Measuring the effect of helicopter rotors on GPS reception

G. J. Brodin and J. A. Cooper
Formerly of CAA Institute of Satellite Navigation
University of Leeds
Leeds, UK

J. R. A. Stevens
Boston, Massachusetts
USA

ABSTRACT

This paper describes an experiment which was performed using an offshore transport helicopter to investigate the impact of the rotor blades upon Global Positioning System (GPS) reception.

The test aircraft was fitted with two separate GPS antennas which were positioned to isolate the effects caused by the main and tail rotors. Testing was undertaken with the aircraft on the ground and this allowed an assessment to be performed at different rotor speeds with accurate control over the relative geometry between the antenna, rotors and satellites.

Recorded data from a measurement system incorporating three dissimilar GPS receivers (including a technical standard order (TSO)-C129()(1,2) compliant aviation unit and a custom research receiver) was analysed to identify the effect of the rotors at the correlator level and to determine the impacts upon ranging accuracy, the availability of ranging measurements, and the receivers' signal level estimates.

Correlation data was used to demonstrate that the rotor blades were capable of generating both destructive and constructive interference effects, and the periodic nature of these oscillations was shown to correspond directly to the blade passing frequency. It was identified that signal degradation was not limited to satellite signal paths which intersected the rotor discs.

No evidence was found for any increase in code measurement error due to the rotor interference, but it was demonstrated that there could be a significant impact upon a receiver's ability to maintain continuous tracking of the satellite signals. The overall effect of this availability problem for a given installation and type of operation will be dependent upon satellite geometry and other factors which are beyond the scope of this study.

The ability of a receiver to identify the presence of rotor interference was investigated by examining estimates of carrier-to-noise, and this revealed inconsistencies between the results from different receivers implying differences in the estimation algorithms employed. It was also identified that two alternative 'textbook' estimators do not give identical results in the presence of rotor interference and it is suggested that such data should therefore be interpreted with caution.

NOMENCLATURE

I_P	in-phase punctual correlator measurement
Nr	rotor speed
$P(t)$	signal power quantity
Q_P	quadrature-phase punctual correlator measurement

1.0 INTRODUCTION

In the United Kingdom, the helicopter fleet which supports the offshore petroleum exploration and production industry has become exclusively reliant on satellites for long-range navigation following the demise in the mid to late 1990s of hyperbolic navigation systems such as very low frequency (VLF)/Omega and Decca. GPS has now been accepted(3) as an alternative to these systems for en-route purposes in the offshore environment.

For the past several years the Safety Regulation Group of the UK Civil Aviation Authority (CAA) has been conducting a research project addressing the application of satellite navigation equipment and procedures to offshore helicopter operations. These studies included a campaign of flight trials(4,5) to investigate the feasibility of

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Figure 1. Sikorsky S76C trials airframe showing GPS antenna positions.

using GPS and/or differential GPS (DGPS) as sources of approach guidance in the offshore environment.

Subsequent analysis(6,7) of the data collected during these offshore approach trials suggested that reception of GPS ranging signals may have been affected by interference effects associated with the helicopter rotors. The effects attributed to the rotors included discrepancies in the instantaneous availability of the GPS ranging measurements compared to that which was predicted by off-line simulation, and a significant reduction in the carrier-to-noise figures reported by some of the receivers.

The data from the offshore approach trials was obtained using a single mounting location for the GPS antenna, at the top of the helicopter's vertical tail immediately adjacent to the tail rotor. It was therefore conceivable that better results could have been obtained with the antenna in a different location where the impact of the rotor blades might be lower. However an antenna position with completely unobstructed visibility to the satellite constellation is often difficult or impossible to attain on a helicopter particularly when other constraints such as a narrow fuselage section and the position of the engines and drive train are taken into account.

Examination of the literature revealed little in the way of guidance material which might usefully assist the avionics design engineer in the selection and validation of a suitable GPS antenna position on a helicopter. For example in paragraph 8c(1)(ii)(G) of (8), the importance of the antenna installation is recognised and it is stated that the effects of helicopter rotor blades on antenna performance must be considered, but no guidance is provided as to how a potential antenna position could be evaluated.

To permit a more detailed investigation under controlled conditions of the effects which had been observed on the earlier trials, the CAA commissioned a programme of experimental work which was undertaken in late 2002 by Cranfield Aerospace Ltd and the CAA Institute of Satellite Navigation (ISN) at the University of Leeds.

The tests were performed using the same offshore transport helicopter which had been used for the previous flight trials campaign. However, in addition to the tail mounted antenna described above, a second antenna position on the forward fuselage was also employed in order to assess the impact on GPS reception of both the main and tail rotors. The helicopter remained on the ground throughout the trial in order to collect data at a range of rotor speeds, and to allow tight control of the relative geometry between the antenna, rotors and satellites.

This paper describes the measurement equipment which was fitted to the test airframe for the rotor interference investigation and outlines the experimental procedures which were employed. A summary of the results is then presented based upon an analysis of the experimental data addressing the impact of the rotor blades upon the following:

- GPS signal-in-space at the correlator level
- Pseudorange measurement accuracy
- Availability of ranging measurements
- Receiver signal level estimates

A more detailed report(9) has been published separately by the CAA and contains additional details of the background to the investigation, experimental procedures, results, conclusions, and recommendations.

Table 1
Nominal rotor speeds for S76C (107% *Nr*)

Rotor	Rotational speed	Blade passing interval
Main rotor	313rpm	48ms
Tail rotor	1,723 rpm	9ms

2.0 EXPERIMENTAL PROCEDURE

2.1 Trials airframe

The rotor interference experiment was undertaken using a Sikorsky S76C which is considered to be representative of the small to medium-size helicopters currently in use for offshore support operations in the North Sea region.

Two GPS antennas were temporarily installed on the helicopter in the positions shown in Fig. 1. These positions allowed the effects of the main and tail rotors to be investigated independently. An existing antenna located close to the midpoint of the tail boom, which forms part of the flight-cleared GPS installation used by the helicopter operator for en-route navigation, was left undisturbed.

One of the temporary antennas was fitted at the top of the vertical tail adjacent to the tail rotor, replicating the antenna position which had been used for the previous flight trials. The tail rotor is located on the port side of the aircraft and rotates in a vertical plane displaced laterally from this antenna by approximately 450mm. The tail antenna was above the plane of the main rotors.

The second GPS antenna was installed on the fuselage nose immediately forward of the cockpit windshield in a position underneath the main rotor disc. In this position the antenna was approximately 1,500mm below the plane of the main rotor.

2.2 Rotor blades

Both the main rotor and tail rotor on the S76C comprise four blades and rotate at a constant speed in flight. The nominal rotation speeds and the interval between the passage of successive blades for the two rotors are shown in Table 1.

