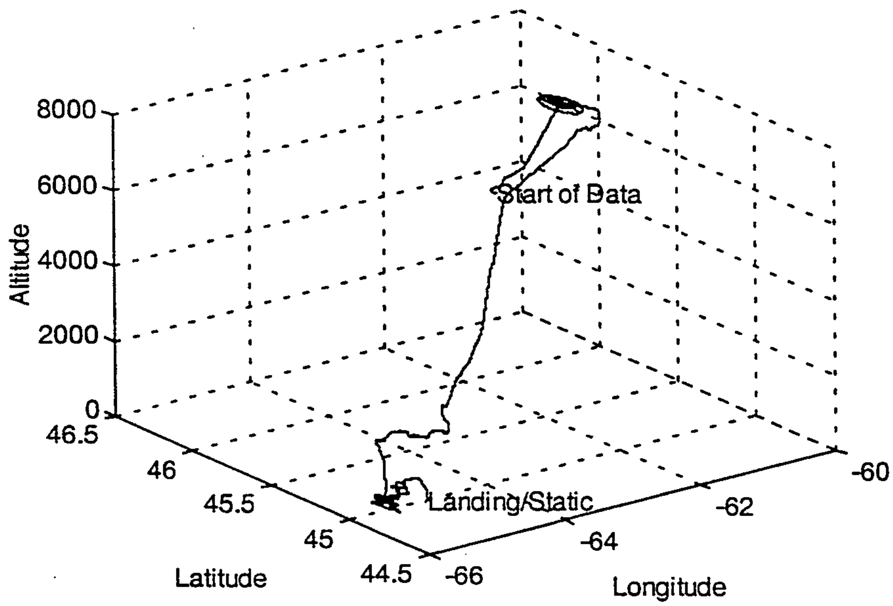

Figure 7: 3D MPA Trial Flight

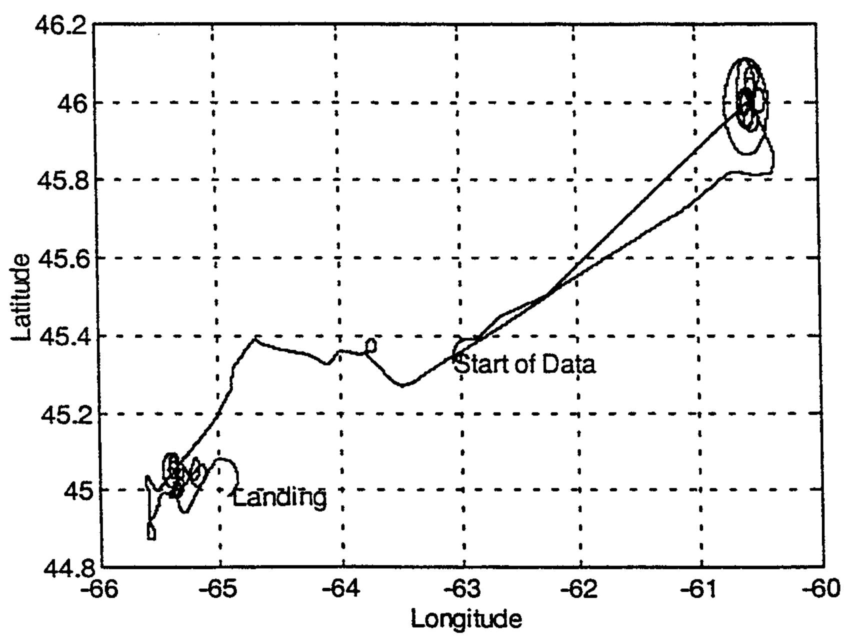

Figure 8: MPA Ground Track

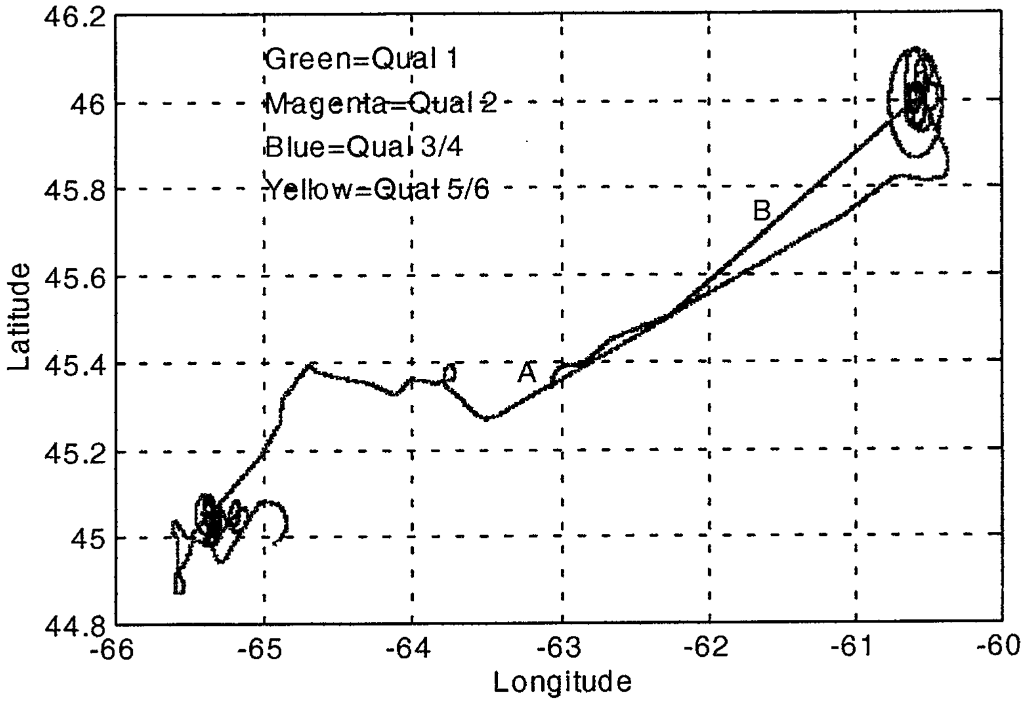

Figure 9: Ground Track with Quality Factors Displayed as Colours

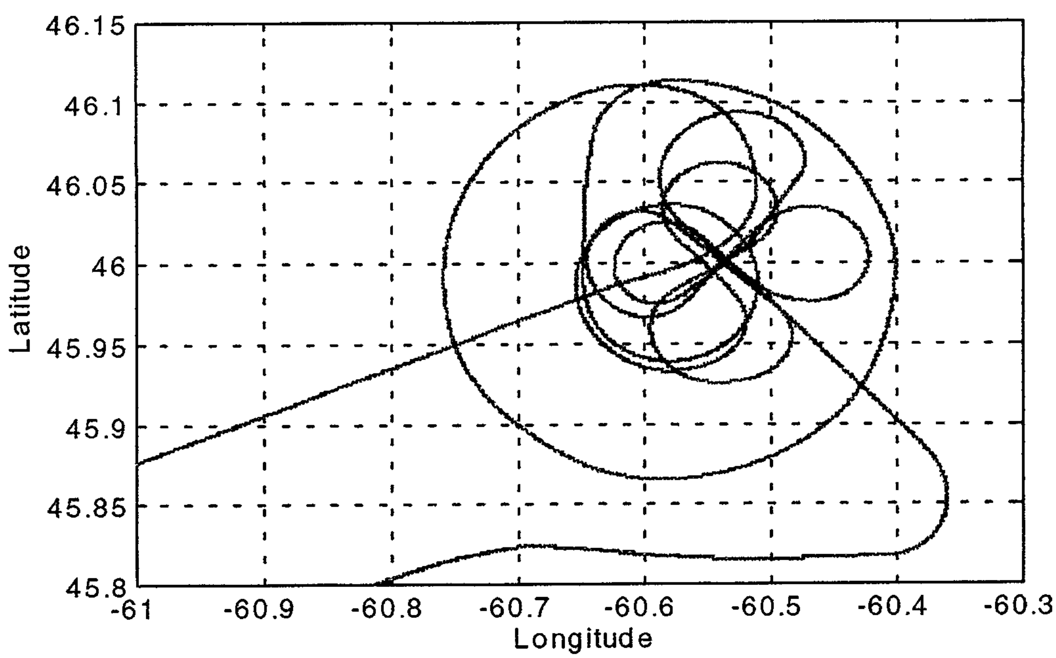

Figure 10: High Altitude Manoeuvers with Quality Factors

