Performance and Guidance System Testing using Differential GPS on a Falcon 20 Aircraft

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1.0 SUMMARY

Using a Falcon 20 research aircraft, a program was conducted at the Canadian National Research Council (CNRC) to investigate the use of a differential Global Positioning System (GPS) to 1) provide aircraft guidance on precision instrument approaches, and 2) measure aircraft performance parameters during typical flight test manoeuvres needed for aircraft certification. The initial series of tests used a differential GPS with NovAtel 951R receivers installed in the aircraft and at the ground station, and with a VHF radio link to provide real-time differential corrections. This system fell slightly short of the vertical accuracy criteria needed for precision approaches to Category I limits, and did not meet the accuracy criteria desired for flight test measurement.

Following an upgrade to a NovAtel RT-20™ differential GPS, a program was conducted to determine the landing performance of the Falcon 20 on winter contaminated runways (covered with ice or snow). The real-time position and height accuracies of the upgraded system were determined to be less than 20 centimeters, falling well within the accuracy criteria for Category I approaches, and enabling this system to be used as the primary device for measuring aircraft landing distances from a height of 50 feet (15 meters) to a complete stop. During this program, a strong correlation was found between aircraft deceleration during full braking and the runway friction index reported by a ground test vehicle, allowing the aircraft landing distance to be accurately predicted as a function of the runway friction index.

2.0 INTRODUCTION

The CNRC Falcon 20 aircraft was acquired from the Canadian Forces in 1991 and converted to a research configuration for two main purposes; 1) to support the Canadian Space Agency as a microgravity research vehicle and 2) to support the Transport Canada Microwave Landing System (MLS) program as a vehicle for the development and demonstration of curved, segmented precision approaches. Modifications were made to the aircraft fuel and hydraulic systems for the zero gravity environment, and the aircraft remains a viable microgravity testbed today. A data acquisition and computing system was developed to provide aircraft positioning and guidance for the curved approaches, and with the cancellation of the MLS program in North America, this system was easily converted to permit the use of the GPS as an aircraft position sensor.

For aircraft precision approaches to at least Category I decision height limits of 200 feet (61 meters), a differential GPS (DGPS) with a real-time position and height accuracy in the order of one meter was desirable. If this degree of position accuracy could be achieved during the execution of an instrument approach, it was evident that the DGPS could also be used for the measurement of aircraft position, and perhaps velocity and acceleration, for flight test work, either experimental or for aircraft certification. This paper describes the initial DGPS installed in the CNRC Falcon 20, it's integration with the aircraft avionics systems to provide guidance to Category I approach limits, and it's accuracy and application as a flight test measurement tool. The improved accuracy resulting from the installation of an upgraded DGPS will be described, and the results of aircraft landing performance tests on winter contaminated runways using this system will be presented.

3.0 EQUIPMENT DESCRIPTION

3.1 Falcon 20 Research Aircraft

The CNRC Falcon 20, C-FIGD, shown in Figure 1, is a business jet designed and built by Avions Marcel Dassault. The aircraft is powered by two General Electric model CF700-2D2 turbofan engines. Conventional flight control surfaces are actuated by two independent hydraulic systems, and pitch trim is accomplished by electrically operated control of the horizontal stabilizer. The aircraft operating speeds are normally in the Category "C" range (121 to 140 knots) for precision instrument approaches. A Sperry SPZ 500 integrated flight control system (IFCS) is available to fly either manual or coupled precision approaches using the normal Instrument Landing System (ILS) or the experimental DGPS. The main components of the IFCS are the pilot's and co-pilot's attitude director indicators (ADI), horizontal situation indicators (HSI), flight director computers (FDC) and mode selectors, and the single autopilot computer and controller.

Figure 1
The CNRC Falcon 20 Research Aircraft

The Falcon 20 had an onboard data acquisition system (DAS) in a standard 19 inch avionics rack mounted on the seat rails in the rear cabin of the aircraft. The rack was modular in the sense that certain components of the DAS, or the entire rack, could be easily removed from the aircraft for maintenance or bench testing. The DAS included all interfaces for the following specially mounted instrumentation sensors:

a. Pitot and static pressure transducers and total temperature probe;
b. Five pressure ports on the aircraft nosecone with transducers for angle of attack and angle of sideslip measurement;

Paper presented at the AGARD FVP Symposium on "Advances in Flight Testing", held in Lisbon, Portugal, 23-26 September 1996, and published in CP-593.

c. Weight on wheels and brake pressure transducers;
d. Accelerometers and rate gyros in all three axes;
e. Pitch, roll and heading sensors; and
f. Radar altimeter.

The DAS was integrated with the aircraft GPS receiver and other aircraft navigation systems through standard digital interfaces, and with the pilot's and co-pilot's flight instruments through the navigation and FDC junction boxes. A Digital Equipment Corporation LSI 11/73 was used as a central processing unit (CPU) to translate the real-time DGPS position and height information into an x,y,z coordinate system referenced to the runway Glide Path Intercept (GPI) point. This aircraft position was compared to the approach path selected by the pilot on a control and display unit (CDU) in the cockpit to determine the lateral and vertical track deviations. These deviations, along with additional computed approach information such as course and distance to go to touchdown, were sent to the Sperry IFCS for approach steering using the cockpit flight instruments.

An equipment rack and project operator's station were located in the aircraft cabin forward of the DAS. The rack contained the DGPS equipment which will be described in the next section. The operator's station was used to initialize and control the airborne software program, and to troubleshoot the DAS when required. The DAS included a digital audio tape (DAT) with a 1.2 gigabyte capacity, which was used as a recording medium for the DGPS information, approach guidance parameters and other aircraft data (angles, rates, accelerations). The recording rate was set at 8 Hz.