The rotor speed (*Nr*) is displayed to the pilots as a percentage value, with the nominal flight speed expressed as 107% *Nr* rather than 100% for equipment compatibility with earlier S76 variants where the rotor speeds were 7% slower. A time history of the *Nr* data was obtained via the aircraft flight data recorder for later comparison against the GPS measurements.

The rotor blades(10) are of composite construction using a combination of materials (including titanium and nickel alloys, aluminium and synthetic honeycomb, and fibreglass) with differing electromagnetic properties. No attempt was made to model the effect of these composite blades on radio frequency propagation. Instead the aim of the trial was to undertake an empirical assessment of their effect on GPS reception as a function of parameters (such as relative geometry and rotor speed) which could be readily controlled.

2.3 GPS receivers

The RF output from either the nose or the tail antenna installation was fed to three GPS receivers in parallel via a signal splitter and preamplifier. Selection between the two antennas was undertaken manually.

Two of the receivers (Receiver 1 and Receiver 2) were commercial Coarse/Acquisition (C/A)-code units with twelve and

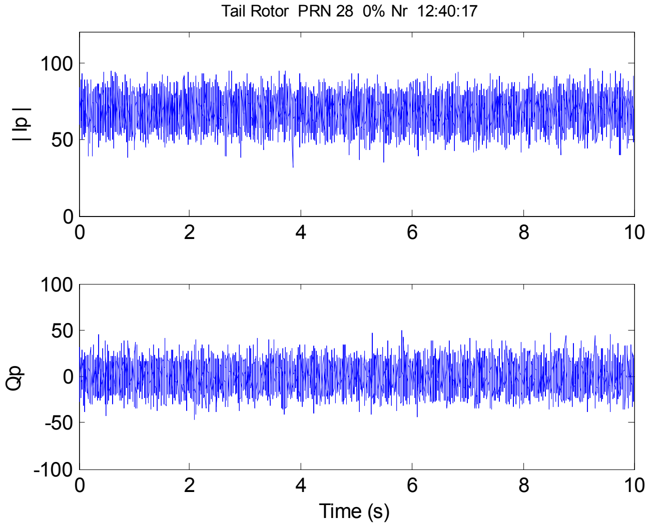

Figure 2. Correlation data with rotors stationary.

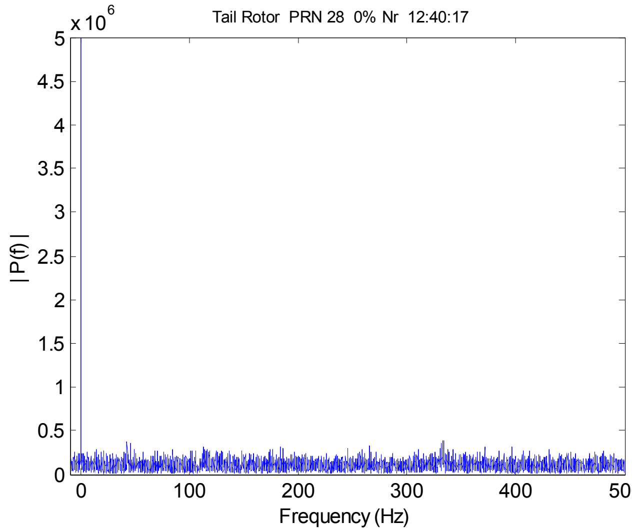

Figure 3. Frequency spectrum with rotors stationary.

eight channels respectively. Receiver 2 was based upon a TSO-C129() compliant design. These receivers had been used on the earlier flight trials programme; their inclusion was essential for compatibility with the previous results.

The third receiver was an experimental 20 channel survey quality system(11) developed by the ISN for research purposes. The installation included a rubidium frequency standard which the receiver employed as a highly stable frequency reference.

The data from each of the receivers was recorded at a 1Hz rate and included (in addition to the navigation solution information) a tracking status flag and a signal level indication for each receiver channel, with Receiver 1 also providing code and carrier observables. The ISN receiver included a feature, described in more detail later in the paper, which allowed 10s 'snapshot' time histories of the tracking correlator data for a selected channel to be logged for subsequent analysis.

2.4 Test procedure

The rotor experiment was conducted in an unobstructed area of the manoeuvring apron at Aberdeen airport in Scotland.

Although the aircraft remained on the ground throughout the trial, its heading was varied periodically in order to attain predetermined aircraft orientations relative to the GPS satellite constellation. For example when performing tests using the tail antenna, it was a requirement that the signal path from at least one satellite to the antenna should intersect the tail rotor disc at all times.

The majority of the testing comprised a series of rotor start/stop sequences in which the rotors were accelerated from rest up to a maximum speed of 107% *Nr*. Following a period of constant speed operation (typically around 1-2 minutes, although some longer runs were also undertaken) the speed was then reduced back to zero. Each rotor speed change were undertaken in two stages owing to the need to start or stop the two aircraft engines separately. These sequences were designed to investigate whether the GPS interference effects varied significantly with rotor speed.

In addition to the rotor start/stop sequences, some low speed testing was also undertaken with the rotors turned by hand such that successive blades would intersect the signal path from appropriate satellites to the antenna. The engineer turning the blades was positioned as far as practicable from the antenna to avoid the introduction of any additional multipath effects.

3.0 TEST RESULTS

3.1 Effect of rotors on signal-in-space

Recordings of the internal correlation measurements from the ISN receiver were employed to examine the effect of rotor blade passage on the received GPS signals. The receiver performs correlation by comparing the incoming and local versions of a satellite's pseudo random noise (PRN) code, with the net number of agreements minus the number of disagreements being integrated over 1ms as the correlation count.

The correlation counts which were used for this analysis are the in-phase and quadrature-phase punctual measurements I_P and Q_P. A modification to the ISN receiver software allowed a 10s long snapshot, containing 10,000 samples of these two quantities obtained at a 1kHz rate, to be captured for analysis.

Figure 2 shows an example of an I_P and Q_P time domain plot based upon a 10s snapshot obtained with the rotors stationary. The units of the vertical axes are arbitrary and correspond to the internal correlation count totals, but can be considered as scaled amplitude measurements. To improve clarity, the absolute value of the I_P data has been plotted in order to eliminate the phase transitions caused by the GPS navigation data message.

This snapshot profile is typical of all of the data acquired with the rotors stationary and is also typical of data collected using a fixed reference antenna at the ISN. All of the signal energy is contained in the I_P channel with the Q_P data consisting only of zero mean Gaussian noise. Figure 3 represents the same data converted to the frequency domain by means of a discrete Fourier transform operating on the signal power quantity $P(t)$, defined as

$$P(t) = I_P^2(t) + Q_P^2(t) \qquad \ldots (1)$$

The frequency domain plot reveals a flat spectrum with the exception of the large DC component, which extends to a value of 5×10^7 on the vertical axis (though for clarity the axis has been clipped at 5×10^6).