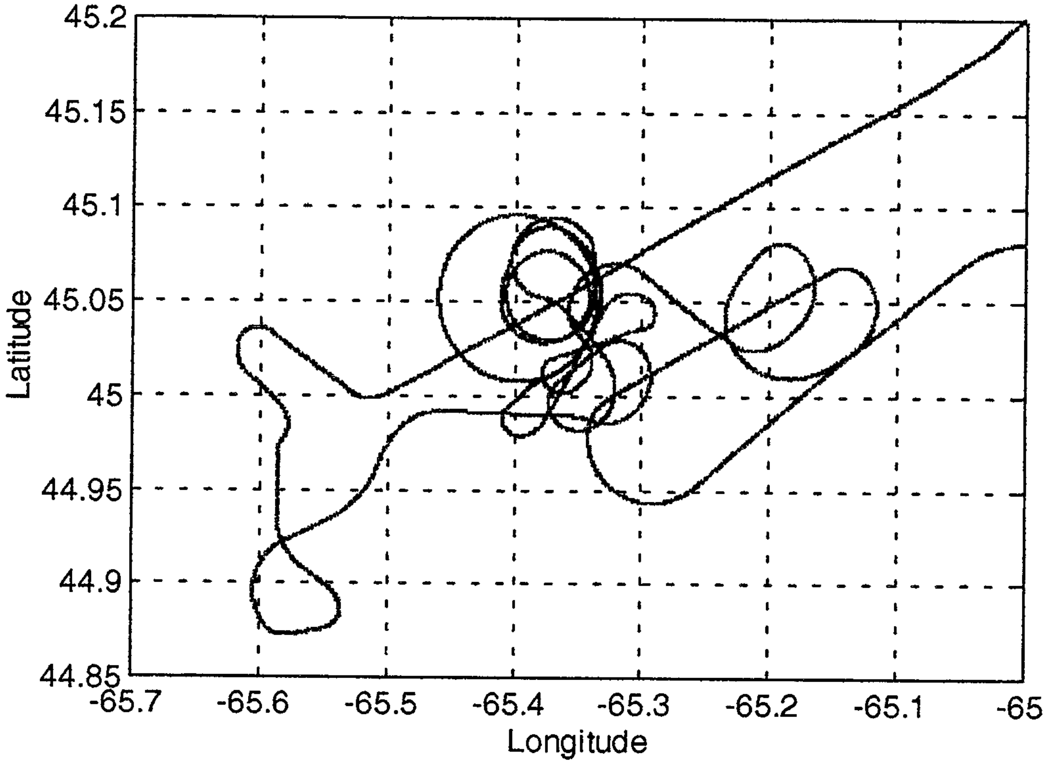

Figure 11: Low Altitude Manoeuvers with Quality Factors

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In August 1995, the Esquimalt Defence Research Detachment and the Maritime Proving & Evaluation Unit (MP&EU) used post-processed GPS data to yield highly accurate position estimates for a CP-140 flight. The results of this trial indicate and ability to determine the aircraft's position within 4 m when up to 400 km from the GPS reference station and within less than a metre when 20 km from the reference. These results are independent of aircraft altitude, attitude, and flight manoeuvres.

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