3.2 Differential GPS Equipment

Figure 2 shows a block diagram of the DGPS setup. The initial GPS receiver installed in the Falcon 20 was a NovAtel 951R single frequency (L1=1575.42 MHz) ten channel receiver. Rather than being a self-contained unit, this was a receiver card installed in a Dell 486 computer and connected to an antenna on top of the aircraft. A second identical receiver card was installed in a computer at the ground station, and connected to an antenna whose exact position had been surveyed by standard control survey techniques. With both receivers running at the same time and referenced to the same satellite vehicle (SV) constellation, the ground station position and height corrections were applied to the airborne system, providing a basic DGPS system. For real time corrections, a VHF data link provided updates from the ground station every two seconds on an assigned frequency of 172.725 MHz. Post-flight solutions for aircraft position and height were also determined to a very high degree of accuracy by using a program to resolve the carrier phase ambiguities to within one carrier wavelength of about 19 cm. Real-time DGPS data was updated at 5 Hz, while data for post-flight processing was updated at 1 Hz.

In order to determine the accuracy of the NovAtel DGPS during approaches and flight test manoeuvres, a second DGPS was used as a positional "truth" system. Shown in Figure 2 along with the NovAtel DGPS, this system included two Ashtech Z-12 dual frequency 12 channel GPS receivers, one in the aircraft and one at the ground station. The Ashtech DGPS system was not used in the real-time mode, but processed post-flight to a solution with full carrier phase ambiguity resolution. As such, it qualified as a Time Space Position Information System (TSPI), according to tests conducted on an identical system at the FAA Technical Center in Atlantic City, NJ (Reference 1), which showed the Ashtech Z-12 DGPS to be more accurate than two different configurations of laser trackers. For this reason, the Ashtech DGPS was used as a stand-alone "truth" system, without reference to additional systems, other than the occasional visual confirmation of the aircraft position on the runway with respect to the GPI point.

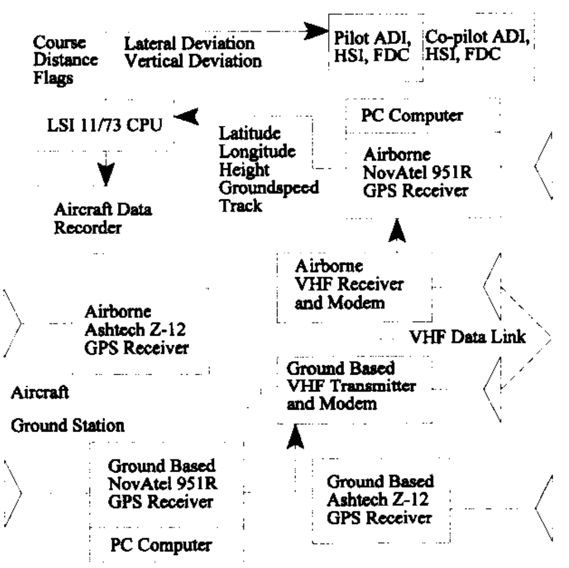

Figure 2
Falcon 20 Differential GPS System Setup

4.0 GUIDANCE SYSTEM TESTING

The NovAtel DGPS guidance system was tested to determine its Total System Error (TSE) during the conduct of straight-in precision approaches to Category I limits. The TSE was the root-sum-square of the Navigation System Errors (NSE), or the differences between the DGPS derived aircraft position (real-time) and the true aircraft position, and the Flight Technical Errors (FTE), or the pilot/autopilot errors in flying the approach commanded by the guidance system. TSE is related to FTE and NSE by the formula:

$$TSE = \sqrt{FTE^2 + NSE^2} \qquad (1)$$

The flight tests consisted of three separate flights used to fly a total of 24 approaches to the Ottawa International Airport, Runway 25, where there was no equivalent ILS precision approach. Standard left or right hand patterns were flown for each approach, with an intercept angle of about 30 degrees to the final approach segment. The final approach segment was 5 to 6 nautical miles (nm) long, and descended along a 3 degree glidepath, intercepting the runway surface at approximately 1000 feet (300 meters) from the threshold. Two or more approaches on each flight were flown coupled to the aircraft autopilot, with the remainder manually flown using the Sperry SPZ-500 flight director. The approaches were all flown as closely as possible to the intended approach path down to Category I limits, after which the pilot took over visually for the remainder of the descent profile to the runway. Most of the approaches were terminated with a touch-and-go on the runway; two were low approaches and three were full stop landings.

Figure 3 shows the cross-track deviation (CTD), in feet, plotted against the along-track distance (ATD), in nautical miles, for all 24 approaches. The ATD was the computed horizontal distance, along the approach track, from the aircraft position to the GPI point. The approaches progress from right to left in Figure 3, with the pilot taking over visually at an ATD of 0.5 nautical miles. The solid lines converging towards the approach path from either side depict the standard full scale (two dot) lateral deviation limits on the pilot's HSI, beyond which the pilot would have to break off the approach due to a failure to meet obstacle clearance criteria. These deviation limits decrease with decreasing ATD, resulting in an increasing steering sensitivity over the last 4.5 nautical miles of the approach. This effect can be seen by the gradual decrease in CTD as the approaches progress towards the GPI point. For all approaches, the achieved CTD can be seen to be well within the full scale limits.