Figure 4 shows a 10s snapshot collected with the rotors turning, for a satellite whose signal path to the antenna intersected the tail rotor disc. The data is for the same satellite as was used for Fig. 2 and was recorded less than three minutes later. Compared to the stationary data, it is apparent that the variance of both I_P and Q_P has increased significantly.

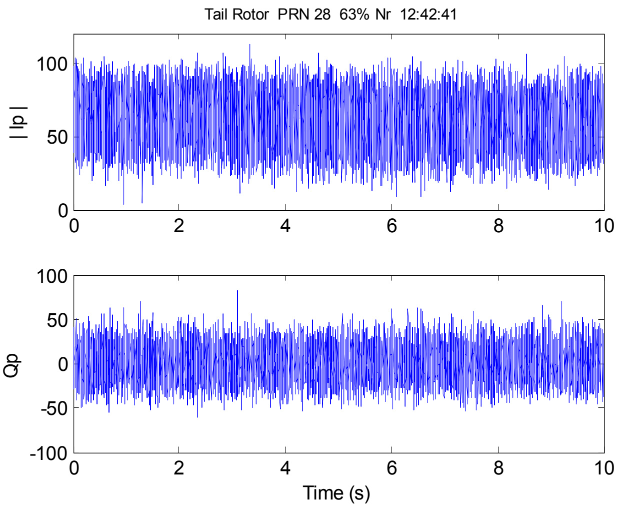

Figure 4. Correlation data for tail antenna with rotors turning.

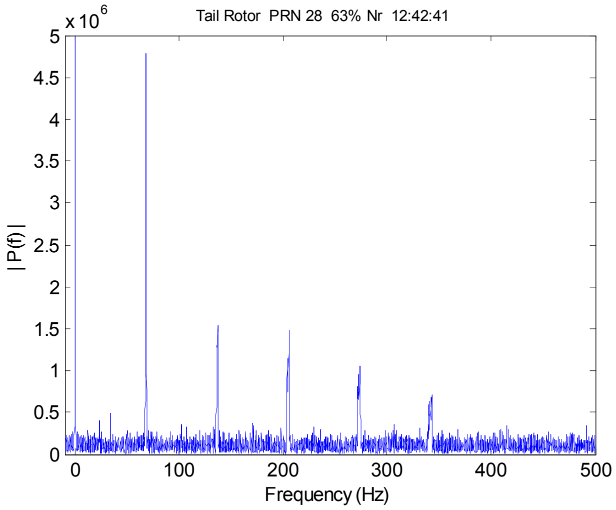

Figure 6. Frequency spectrum for tail antenna with rotors turning.

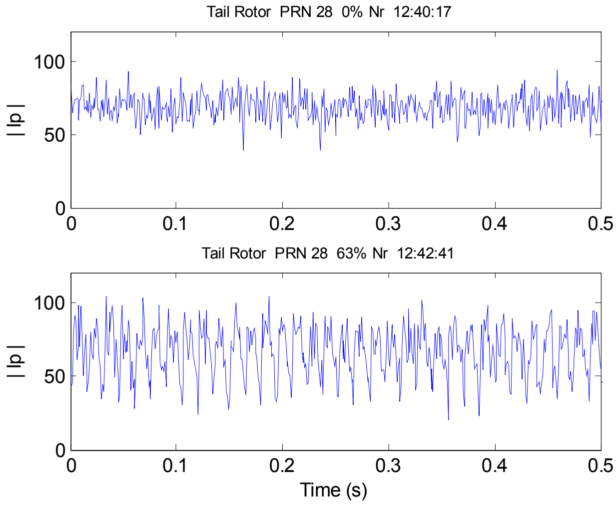

Figure 5. Comparison of tail antenna correlation data with rotors stationary and rotors turning.

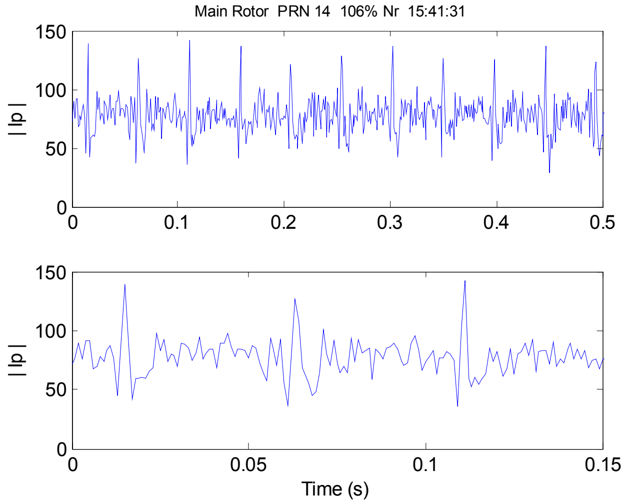

Figure 7. Correlation data for nose antenna with rotors turning.

Expansion of the horizontal axis and comparison with the corresponding I_P data with the rotors stationary (Fig. 5) reveals oscillations which can be assumed to be associated with the passage of successive tail rotor blades. Each oscillation appears to consist of a short period of reduced amplitude (approximately 50% of the steady-state I_P value) followed by a longer period where the amplitude returns to somewhere around the steady-state level. Calculations show that each tail rotor blade was ‘blocking’ the direct signal with a duty cycle of approximately 14% and this suggests that the periods of reduced amplitude were due to signal attenuation by the blades.

Transformation of this data to the frequency domain (Fig. 6) reveals a series of spectral ‘spikes’ of which the lowest is at a frequency of approximately 68Hz, which can be shown to be identical to the blade passing frequency. The higher frequency components are all at harmonics of 68Hz.

Examination of other snapshot recordings for signals passing through the tail rotor revealed oscillatory effects similar to those shown in Fig. 5. Changes in rotor speed and thus the blade passing frequency were observed to have a direct impact upon the frequency of the oscillations, but the reduction in amplitude associated with each blade passage did not appear to vary significantly with changes in rotor speed.

In order to estimate the attenuation caused by the passage of a rotor blade, it was assumed that the signal power time histories $P(t)$ could be approximated by a two-level square wave model in which the lower level corresponded to the reduced amplitude portion of each cycle, and the upper level corresponded to the steady-state power during the remainder of the cycle. A least-squares technique was used to obtain a fit between this model and the recorded data with the ratio of the upper and lower power levels providing an estimate of the attenuation during the blade passage.

