Is it a Bird or is it a Plane?

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***Abstract*— This paper describes the application of low-cost radar technology for the detection and analysis of the Doppler signatures of wild life, in particular birds and bats. We demonstrate the ability to extract the wing beat frequency in real-time. Such processing affords a method of readily discriminating between animals and other flying objects such as micro- unmanned aerial vehicles. The timing waveforms used for sampling and integration can have a significant impact on the fidelity of the data that can be captured and on the response time of the system to detect and analyse animals in motion. This work paves the way for future research in support of target classification and conservation ecology.**

I. Introduction

Recent work at Cranfield University, Shrivenham, United Kingdom (UK) in collaboration with the Conservation Ecology Research Team Swansea (CERTS), Swansea University, UK, has applied low-cost radar technology for the detection and tracking of wild life, particularly, birds, bats, lizards and insects. There are a number of applications of the technology, including:

Discrimination of stealthy targets. Stealthy military aircraft are reputed to have a monostatic radar cross section (RCS) in the head-on aspect at centimetric wavelengths equivalent to that of a medium sized bird (i.e. wing span in the range 10 to 40cm). In order to counter this low RCS, radars must be designed with a far greater detection performance, in which case, they may detect targets of this size. Whilst the track of a bird will rapidly discriminate it from a military aircraft, the track formation and subsequent processing would sap the radar computing resources and even a modest number of birds could overwhelm the resources of the radar. Methods of early discrimination between birds and aircraft are clearly required.

Conservation ecology. In the field of conservation ecology, low-cost sensors can be used to monitor the positions of animals and cue photographic equipment to capture images for animal identification. The information gathered is used to estimate populations, determine periods of activity/inactivity and the energy expenditure of the animal and to ascertain the range of an animal. Passive infra-red (IR) based sensors are commonly used but are prone to detection problems and are slow to respond such that they often fail to detect the passage of an animal (e.g. a wet otter recently emerged from cold water, or an insect or a reptile which have a low thermal contrast). Infra Red 'beam break' systems have also been deployed, however, the placement of the devices is critical and requires areas of restricted motion to be known, such as across the entrance to tunnels, under roads etc. The beam-break systems are difficult to configure and provide little information regarding the characteristics of the animal. It is also very difficult to cater for a wide variety of animal sizes as the effective width of the beam is small. The low cost of commercially available radars offers an attractive alternative to traditional IR based sensors, particularly since they offer the ability to monitor the animals in a completely non-interventional manner. This is important because it does not appear to influence the natural behaviour of the animal.

Trials are underway at Cranfield and Swansea Universities using a range of low-cost 24GHz coherent Continuous Wave (CW) Doppler sensing radars to record the Doppler signatures of a variety of animals. The RFbeam Microwave GmbH K-MC2 radar [1] is used in conjunction with a standard video camera to record the video and quadrature output data, which is recorded as a dual channel (stereo) '.wav' file. Since the Doppler data fall within the audio band, the Doppler '.wav' file may be inserted onto an audio track and aligned with the video using video editing software. The combination allows characteristics of animal motion to be correlated with the observed Doppler signatures.

Furthermore, processing the quadrature outputs from the radar enables one to display the signals (or play back previously stored files); additionally, the Fast Fourier Transform (FFT) of the data can be taken and velocity and amplitude limits applied in order to allow target detections to be declared within the user defined limits. The detection events are output by setting a serial-port control line high, which in turn is used to trigger a camera to capture an image.

Figure 1: A K-MC2 radar module mounted on a tripod along with a video camera. Both the radar and video camera are aligned to share a common bore-sight.

Figure 1 shows the mechanical arrangement where a K-MC2 radar module has been mounted along side a video camera so that they share a common boresight and field-of-view. The tripod has a panning head and the alignment of the sensors is maintained even if the radar is steered manually.

The radar system may also be used to trigger a high-resolution stills camera to allow accurate visual recognition of animals, despite using large stand-off ranges combined with a large field-of-view. The ability to capture still images is important as even high definition video often does not have sufficient resolution to allow accurate identification of some species, for example in the differentiation of pollinating insects.

The waveform design issue concerns the required integration period. Long sampling periods improve integration gain and therefore detection performance and improves the velocity resolution but does also require increased processing. Long sample times also blur the signal variations due to micro-Doppler and most importantly, delay the time before the camera can be triggered. For capturing images of bats and birds, the delay time is critical since they rapidly move outside the field of view. As ever, there is a trade between the velocity resolution and the time resolution.

Short sample times are fast to process but result in a reduced integration gain and therefore the detection range is compromised. Also with the present software, there are more 'blank' periods (eclipsing of sorts) while the graphics update and the operating system prepares to capture the next block of data samples.

II. WING-BEAT ANALYSIS

The radar system is able to detect a $1m^2$ target (approximately that of an adult human) at a range of approximately 70 metres. It has been used to detect a Peregrine Falcon (*Falco peregrinus,* Figure 2) in flight at a range up to approximately 50 metres.