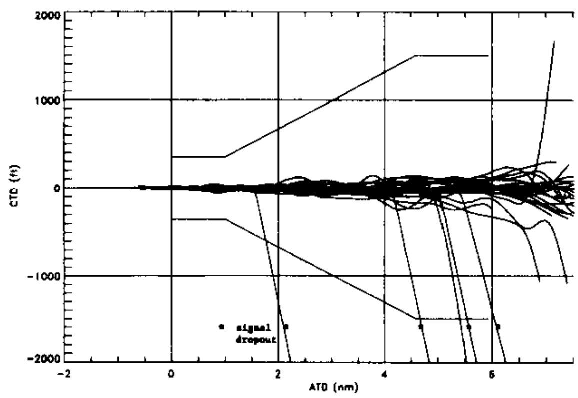

Figure 3
Cross-track Deviation versus ATD, using DGPS Guidance

Figure 4 shows the vertical-track deviation (VTD), in feet, plotted against ATD, in nautical miles, for all 24 approaches. All of the intercepts, except one, were from below the glidepath. Full scale vertical deviation limits are also shown in Figure 4, with the achieved VTD well within these limits. Following aircraft touch-down at an ATD of about 0.0, the VTD increases because the theoretical glidepath extends below the runway surface at a 3 degree angle.

The DGPS signal dropouts shown in Figures 3 and 4 occurred four times over the course of the 24 approaches. These dropouts caused a momentary full scale deflection of the instruments being used to fly the approach, distracting the pilot, but not causing the approach to be aborted. A GPS dropout test was added to the Falcon airborne software program following these tests to maintain continuity of data on the flight instruments, while allowing the dropouts to be recorded for future investigation.

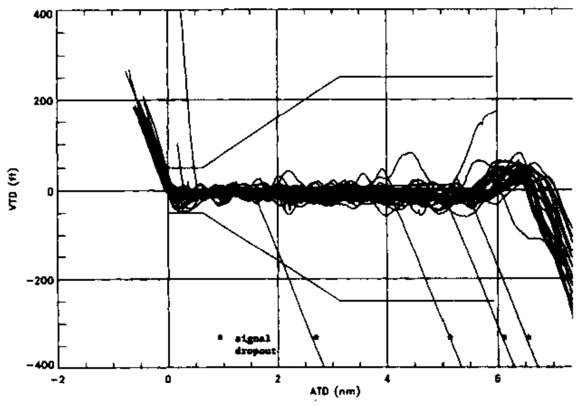

Figure 4
Vertical-track Deviation versus ATD, using DGPS Guidance

The FTE and NSE are each determined to a 95% confidence level by adding the absolute value of the mean error to twice the value of the standard deviation (sigma). For the FTE, these values are calculated from the deviations shown in Figures 3 and 4 at an ATD between 0.5 and 0.6 nautical miles, equivalent to a decision height of 200 feet (61 meters). As shown in Table 1, the lateral FTE is 12.3 meters and the vertical FTE is 7.4 meters. Analysis of the NovAtel 951R real-time DGPS position and height versus the Ashtech Z-12 TSPI post-flight processed solution for the 24 approaches resulted in lateral and vertical NSE's of 6.5 meters and 8.2 meters respectively. The TSE's shown in Table 1 are computed from Equation 1. In order to meet the required navigation performance (RNP) criteria being introduced by the FAA (Reference 2), an aircraft must pass through an inner "tunnel," whose dimensions vary with height above touchdown, within a 95% confidence level. At a height of 200 feet (61 meters), the tunnel halfwidths, or total system error (TSE) requirements are ±33.5 meters laterally and ±9.8 meters vertically.

	Lateral Errors (meters)		
	Mean	Sigma	*Mean* + 2 Sigma
FTE	-1.3	5.5	12.3
NSE	0.9	2.8	6.5
TSE	-	-	13.9
RNP	-	-	33.5
	Vertical Errors (meters)		
	Mean	Sigma	*Mean* + 2 Sigma
FTE	-2.2	2.6	7.4
NSE	0.2	4.0	8.2
TSE	-	-	11.1
RNP	-	-	9.8

Table 1
Summary of Errors - DGPS Category I Approaches

Table 1 shows that the lateral system errors were within the RNP for Category I precision approaches, and even within the more stringent RNP for higher category approaches, which are ±23 meters at 100 feet (30 meters) height, and ±15.5 meters at 50 feet (15 meters) height. The vertical system errors, however, did not quite meet the RNP criteria for Category I approaches. The reasons for this were twofold. First, a mean vertical FTE of -2.2 meters occurred consistently during the approaches due to a calibration error in the aircraft flight director. Second, the large standard deviation of 4.0 meters for the NovAtel DGPS height error resulted in an unusually large NSE for the system under test. This was influenced to some extent by a non-standard configuration of the NovAtel ground station GPS antenna, which made it more susceptible to multi-path effects. Correction of either one of these error sources, especially the NSE, would have brought the vertical TSE to within the RNP criteria for Category I approaches. The concept of using DGPS guidance to fly precision approaches was well demonstrated during these tests, but a more accurate system was required to determine the aircraft height above the runway.