The results obtained using this technique exhibited considerable variation between successive recordings and this was attributed to the difficulties associated with modelling the noisy input data. A total of 39 snapshots (based upon data from two different satellites obstructed by the tail rotor, at elevations of between 24° and 36°) were analysed and the mean attenuation during passage of a tail rotor blade was estimated as 4·3dB.

Figure 7 shows snapshot data which was obtained using the nose antenna, for a satellite whose signal path intersected the main rotor with a duty cycle of approximately 5%. This data was obtained while the rotors were turning at full speed and has been plotted using two different scales for the horizontal axis. In contrast to the tail rotor, it appears that the passage of each main rotor blade results in a

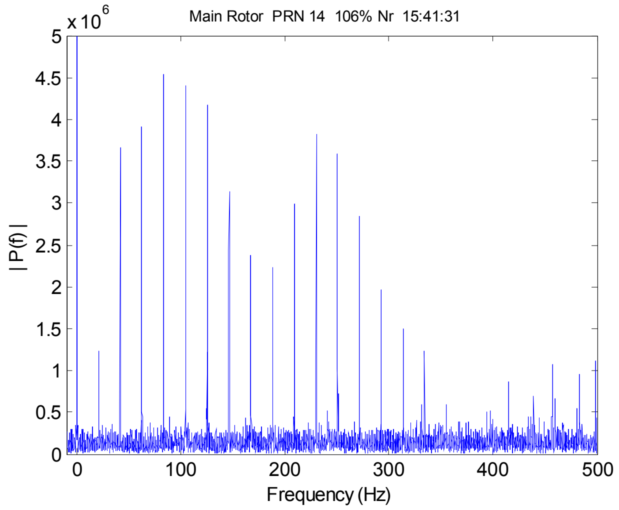

Figure 8. Frequency spectrum for nose antenna with rotors turning.

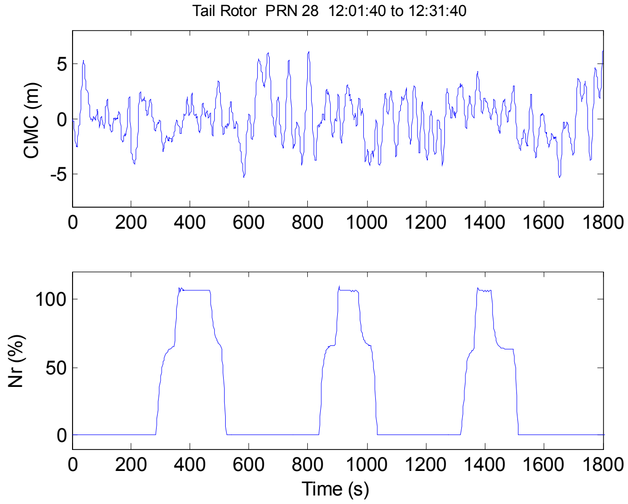

Figure 9. Code-minus-carrier results for tail antenna during rotor start/stop sequences.

sequence of excursions in which the amplitude first reduces, then increases to a level considerably in excess of the steady-state value (approximately a 100% increase), followed by a second reduction before the signal returns to its original level.

The corresponding frequency domain results (Fig. 8) reveal a very rich spectrum. Unlike Fig. 6, the spectral component with the greatest amplitude is at a harmonic of the blade passing frequency (approximately 21Hz) due to the presence of the large amplitude excursions in the time domain data. This suggests that multiple effects – both destructive and constructive – were occurring as each blade passed in front of the antenna.

Similar results were also observed in a second set of main rotor snapshot data which was recorded at a slower rotor speed. The two-level square wave technique for estimating the blade attenuation was not deemed appropriate for modelling time history data containing both positive and negative excursions.

The above results provide examples of the oscillations which were induced in the correlation data in situations where the satellite signals passed through the helicopter rotors. However, there was also (limited) data that identified the fact that it was not necessary for the signals to be propagating through a rotor disc in order for oscillations to be present: oscillations in the correlation data were observed for a low elevation satellite on the opposite side of the aircraft to the tail rotor. As this effect had not been prominent during the previous trials there was no specific attempt made to capture data from satellites whose signals approached the aircraft from this side of the tail rotor. In the absence of such data it is only possible to speculate on the cause of the observed oscillations. It is believed they were the result of rotor-induced multipath since, dependent on the relative satellite-rotor-antenna geometry, the tail rotor blades can act as a reflector to the GPS signal. Rotation of the blades causes the reflector to move and hence the multipath signal can ‘appear’ and ‘disappear’. To validate this theory would require further collection of data from satellites at the appropriate relative geometries.

3.2 Effect of rotors on pseudorange measurement accuracy

Having identified that the main and tail rotors were inducing perturbations in the received signals, an analysis was undertaken to investigate whether these effects had any adverse impact upon the accuracy of the ranging measurements, since a reduction in the received signal amplitude is likely to cause an increase in the code measurement noise.

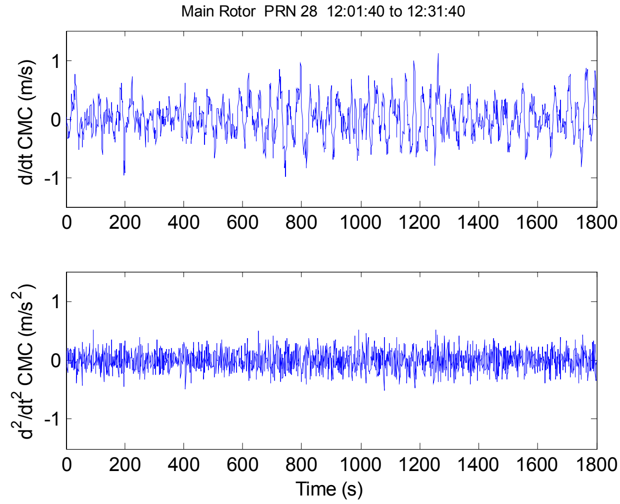

Figure 10. First/second derivatives of CMC results for tail antenna during start/stop sequences.

To investigate the effect of the rotors on pseudorange errors, a code-minus-carrier (CMC) evaluation was undertaken using data from Receiver 1. This technique requires removal of the carrier phase integer ambiguity and, since only single frequency measurements were available, it was also necessary to remove the effect of the unknown ionospheric delay. For this analysis it proved sufficient to achieve this by applying a quadratic curve fit.

Figure 9 shows a time history of the CMC results and rotor speed for a satellite whose signals were subjected to blockage by the tail rotor. Continuous carrier tracking was maintained on this satellite throughout three complete rotor start/stop sequences.

Examination of the data reveals that multipath effects (the oscillatory structures with periods of several tens of seconds or longer) were present throughout the period in question, and these were attributed to the airframe and ground reflections at the test site (the aircraft was located far from buildings or other aircraft to avoid those objects as sources of reflection). There is no evidence in the figure for any significant increase in the code tracking noise during the periods when the rotors were turning and this appears to be confirmed by Fig. 10 in which the first and second derivatives of the CMC data are plotted.