Figure 2: Peregrine falcon used in the study in flight.

The wing beat is readily heard in the Doppler (audio) data. The action of the wing flap of birds and bats has been observed by others using non-coherent (non-Doppler sensing) radar detection techniques [2],[3], since the action causes a changing RCS which amplitude modulates the radar return. Coherent Doppler radar detection, as used in this study, offers better clutter rejection capabilities and the opportunity to observe the wing beat frequency and Doppler signature of the wing in the Doppler (velocity) domain, providing that adequate Doppler resolution is attainable. In addition to measuring the wing beat frequency, with certain radar configurations, information on the wing tip speeds may be available for both the up-stroke and down-stroke of the wing, allowing differentials in wing configuration to be observed and the energy expenditure to be estimated.

The wing beat frequency of a large bird is typically in the range of 5 to 10Hz; larger birds having a lower wing beat frequency. The amplitude modulation results in a frequency component above and below the Doppler return from the body of the bird at an offset equal to the modulating frequency i.e. the wing beat frequency. An integration time, t_{int} of:

$$t_{\text{int}} = 1/\Delta f_D \quad (1)$$

is required, in order to obtain a frequency resolution of Δf_D. Thus, in order for wing beat components to be resolvable from the body return, integration times >200ms are required.

Alternatively, if the velocity of the wing-tips themselves can be resolved as micro-Doppler modulations on the signal, then the time between beats may be used to extract the wing beat frequency. Much shorter integrations may be applied, however time-frequency analysis must be employed in order to detect and extract the individual wing-stroke events. Using time-frequency analysis may also provide information on the pattern of the wing strokes and reveal differences between up and down beats, however due to the shorter integration times needed to resolve the beats in the time axis, the signal to noise ratio (SNR) is correspondingly lower. A coherent processing interval (CPI) of 50ms will give a velocity resolution of $0.125ms^{-1}$, potentially allowing the velocity of the different sections of the wing to be observed during each beat phase. A Short-Time Fourier Transform (STFT) approach has been employed where a sliding 50ms sample is processed every

10ms in order to visualise the wing-beat patterns in recorded data, however the processing requirements are too high to employ the full STFT in real-time when processing on a laptop computer and attempting to trigger a camera.

Trials with a Peregrine Falcon have detected the wing beat signatures in the radar data. From the video evidence, the bird's wing beat frequency has been estimated at around 6Hz as she launches from the arm of the falconer and flies directly towards the radar, passing just above the radar/video equipment. A one second burst of data corresponding to the fly-past is processed to extract its amplitude modulation (AM) envelope. The magnitude of the complex (I/Q channel) data is filtered with a sliding window which computes the root mean squared (rms) value within the window at each time increment. The sampling rate is 44.1kHz and the sliding window has a width of 882 samples, giving a time constant of 20ms. The filtered magnitude data is then transformed via an FFT into the frequency domain which now reveals spectral components corresponding to the AM frequencies in the original data. Since a one second burst of data is processed, the frequency resolution is 1Hz and is sufficiently fine to pick out low frequency AM content. The filtered time data has no obvious periodicity, however, the spectrum of the AM content shown in Figure 3 has a peak response at 6Hz, albeit at a low modulation index. Furthermore, the 6Hz wing beat modulation is affirmed later (Figure 7) using a time-frequency spectrogram where the wing beat is estimated at 5.9Hz just before the bird crosses over the top of the radar; the estimation of the wing-beat frequency from the radar is very similar to that estimated from the video data. All measurements of the wing beat frequency are drawn from the same section of data.

A Short Time Fourier Transform (STFT), otherwise known as a *waterfall diagram*, shows the velocity/time characteristics of the bird when crossing the radar beam and is illustrated in Figure 4.

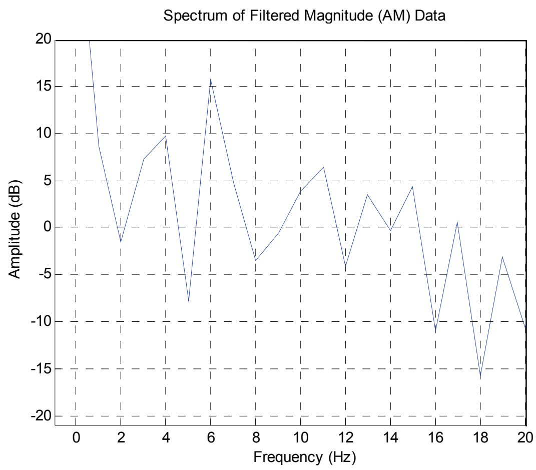

Figure 3: Spectrum of the amplitude modulation on the radar data corresponding to the Peregrine flight trial.