5.0 FLIGHT TEST MEASUREMENT

The application of the Falcon 20 NovAtel DGPS as a flight test measurement tool was explored during the same time period, and with the same DGPS configuration, as the precision approach testing described above. The objectives of the tests were to demonstrate DGPS based measurement techniques in collecting aircraft performance data during certification type flight test manoeuvres, and to determine the NovAtel 951R receiver based DGPS position and height accuracies, both real-time and post-flight processed, in comparison with the Ashtech Z-12 TSPI. Among the test points conducted were:

a. Airfield performance manoeuvres including maximum power takeoffs, simulated single engine takeoffs, a rejected takeoff from V_1, performance landings, and a simulated V_{mcg} ground run;
b. Autopilot performance tests to include simulated autopilot malfunctions on an ILS or MLS glidepath, and simulated autopilot touchdown accuracies;
c. Flight performance manoeuvres to include airspeed calibration runs and climb profiles; and
d. Community noise tests to include low altitude fly-bys and intercepts of the fly-by profile from a normal takeoff.

5.1 DGPS Accuracies

Table 2 shows the results of the accuracy tests, with the real-time errors being the differences between the NovAtel real-time DGPS solution and the Ashtech TSPI solution, and the Carrier Phase Ambiguity Resolution (CPAR) errors being the differences between the NovAtel DGPS post-flight processed solution with full CPAR and the Ashtech TSPI. As noted earlier, the Ashtech TSPI solution always included full CPAR. Since most flight test manoeuvres are measured from one position relative to another, only the "2 sigma" errors are shown in Table 2, as opposed to the absolute errors (*mean* + 2 sigma).

	Horizontal Errors (2 Sigma)	
	Real-time (m)	CPAR (m)
Takeoffs	1.5	0.02
Landings	0.68	0.02
Climbs	1.4	0.08
Airspeed calibration	3.2	0.30
	Vertical Errors (2 Sigma)	
	Real-time (m)	CPAR (m)
Takeoffs	1.8	0.02
Landings	1.4	0.02
Climbs	2.0	0.39
Airspeed calibration	7.6	0.24

Table 2
DGPS Accuracy for Typical Flight Test Manoeuvres

The real-time errors shown in Table 2 were computed for specific (short duration) events such as takeoff and landing, and are therefore smaller than the NSE's shown in Table 1, which were computed for the entire series of approaches. It is also obvious from Table 2 that there is a large difference between the real-time errors and CPAR errors, where the real-time errors are in the order of meters, and the CPAR errors are in the order of centimeters. If accuracy was the only issue, the CPAR solution could be used for all flight test work, since it was generally within the desired one meter accuracy requirement, at least for relative measurements (2 sigma). However, the CPAR solution has the following significant disadvantages:

a. It requires a considerable amount of time for post-flight processing;
b. It cannot be used in flight to determine real-time performance parameters as a guide to progressing to the next test point; and
c. It cannot be used for aircraft guidance.

The real-time solution, on the other hand, is immediately available in flight for the purposes mentioned above, but unfortunately includes errors larger than one meter.

Table 2 also shows the effect of an increasing baseline, or distance between the aircraft and the ground station, on the position and height errors for a single frequency DGPS. With the ground station set up at the airfield, the errors associated with takeoffs and landings are relatively small, while the errors for the climbs, with baselines out to about 15 nautical miles, are larger. The airspeed calibrations, flown at altitudes up to 35,000 feet at distances out to 100 nautical miles, have significantly larger DGPS errors, both real-time and CPAR.

5.2 DGPS Flight Test Application

As noted earlier, the DGPS latitude, longitude and height information was translated into an x,y,z coordinate system which was referenced horizontally to the GPI point, and vertically to the runway threshold. The "x" axis gave the distance along the runway length, while the "y" axis gave the deviation (left or right) from the runway centreline. The "z" axis gave the height of the aircraft main wheels above the runway surface as a function of the aircraft pitch angle and fixed GPS antenna position. The real-time x,y,z values, along with the DGPS-derived groundspeed, were displayed on one of the data pages of the cockpit CDU. When lining up for takeoff, the pilot could monitor the accuracy of these parameters in comparison with his position on the runway, thus ensuring the proper functioning of the differential link prior to takeoff.

The recording of aircraft distance along the runway led to a simple data reduction scheme for airfield performance manoeuvres such as takeoffs and landings. The takeoff distance to a 35 foot screen height was determined simply by establishing the aircraft x-axis position at a DGPS height of 35 feet (11 meters) above the lift-off point, and then subtracting this value from the x-axis position recorded at the beginning of the takeoff roll. The landing distance from 50 feet (15 meters) above the runway to a complete stop was determined in the same manner. Real-time DGPS position errors of about 1.5 meters in the horizontal plane were slightly higher than the desired measurement accuracy. However, because of the dependence of takeoff and landing distances on height above the runway, the real-time DGPS height errors of about 2.0 meters influenced their measurement accuracy to an unacceptable extent.

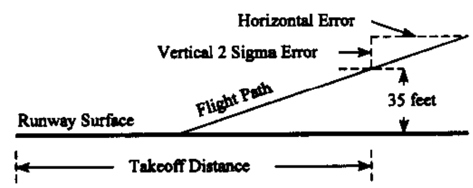

Figure 5
Effect of Vertical Errors on Measurement Accuracy

Figure 5 shows how the measurement of takeoff distance is dependent on climb gradient and DGPS height accuracy (2 sigma for a 95% confidence level). For a low climb gradient of about 5%, typical of single engine performance, a 2.0 meter error in height would result in a 40.0 meter uncertainty in the measurement of takeoff distance, representing about 4.0% of a typical Falcon 20 takeoff distance of 1000 meters. The measurement of landing distance from a height of 50 feet (15 meters) would be similarly affected, with a 3 degree glidepath angle being roughly equivalent to a 5% gradient. On the other hand, flight test manoeuvres performed only in the horizontal plane, such as rejected takeoffs and V_{mcg} ground runs, were not affected by errors in height, and could be measured (real-time) to within about 1.5 meters. This figure represents a very small percentage of a rejected takeoff roll, but a much higher percentage of the deviation permitted left or right of the runway centreline during V_{mcg} testing.