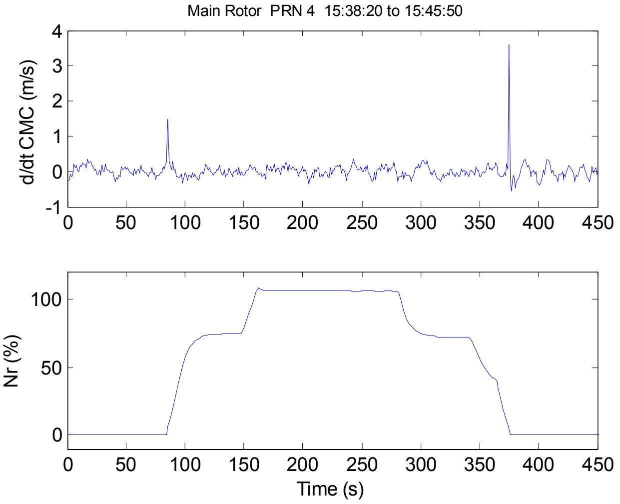

Figure 11. First derivative of CMC results for nose antenna during start/stop sequence.

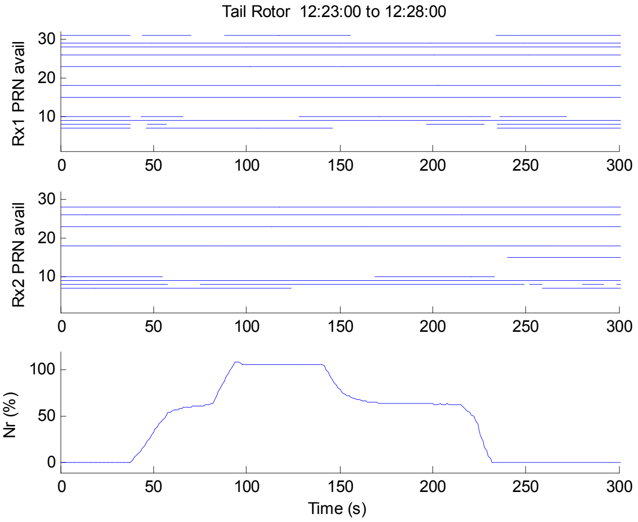

Figure 12. Ranging measurement availability for tail antenna during rotor start/stop sequence.

A similar analysis was undertaken for several other satellites subjected to blockage by either the tail or main rotors, and confirmed the lack of evidence for any discernable increase in code noise while the rotors were turning. The results suggest that, if any such error exists, it will most likely be below the sub-metre level and can therefore be considered to be negligible.

The only pseudorange effect which could be attributed to the rotors was observed in the nose antenna results, and consisted of CMC step changes of a few metres at the instants when the main rotors were started and stopped. An example is shown in Fig. 11 where the step changes give rise to ‘spikes’ in the first derivative. Examination of the data confirmed that these effects were due to step changes in the code measurements (and not to any changes in the carrier data) and also revealed that they coincided with brief transient losses of lock reported by the receiver. One explanation for this effect might be a small multipath error contribution from the stationary blades which disappears when they commence rotation.

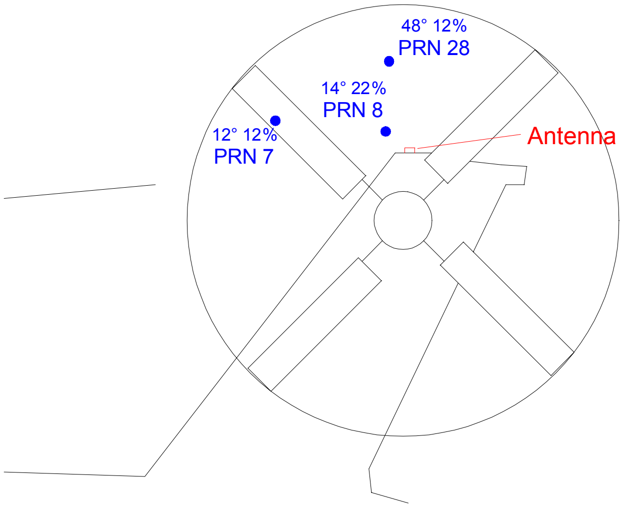

Figure 13. Intersection of signal path with tail rotor for data in Fig. 12– numeric values above PRNs represent elevation angle and rotor blade duty cycle.

Table 2
Ranging measurement availability probabilities observed for tail antenna

Test number	Sample length (s)	Receiver 1 range available	Receiver 2 range available
1	238	0·87	0·99
2	198	0·84	0·95
3	192	0·86	0·91
4	213	0·95	0·93
All tests	841	0·88	0·95

3.3 Effect of rotors on ranging measurement availability

Although the results suggest that the impact of the rotors on the range measurement accuracy is negligible, it was also necessary to examine whether they caused any detrimental effect on the ability of a receiver to maintain continuous tracking of the satellite signals and thus to ensure a sufficient number of ranging measurements for incorporation into a navigation solution.

To perform this evaluation, time histories of the tracking status flags output by Receivers 1 and 2 during the rotor start/stop sequences were examined. The analysis did not consider the different tracking state indications (e.g. code lock, carrier lock, data demodulation) in detail, instead a satellite was treated as either ‘available’ or ‘unavailable’ dependent upon whether the receiver was capable of using the measurement in its navigation computation.

Figure 12 shows the ranging measurement availability results from a start/stop sequence using the tail antenna, with the solid horizontal lines indicating the presence of valid measurements from each satellite tracked. Examination of the data reveals that both receivers experienced losses of lock on several satellites during the period with rotors running.

Receiver 1 is based on a twelve channel architecture whereas Receiver 2 is an eight channel unit, so the two sets of results are not fully comparable. However, both receivers were attempting to track three satellites (PRN 7, PRN 8 and PRN 28) whose signals were obstructed by the tail rotor blades and in both cases the ranging measurements from two of these satellites were observed to be intermittent while the rotors were running. Figure 13 is a ‘pierce-point’ diagram depicting the positions at which the signal paths from these three satellites intersected the plane of the tail rotor (viewed from the port side of the aircraft): the satellite (PRN 28) for which

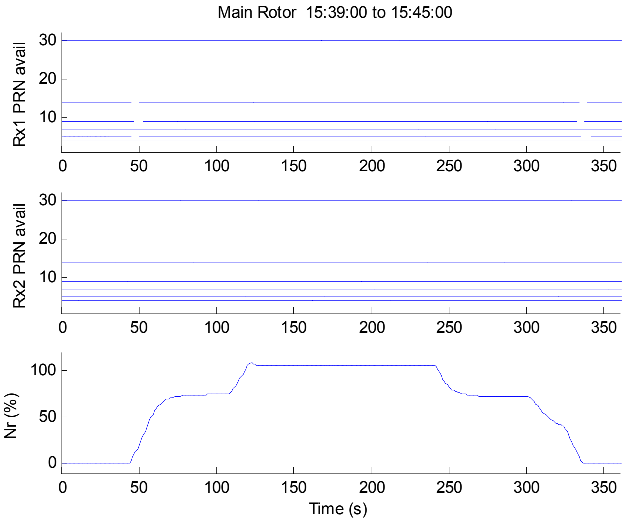

Figure 14. Ranging measurement availability for nose antenna during rotor start/stop sequence.