To simulate autopilot coupled landing performance, the DGPS-derived aircraft touchdown positions were recorded in comparison with videotaped images of the actual aircraft touchdown points on the runway. Unfortunately, these comparisons were inconclusive due to the lack of a functional weight-on-wheels switch during the actual tests. In addition, with a DGPS sample rate of only 5 Hz applied at landing speeds of about 200 feet/sec (61 meters/sec), an ambiguity of about 40 feet (12 meters) existed in the aircraft touchdown point. This was considerably larger than the absolute (*mean* + 2 sigma) horizontal error of 2.1 meters for landings, even with signal latency and transport lag included. For future tests, the sample rate would have to be high enough for the desired level of accuracy, or an interpolation routine would have to be implemented.

The existing Falcon 20 guidance with DGPS proved useful for test points such as simulated autopilot malfunctions on a precision approach glidepath and community noise test profiles. Since vertical deviations from the glidepath were already being computed and recorded for the purpose of providing guidance, they could also be used to determine the extent of autopilot induced pitchover and recovery time. Lateral guidance was essential to accurately fly community noise profiles to selected noise recording sites. For these tests, the DGPS reference point was changed from the GPI point to the end of the active runway, and the lateral steering sensitivity was increased from a precision approach setting of ±350 feet (107 meters) to ±250 feet (76 meters) full scale deflection. A track down the runway centreline could be flown at low altitude, or intercepted from takeoff, to a simulated noise recording site at the end of the runway. The lateral steering accuracy achieved was about 4.5 meters (one sigma), slightly better than the FTE of 5.5 meters shown in Table 1, due to the increased sensitivity. Increasing the steering sensitivity beyond ±250 feet (76 meters) full scale deflection resulted in undesirable lateral tracking oscillations left and right of track.

Airspeed calibration test points were flown in "windbox" patterns to demonstrate that DGPS-derived groundspeed and track could be used to determine the true airspeed of the aircraft by eliminating the wind vector determined from reciprocal flight tracks. This process has evolved to a more comprehensive calibration of aircraft position error and airflow angles using DGPS measurement techniques, and is described in Reference 3.

The NovAtel 951R DGPS system described in sub-section 3.2 was demonstrated to be a viable measurement tool for the flight test manoeuvres flown with the Falcon 20, but it's real-time position and height accuracies did not meet the desired values. This resulted in unacceptable errors in the measurement of certain performance parameters, particularly takeoff and landing distances, where shallow climb or descent gradients translated small height errors into large horizontal errors. The next section will describe the accuracies obtained with an upgraded DGPS system, the NovAtel RT-20, and its application to the measurement of Falcon 20 landing performance on contaminated runways.

6.0 LANDING PERFORMANCE TESTS

It was clear that the real-time accuracy of the Falcon 20 DGPS had to be improved prior to using it as a primary flight test measurement tool for aircraft landing performance on winter contaminated runways. Two NovAtel RT-20 GPS receivers were obtained and installed as replacements for the 951R receivers in both the Falcon 20 aircraft and the DGPS ground station. Like the 951R, the RT-20 was a single frequency receiver card installed in a PC-compatible computer. However, the RT-20 incorporated double differencing techniques, based on carrier phase measurements and a floating ambiguity program, to provide real-time accuracies at the 20 centimeter level within a few minutes after system power up. It had a significant performance advantage over the 951R through the real-time incorporation of carrier phase ambiguity resolution. Other than the type of GPS receiver used, the DGPS system setup for the landing performance tests was identical to that shown in Figure 2.

6.1 Upgraded DGPS Accuracies

The validation of the RT-20 real-time position and height accuracies was done in comparison with the Ashtech TSPI during the first nine flights of the actual performance testing done at the airport in North Bay, Ontario. The flights included typical airfield performance manoeuvres within a 15 nautical mile baseline from the ground station, including maximum performance takeoffs, landings, and accelerate/stops. As with the previous DGPS accuracy tests, both real-time and post-flight CPAR solutions were obtained.

The post-flight processed CPAR solution for the RT-20 was within 3 centimeters (one sigma) of the Ashtech TSPI solution, with survey biases removed. This provided strong support to the qualification of the NovAtel RT-20 as a TSPI, in its own right, for short baseline flights. The differences between the RT-20 real-time solutions and the Ashtech TSPI (2 sigma values) are shown in Table 3 for each of the nine flights.

	Two Sigma Errors (meters)	
Flight No.	Horizontal	Vertical
01	0.48	0.14
02	**0.70**	0.22
03	0.16	0.18
04	0.30	0.12
05	0.48	0.14
06	**1.06**	**0.40**
07	0.54	0.20
08	0.26	0.32
09	**0.74**	0.30

Table 3
RT-20 Real-time DGPS Accuracy versus Ashtech TSPI

The errors shown for each flight in Table 3 are computed for the entire time of operation of the RT-20, from power-up to shutdown, including the period of initial convergence of the latitude, longitude, and height parameters during static operation on the ramp. Relatively high initial errors in longitude occurred prior to convergence, especially on flights 02, 06 and 09, and these affected the overall horizontal errors for these flights (shown in bold print). Disregarding the effects of initial convergence, the airborne horizontal errors were generally less than 0.5 meters (2 sigma).

Since the horizontal error is equal to the root-sum-square of the errors in latitude and longitude, the individual one sigma errors of latitude and longitude were less than 20 centimeters, meeting the manufacturer's performance specification.