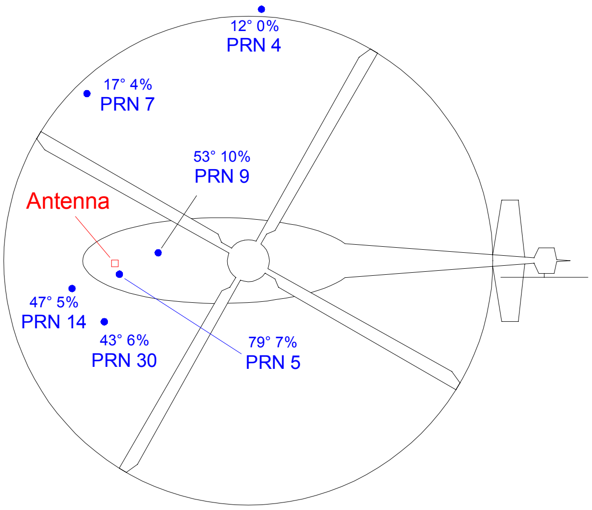

Figure 15. Intersection of signal path with main rotor for data in Fig. 14 – numeric values above PRNs represent elevation angle and rotor blade duty cycle.

continuous tracking was maintained was at a considerably higher elevation than the other two.

Intermittent tracking while the rotors were running was also observed on two other satellites which, although not obstructed by the tail rotor, were both at very low elevations (6° for PRN 10 and 4° for PRN 31). This is consistent with the observation that satellites whose signals do not pass through the rotor disc can still be impacted by interference effects.

Similar effects were observed on the other start/stop tests using the tail antenna, and a statistical measure for the effect on ranging measurement availability was computed in the form of a probability (Table 2) that a healthy satellite continues to be tracked by the receiver while the rotors are turning.

The results were obtained by averaging over all of the visible satellites irrespective of whether the rotor disc was obstructing the signal path, but with a mask angle of 10° applied to eliminate the lowest elevation satellites.

A similar availability assessment (Fig. 14) using data from the nose antenna installation revealed that the main rotor appeared to have negligible impact upon the receiver tracking performance. The test geometry (Fig. 15) was such that there were five visible satellites for which the signal path intersected the main rotor disc, plus a sixth satellite where the 'pierce-point' was at the edge of the disc. Receiver 2 did not lose any ranging measurements during the start/stop sequence, and Receiver 1 experienced transient losses of lock on three of the higher elevation satellites while the rotors were turning very slowly (less than 10% *Nr*) but was able to maintain continuous track at all higher rotor speeds. Little significance was attached to the transient outages at low rotor speeds since this is not representative of the conditions attained in flight.

The data which was collected from the two antennas during manual rotations of the rotors was also examined. There was no evidence of any transient tracking losses in the main rotor data. However it was observed that it was sometimes possible to produce an interruption in the tail antenna ranging measurements by interposing a rotor blade into the signal path. This result suggests that factors such as the separation between the blades and the antenna, or the nature of the blade construction, may be more significant than the rotational speed in explaining the differences in tracking performance between the tail and main rotor data. Additional testing would be required to investigate these hypotheses further.

The effect on a receiver's navigation function of losing a proportion of the ranging measurements will be dependent upon the number of visible satellites and hence will vary with the user's location and the time of day. The likelihood of an availability failure occurring at the navigation solution level will be greatest in marginal geometry situations and these tend to occur infrequently – for example with a 5° mask angle, fewer than six satellites are in view for less than 0·1% of the time on average(12) using the nominal 24-satellite constellation. However the possibility of loss of lock due to the rotors must be considered in combination with all of the other failure modes which can result in loss of ranging measurements, such as the effects of aircraft dynamics or attitude changes.

A more comprehensive assessment of the impact of these effects could be undertaken by means of availability modelling but this was outside the scope of the study. The results of any such analysis would need to be assessed against the requirements for a specific type of operation and phase of flight. However even without undertaking an availability simulation analysis, it is possible to state that for some installations helicopter rotors can have a significant impact upon a receiver's ability to generate ranging measurements.

3.4 Effect of rotors on signal level estimates

Each of the receivers employed for the experiment provided a real-time estimate of the signal level for each channel. For Receiver 1 and the ISN receiver, this information was expressed as a carrier-to-noise ratio (CNR) in units of dB-Hz. Receiver 2 did not directly output CNR but a dimensionless 'signal level' parameter was available in its place.

Figure 16 shows a time history of the real-time CNR estimates which were generated by Receivers 1 and 2 during a rotor start/stop sequence. These results are for the tail antenna and the three satellites for which data is plotted are those which were obstructed by the tail rotor disc (the corresponding ranging availability results were previously presented in Fig. 12 which revealed that tracking of PRN 7 and PRN 8 was intermittent while the rotors were running).

It can be observed that the CNR reported by Receiver 1 was reduced by approximately 10dB-Hz with the rotors turning. It appears that this CNR reduction comes into play at low rotor speeds (between zero and 20% *Nr*) and that there is little correlation with rotor speed thereafter – although there is some evidence for a slight increase in CNR above 90% *Nr*. In contrast the reduction in signal level reported by Receiver 2 clearly appears to be far less significant. Without knowledge of the meaning of the signal level output provided by this receiver, and the method used to calculate it, it is

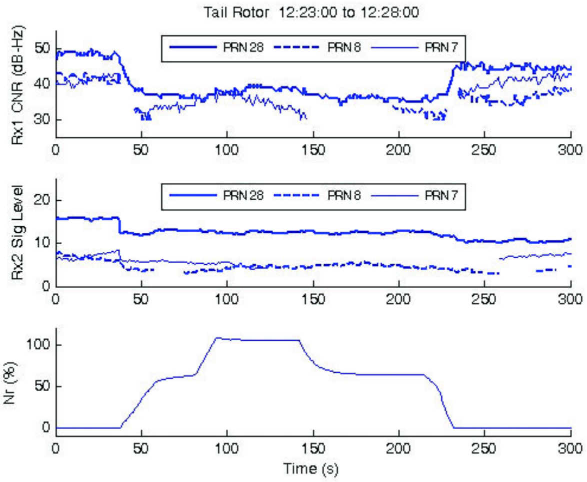

Figure 16. Receiver signal level estimates using tail antenna during rotor start/stop sequence.