The vertical errors shown in Table 3 were generally less than 0.3 meters (2 sigma) except for flight 06 (shown in bold print), which was affected by a relatively large initial convergence error in height. The effect of this vertical error on the measurement of takeoff or landing distance, assuming a shallow climb or descent gradient of 5%, would be an uncertainty of about 6.0 meters in the horizontal plane. This is less than 1% of a typical Falcon 20 takeoff or landing distance, and represents a significant improvement over the results described in sub-section 5.2.

6.2 Test Objectives and Procedures

The primary objectives of the landing performance tests were:

a. to determine the Falcon 20 coefficient of braking and contaminant drag for various contaminated runway surfaces; and
b. to determine the Falcon 20 landing distances for various contaminated runway surfaces, and use these data to validate or refine the existing James Brake Index (JBI) tables in the Transport Canada Aeronautical Information Publication (AIP, Reference 4).

The JBI is a runway friction index between 0.0 and 0.8, used in Canada to give the pilot of an incoming aircraft the anticipated braking performance on the active runway. A JBI of 0.8 is representative of maximum braking capability on a bare and dry runway surface, while a JBI of 0.0 is representative of zero braking. A surface covered with wet ice may have a JBI of 0.1; a surface covered with loose snow may have a JBI of 0.3; and a rain soaked surface may have a JBI of 0.5. The value of the JBI is determined by an electronic recording decelerometer (ERD) mounted on a ground test vehicle which does several braking runs at intervals along the runway surface.

The North Bay airport, shown in Figure 6, was used as the test site, with Runway 31 designated as the primary test surface. A 1500 foot (450 meters) test section was set up on Runway 31, starting at 1000 feet (300 meters) from the runway threshold and ending just short of the intersection between Runways 13-31 and 08-26. The test section could be purposely covered with various types of contaminants (snow, slush, ice) by airport vehicles for unrestricted testing by the Falcon 20 and the various ground friction vehicles. The test section was covered to about 80 feet (25 meters) in width, centred on the runway centreline, leaving a bare and dry surface on each edge of the runway to allow the pilot to regain control of the aircraft in the event of a lateral departure from the test surface. Runway 13-31 remained closed to normal airport traffic throughout the test period.

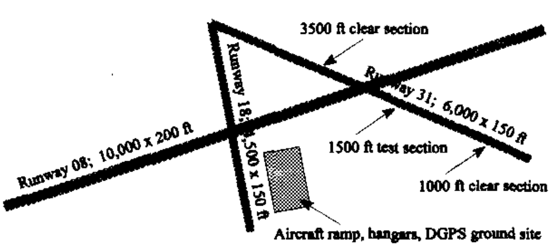

Figure 6
North Bay Airport Runway Layout

The location of the test section on Runway 31 was planned to accommodate both ground runs and landings. Starting at the threshold of Runway 31, the aircraft could accelerate to about 80 knots prior to entering the test section for a braking run. Approaches for landings were made on a 3 degree glidepath, using DGPS guidance, to a GPI point 400 feet (120 meters) from the threshold of Runway 31. This allowed a distance of about 600 feet (180 meters) for the nose to be lowered and the airbrakes to be extended prior to entering the test section for a high speed run. The last 3500 feet (1070 meters) of Runway 31 was kept bare and dry to permit maximum performance braking following a potentially high speed exit from the test section.

Prior to each flight, the test section was prepared by the airport maintenance vehicles to a desired surface condition, and a qualitative description of the surface was recorded. The ground test vehicle then conducted runs to determine the JBI, after which the aircraft conducted a flight which included several landings and accelerate/stop manoeuvres with full anti-skid braking applied throughout the test section. Following the aircraft flight tests, the ground test vehicle conducted a second series of runs to determine a JBI which could be compared, and averaged if appropriate, with the initial value.

The total landing distance (LD) was computed as the sum of the following three distances, shown in Figure 7:

a. Air distance (D1) – horizontal distance from a height of 50 ft above the touchdown zone elevation (GPI point) to the aircraft touchdown point (weight on wheels);
b. Delay distance (D2) – distance from touchdown to airbrake extension and application of full braking; and
c. Braking distance (D3) – distance from the application of full braking to a complete stop.

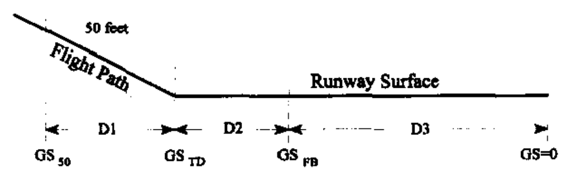

Figure 7
Landing Distance Definition

DGPS-derived aircraft groundspeed (GS) was determined at the start of each landing segment as shown in Figure 7. The groundspeed at 50 feet (15 meters), labelled GS_{50}, was assumed to be the same as the approach groundspeed for the purpose of comparison with the Aircraft Flight Manual (AFM) landing distance. The groundspeed at touchdown (GS_{TD}) was recorded at the engagement of the aircraft weight-on-wheels switch, and the groundspeed at full braking (GS_{FB}) was recorded at the application of full braking as determined by data from the brake pressure transducers.

DGPS-derived aircraft positions were used to determine actual air distances and delay distances. In a manner similar to that described in sub-section 5.2, the air distances, D1, were determined by finding the aircraft x-axis position at a DGPS height of 50 feet (15 meters) above touchdown, and subtracting this value from the x-axis position recorded at the touchdown point. Delay distances, D2, were calculated in the horizontal plane between the touchdown point and the application of full braking. Braking distances, D3, could not be measured directly with DGPS positioning, because the Falcon 20 could not generally be stopped completely within the 1500 foot (450 meter) test section, especially with the lower JBI's, from its nominal brake application speed of 100-110 knots. Instead, the braking distance for a particular surface condition had to be computed as the sum of two distances resulting from two separate test runs within the test section. A performance landing produced a high speed full braking segment (about 110 knots down to 65-75 knots), and an accelerate/stop run produced a lower speed full braking segment on the same surface (75 knots down to 20-30 knots). Braking distance was interpolated from acceleration data for any gaps between the speed bands, as well as for groundspeeds below 20-30 knots, where full braking was not accomplished.

The ensuing paragraphs will discuss and compare several different types of "total landing distance" (LD). These are defined as follows:

a. AFM LD: The landing distance taken from the AFM as a function of gross weight, true airspeed, and wind. It is based on very aggressive deceleration techniques on a bare and dry runway surface.
b. Actual LD: The actual landing distance of the Falcon 20 on the various contaminated surfaces as determined from DGPS-derived aircraft positions described above.
c. Predicted LD: The landing distance of the Falcon 20 computed as a function of approach groundspeed (GS_{50}) and JBI, developed in sub-section 6.3.
d. Factored LD: The predicted LD increased by a safety factor which accounts for variations in pilot technique, braking performance, or runway condition, developed in sub-section 6.4.

6.3 Predicted Landing Distance

The DGPS-derived time, speed and distance data recorded during a total of 25 approaches and landings were averaged and used to establish equations for air distance, D1, and delay distance, D2. All approaches were flown using DGPS guidance to a 3 degree glidepath, providing a consistent flight path at least to a height of 200 feet (61 meters), where the pilots took over visually for landing. Even though the pilots attempted to land firmly and lower the nose quickly on all landings, distances D1 and D2 varied considerably with pilot technique. The standard deviations associated with these times and distances were used to determine the factored LD (sub-section 6.4) to a 95% (2 sigma) confidence level. The equations developed for D1 and D2, based on flight test data, are:

$$D1 = 1.55 \times (GS_{50} - 80)^{1.35} + 975 \qquad (2)$$

$$D2 = 4.946 \times (GS_{50} - 9.65) \qquad (3)$$

where distances D1 and D2 are expressed in feet, and approach groundspeed, GS_{50}, is expressed in knots.

For each braking run, the DGPS-derived groundspeed was smoothed and differentiated with respect to time. This DGPS-derived deceleration, dGS/dt, compared very well with the aircraft x-axis accelerometer data, and was easier to use because it did not require a correction to the local horizontal using aircraft pitch angle, as did the x-axis accelerometer data. The parameter dGS/dt was plotted against groundspeed, GS, during each braking run, and found to approximate a linear relationship. Continuing the process for different runway surface conditions, each with a specific JBI value, a three way linear relationship was established among the parameters dGS/dt, GS and JBI, of the form:

$$dGS/dt = (k_1 + k_2 \times JBI) + GS \times (k_3 + k_4 \times JBI) \qquad (4)$$

where k_i are non-dimensional constants. Figure 8 is a graphical representation of this relationship, based on linear approximations, and shows the Falcon full braking deceleration in "g" units plotted against groundspeed in knots for JBI values between 0.0 and 0.8.

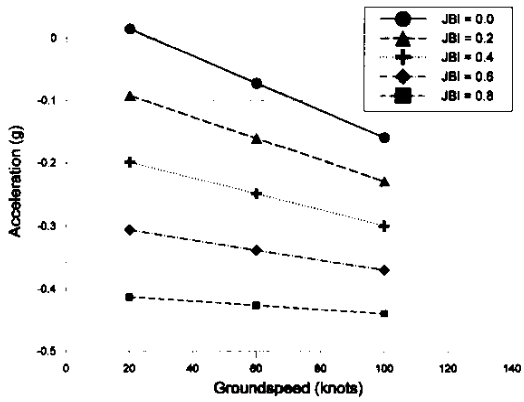

Figure 8
Full Braking Deceleration versus GS and JBI

An equation for braking distance, D3, was developed as a function of approach groundspeed and average deceleration, dGS/dt_{AV}, during the braking run. The average deceleration was computed at a point midway through the braking run as a function of approach groundspeed and JBI, as expressed in Equation (4) and shown in Figure 8. This equation is:

$$D3 = \frac{-((GS_{50} - 13.15) \times 1.69)^2}{64.35 \times dGS/dt_{AV}}$$
$$\text{where } dGS/dt_{AV} = (k_1 + k_2 \times JBI) + \frac{(GS_{50} - 13.15)}{2} \times (k_3 + k_4 \times JBI) \qquad (5)$$

Using Equations (2), (3) and (5) for the three components of the total landing distance, the predicted LD can now be determined as a function of GS_{50} and JBI from the equation:

$$Predicted\ LD = D1 + D2 + D3 \qquad (6)$$

To a large extent, Equation (6) is based on an accurate modelling of aircraft deceleration under full anti-skid braking versus both groundspeed and JBI number. In fact, the standard deviation of the linear curve fit was 0.022 "g" units, which represents about 10% of the average deceleration at mid values of JBI. This number will be applied to the factored LD developed in sub-section 6.4.