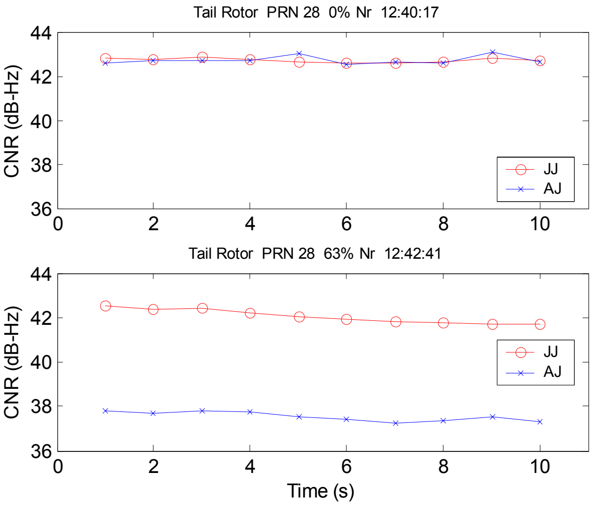

Figure 17. Comparison of AJ and JJ estimators with rotors stationary and rotors turning.

not possible from this data to definitively determine whether one receiver is being affected by the turning rotors more than the other. However assuming the Receiver 2 measurements to truly be representative of the received signal amplitude it is possible to calculate the CNR reduction that is produced. When the rotors are turning the CNR reduces by approximately 2dB-Hz, which is clearly far less than that observed by Receiver 1. It is also interesting to note that in both cases the signal levels at the end of the test are reduced with respect to those at the beginning. The difference for Receiver 1 is of the order of 5dB-Hz whilst the reduction for Receiver 2 is calculated to be of the order of 4dB-Hz (based on the relative amplitudes), hence they are in good agreement. Therefore from this (and other data) it appears that the signal level behaviour for Receiver 1 and Receiver 2 are consistent when the rotors are stationary but differ significantly when they are turning.

These results, which were shown to be typical of the CNR time histories during the start/stop sequences for both the tail and nose antenna installations, illustrate the difference between the responses of the two receivers.

Real time CNR estimates from a GPS receiver are normally based upon the correlation counts. Since snapshot recordings at a 1kHz rate of the I_P and Q_P data were available from the ISN receiver, it was possible to directly examine the behaviour of different estimation techniques in the presence of the oscillations due to the rotors. This assessment was performed using two ‘textbook’ CNR estimators taken from the literature:

The ‘AJ estimator’(13) performs a comparison of the total signal-to-noise power in two different bandwidths using the I_P and Q_P data. For this analysis, 20ms samples of the correlation data were used to generate the power estimates, and the results were averaged over 1s to provide CNR updates at a 1Hz rate.

The ‘JJ estimator’(14) is a technique applicable to one-bit quantised receivers and generates CNR based on summation of the I_P data over a specified interval – summation over 1s was used for this analysis to provide 1Hz updates.

Figure 17 shows a comparison of the ‘AJ’ and ‘JJ’ estimator results obtained using two snapshot recordings from the tail antenna for the same satellite. The upper set of CNR data was based on the time history in Fig. 2 with the rotors stationary, and the lower CNR data used the time history of Fig. 4 with the rotors at 63% *Nr*. It is apparent that the two techniques produced almost identical CNR estimates while the rotors were stationary but that their outputs differed considerably once the rotor oscillations were introduced: the ‘AJ’ results were approximately 4·5dB-Hz lower than the corresponding ‘JJ’ estimates. It is also evident that there was little variation in the ‘JJ’ CNR estimate between the rotors-stopped and the rotors-running cases.

Although the precise algorithms employed by the two GPS receivers are not known, it is significant that the ‘textbook’ estimation techniques also produced differing results. This suggests that caution must be used when interpreting a receiver’s CNR outputs unless the response of the specific estimation algorithms is known. The Receiver 2 results indicate that signal tracking problems can occur without any significant reduction in the CNR estimates, suggesting that a receiver’s signal level outputs may not always provide a reliable indication of an incipient loss of ranging measurements.

4.0 DISCUSSION

4.1 Characteristics of the rotor modulation

The objective of this study was to undertake a more detailed investigation of the previously observed effects which had been attributed to the rotor motion. The high speed correlation snapshot data from the ISN receiver provided confirmation that an interference source due to the rotors was indeed present and that this was the most likely explanation for the earlier results.

The investigations confirmed that the effect of blade passage is to introduce perturbations, synchronised with rotor speed, onto the received C/A-code signals where the latter pass through the discs formed by either the main or the tail rotors. There was a limited amount of evidence suggesting that it is also possible for perturbations to be present where the satellite signals arrive at the antenna from the opposite side of the aircraft to the tail rotor.

The results, particularly those for the main rotors, indicate that the modulation can consist of a series of positive and negative amplitude changes and this suggests that both constructive and destructive interference effects are at work during each blade passage. No clear correlation was observed between the extent of the interference effect and the rotor speed, or with any speed-dependent parameter such as the blockage time associated with each blade.

These results were obtained using two specific antenna positions on a single type of helicopter, and it cannot be assumed that they would translate directly to different aircraft or antenna installations. Factors which are likely to influence the nature of the modulation include the construction of the rotor blades and the relative geometry between the antenna and the rotors.

4.2 Impact upon the navigation function

The likely impact of the modulation effects upon a GPS receiver's navigation function was assessed using recorded data from commercial receivers (including a TSO-C129() compliant design) which were assumed to be broadly representative of the equipment commonly used by the helicopter operators. The analysis was undertaken by examining the accuracy and availability of the individual ranging measurements for each satellite.

Investigation of the pseudorange errors revealed that the impact on code measurement accuracy was negligible – almost certainly below the metre level. This suggests that rotor modulation is unlikely to introduce any significant errors into a receiver's position solution for unaugmented GPS applications. However a more detailed assessment of the impact of the rotors on code errors might be appropriate if very high accuracy is required.

Examination of the ranging measurement availability (determined using the receivers' channel tracking flags) revealed clear evidence of a reduction in performance which was correlated with the rotor motion. This effect was observed for two different receivers using the tail antenna and was most severe for signal paths which were obstructed by the tail rotor disc. Apart from some transient effects at very low rotor speeds, there was no evidence of any reduction in availability due to the main rotor.

Statistical analysis of the tracking performance data for the tail antenna revealed that, for one receiver, the reduction in the number of available ranging measurements was in excess of 10%. This statistic is a mean value calculated by averaging over several successive tests. To extrapolate from these results to determine the overall impact upon a GPS receiver's navigation function requires a detailed availability assessment, considering all of the different failure modes in addition to the rotor-related effects. Such analysis was outside the scope of this work.

However it can be stated that interference effects due to the rotors are most likely to impact the navigation solution availability in conditions of poor constellation geometry, where only a minimal number of satellites are visible and there is little or no redundancy within the measurement set. Such conditions occur relatively infrequently but it must be recognised that there could be a strong dependence on aircraft attitude – for example it is conceivable that in poor geometry situations, the action of the tail rotor in obstructing signals from particular directions might render the GPS receiver inoperative when the aircraft is flying on specific headings.

The potential must also be recognised for satellite predictions, including those associated with receiver autonomous integrity monitoring (RAIM) functions, to be over-optimistic when determining in advance the number of ranging sources which are expected to be useable.

For the past several years, the performance of the GPS constellation has been in excess of that guaranteed by the Department of Defense: for example the number of healthy satellites on orbit and the received C/A-code signal level have both been higher than specified. With fewer satellites, or a reduced signal power, the availability reduction due to the rotor effects might be greater. Before undertaking an availability assessment it would be important to determine whether the analysis should be based upon the observed constellation performance or upon that which has been guaranteed.

This experiment only considered the impact of the rotors on the accuracy and availability of GPS code measurements. No assessment was performed relating to carrier phase measurements, nor was there any investigation of the receivers' ability to demodulate the GPS navigation messages. In the case of satellite based augmentation systems such as European Geostationary Navigation Overlay Service (EGNOS) or Wide Area Augmentation System (WAAS), geostationary satellites are used to transmit correction and integrity information using a higher symbol rate and at lower signal power than for C/A-code, and these satellites can be at low elevation angles particularly in the high latitude regions where some of the UK offshore operations take place. These factors might increase the susceptibility of those systems to rotor blockage effects.

Since the research described in this paper was undertaken, efforts have begun to investigate the use of a combination of GPS and EGNOS to provide guidance to helicopters conducting low visibility approaches in the North Sea. The EGNOS system may be able to overcome the issue of reduced GPS availability due to the effects of rotors, as the correction signals available with EGNOS obviate the need for RAIM and hence reduce the number of navigation satellites required. In addition, the navigation payload on the EGNOS geostationary satellites can provide a supplementary range measurement source. However, if EGNOS is to compensate for the effects of rotors on GPS reception, then it must be shown that it is itself not unduly affected.

4.3 Receiver signal level estimates

From the results of the earlier trials, which were based upon data obtained using a single receiver design, it had been assumed that the CNR estimates generated by a GPS receiver would provide appropriate indications of the extent of any rotor modulation effects, based upon the assumption that reductions in CNR will correspond to an increased level of interference.

However, this experiment identified significant discrepancies between the CNR estimates which were output by different receivers and it was also demonstrated that similar effects could occur with different 'textbook' estimation techniques. This led to the conclusion that such estimates may be of limited value for assessing rotor effects unless the response of a receiver's CNR estimation algorithm is known in advance, either through characterisation under test conditions for a particular design of receiver, or through the imposition of a requirement that a standard algorithm be employed.

4.4 Testing of operational GPS installations

This study did not permit examination of all the variables which could influence the nature of the rotor modulation and its impact upon a GPS receiver. These variables include:

- Blade shape and construction
- Antenna position
- Shape and construction of the helicopter fuselage
- Separation between the antenna and the rotors
- Rotor speed
- Receiver design

In addition, the GPS equipment employed for the tests was not fully representative of an operational system. The results therefore serve only to indicate that a potential problem exists and must not be considered as a benchmark against which to compare other installations.

If additional data is deemed necessary to quantify the impact of rotors on specific helicopters' GPS installations, then it is suggested that this might be better performed using empirical measurements rather than by attempting to model the effects theoretically.

Assuming that any rotor-related problems are likely to manifest themselves as reductions in ranging measurement availability, then the goal of an empirical aircraft test should be to investigate whether there is any significant variation in the receiver's tracking performance for satellite signals originating from different relative positions. This would effectively allow mapping of the directions in which the reception is poor.

One possible empirical method would be a rotors-running ground trial similar to that described in this paper. The trial would need to be designed such that data was collected from a representative sample of different signal directions, for example by performing the test over an extended time period (several hours or longer) to take advantage of the satellites' natural orbital motion. It might also be necessary to make periodic changes in the aircraft heading during the test.

An alternative approach for the assessment of existing GPS installations would be to perform an in-service measurement trial. Although not as controllable as a ground test environment, this would allow GPS performance data to be captured in an operational situation and would reveal the impact of all the different factors affecting receiver tracking performance (e.g. attitude changes, dynamics, vibration) in addition to any rotor-related effects.

All of the North Sea helicopter operators either have or are in the process of setting up operational monitoring programmes(15) under which the aircraft are configured with data recording equipment. It has been suggested that this equipment could be modified to acquire data on the GPS receivers' tracking performance (e.g. the RAIM available discrete signal) for subsequent analysis. A feasibility study has been commissioned by CAA with GE Aviation (formerly Smiths Aerospace) which will involve a trial using a Bristow Helicopters Super Puma. It is planned that data will be collected on the frequency and duration of any RAIM outages, and any significant features in this data will be investigated using the aircraft data available (e.g. aircraft position and attitude). If successful, it is expected that this scheme will be extended to all aircraft in order to confirm that existing helicopter antenna locations are appropriate, that the end performance of the system remains acceptable, and to provide data to assist accident/incident investigation.

5.0 CONCLUSIONS

This study successfully reproduced the phenomenon observed during previous flight trials whereby GPS signal levels and availability were notably reduced for signals arriving at specific geometries relative to the antenna. High rate correlation data was captured which allowed the effects to be analysed and compared with rotor speed data. The results of this experiment, in combination with those from the previous flight trials, indicate that helicopter rotor blades can disrupt the reception of GPS signals. For the particular aircraft and installation employed in this study the tail rotor blades lead to a marked reduction in pseudorange measurement availability, although range precision was not significantly affected. In contrast the main rotors had very little impact on GPS availability.

When considering the variety of antennas, receivers, rotor blades, fuselage geometry and antenna locations used aboard operational aircraft, it is clear there are many factors that could affect the impact which the rotor blades have on GPS signal reception. Empirical testing of individual installations is an attractive approach to adopt and the study has identified ground-based rotors running trials as well as in-service measurement trials that could be performed. Work is ongoing to determine the feasibility of each of these approaches.

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