A comparison of actual LD's, determined from DGPS-derived aircraft position data, and predicted LD, determined from Equation (6), is shown in Figure 9. The data points in the figure are reasonably close to a line of equality between the actual LD and the predicted LD, demonstrating the validity of Equation (6). The fact that some points are above the line of equality (actual LD greater than predicted) simply indicates that the actual aircraft decelerations during the braking runs (for these points) were above the modelled curve fit (less deceleration than modelled), resulting in a longer actual LD. The concept of a factored LD exists because it is undesirable to use an equation for predicted LD which underestimates the actual landing distance.

To be most useful to the pilot, and independent of aircraft type, predicted LD's should be presented in comparison with the AFM LD's determined prior to each landing, and for the reported value of the JBI for the runway in use.

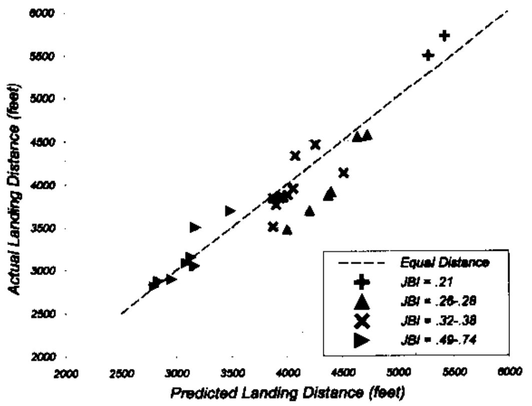

Figure 9
Falcon 20 Actual LD versus Predicted LD

The Falcon 20 AFM LD was approximated as a function of approach groundspeed, GS_{50}, for a full range of landing gross weights, and then compared to the predicted LD from Equation (6) using GS_{50} as a common link. The result of this comparison is a plot of predicted LD versus JBI for selected values of the AFM LD, shown in Figure 10. Since the AFM LD is determined for a bare and dry surface (JBI = 0.8), the predicted LD can be compared directly to the AFM LD at this value of the JBI. Figure 10 shows the predicted LD to be about 400 feet (120 meters) higher than the AFM LD at JBI = 0.8, primarily due to the increased air distances, D1, and delay distances, D2, obtained during testing as compared to AFM certification data. The predicted LD increases markedly with decreasing JBI, reaching a value about double the AFM LD at a JBI of 0.2, equivalent to a runway surface covered with hard packed snow or rough ice.

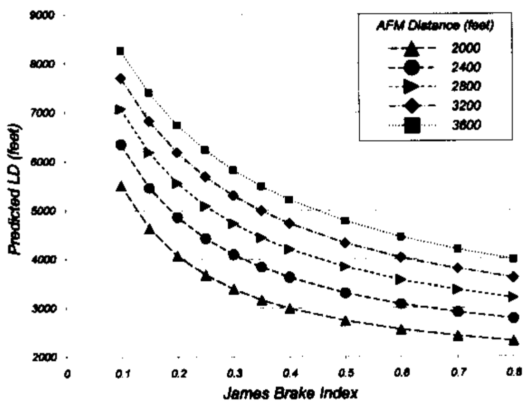

Figure 10
Falcon 20 Predicted LD versus JBI and AFM LD

6.4 Factored Landing Distance

By current regulation, the factored (or required) landing distance is equal to the AFM LD divided by 0.6, applicable only to bare and dry runway surfaces. To apply a safety factor to all runway surface conditions, with a 95% level of confidence that the aircraft could come to a complete stop within the stated distance, equations were developed for the factored air distance, $D1_F$, delay distance, $D2_F$, and braking distance, $D3_F$. The factored LD was computed from the equation:

$$\text{Factored } LD = D1_F + D2_F + D3_F \qquad (7)$$

The data from 25 approaches and landings were used to determine a two sigma time delay which was applied to D1 and D2 to obtain $D1_F$ and $D2_F$. This amounted to an additional 1.7 seconds for $D1_F$ and 1.9 seconds for $D2_F$. The factored braking distance, $D3_F$, was obtained by decreasing the modelled deceleration by a one sigma value of 0.022 "g" units, and using only 75% of the reported value of the JBI to account for changing weather conditions or non-uniform runway surface conditions. The factored LD's thus obtained were compared to AFM LD's and predicted LD's for different values of JBI. Figure 11 shows the specific case where AFM LD = 2800 feet (850 meters). The landing distances from the existing JBI tables in the Transport Canada AIP compare reasonably well with the predicted LD's, but the factored LD's are much higher. The factored LD's are approximately equal to AFM LD/0.6 at a JBI value of 0.8, and progressively less than predicted LD/0.6 as the JBI values decrease.

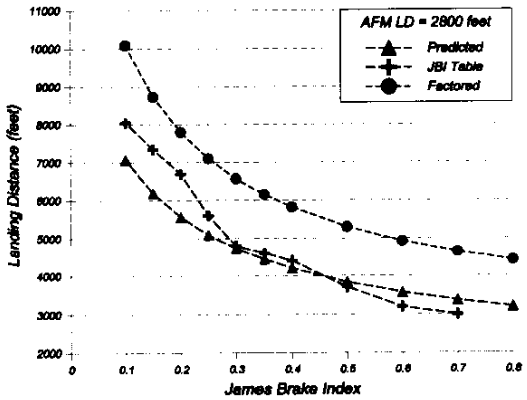

Figure 11
Comparison of LD's for AFM LD = 2800 feet

7.0 CONCLUSIONS

DGPS systems were successfully used to provide Falcon 20 aircraft guidance on precision approaches, and to measure flight test performance parameters. An upgraded DGPS, the NovAtel RT-20, provided real-time position and height accuracies of less than 20 centimeters (one sigma), and was used effectively to determine aircraft landing performance on winter contaminated runways.

8.0 REFERENCES

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