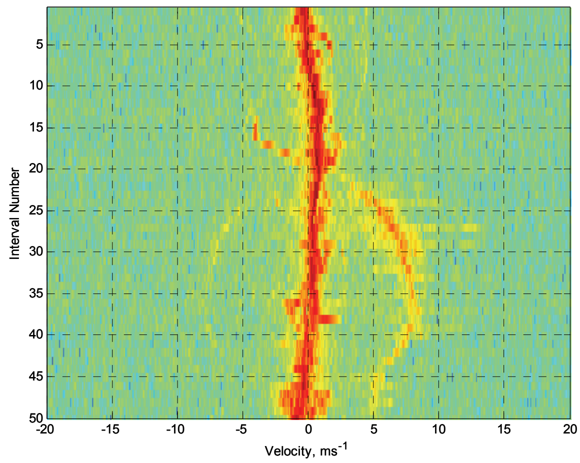

Figure 4: Short Time Fourier Transform of Peregrine on a crossing trajectory in front of the radar. The horizontal axis is the radial velocity measured from the Doppler information and the vertical axis shows individual FFT time slice intervals. Each time interval is over a CPI of 100ms and there is no overlap of the CPI windows in time.

The figure shows a strong clutter return at zero velocity running up the centre of the plot. Data on the right hand side of the plot indicates a closing velocity and on the left, an opening velocity. The integration time is too short and, consequently, the velocity resolution is too coarse to resolve the full sidebands of the wing beat characteristics in this plot, however the short time frames are beginning to capture the individual wing beats instead. The non-uniform velocity of the bird does not permit very long time sampling without smearing the data in the velocity domain which would, in turn, mask any close in sidebands associated with the wing beat.

Figure 5 shows an STFT plot of the Peregrine taking off and then flying towards and over the top of the radar. A CPI of 100ms has been used so that a significant section of the flight can be observed. Although the body velocity of the bird is visible (approximately 6.5m/s when passing over the top of the radar), there is no clear wing-beat pattern visible, however there are 'smeared' returns emanating from the body velocity trace at higher and lower velocities. Thus the 100ms time sampling interval is providing good integration and therefore a good signal-to-noise ratio, however the wing-beat pattern is not clear.

Figure 6 shows the same data as Figure 5, however the CPI time has been reduced to 50ms. Now there is an apparent modulation to the Doppler trace, however the timing resolution just fails to allow an accurate determination of the wing beat frequency. In Figure 7, however, the same 50ms CPI has been used, but a new FFT is performed on a 50ms window every 10ms; i.e. the processing windows are overlapped. Thus in Figure 7 the time intervals on the vertical axis correspond to 10ms intervals. Now a very clear pattern of wing beats can be discerned, allowing both the wing-beat frequency and wing tip velocities to be established.

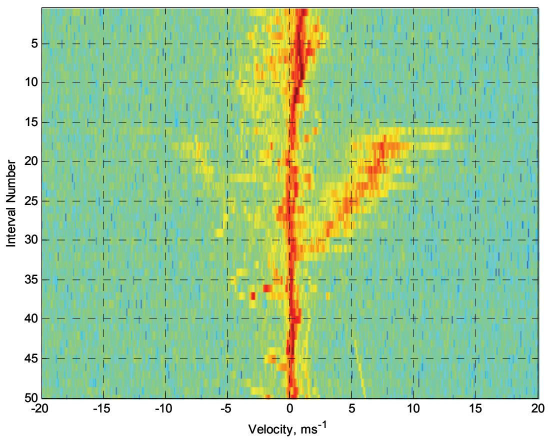

Figure 5: Short Time Fourier Transform of Peregrine on a radially inbound trajectory that passes over the top of the radar. The horizontal axis is the radial velocity measured from the Doppler information and the vertical axis are individual FFT time slice intervals. Each time interval is over a CPI of 100ms and there is no overlap of the CPI windows in time.

Thus the choice of the coherent integration time and the time step between integration events can be adjusted to trade the ability to detect an animal against the ability to extract temporal patterns from the data.

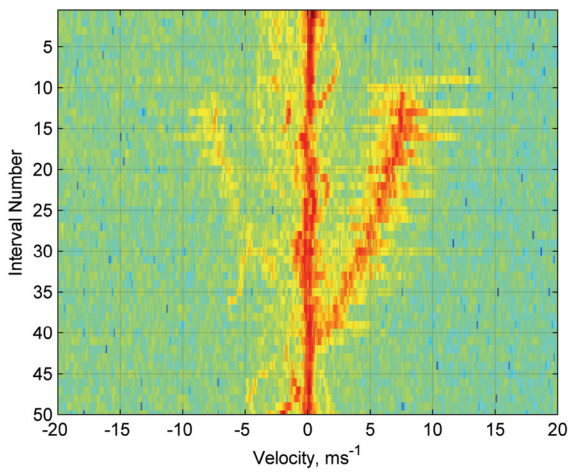

Figure 6: Time-velocity spectrogram of data imaged with 50ms per interval showing takeoff and then the Peregrine passing over the top of the radar.

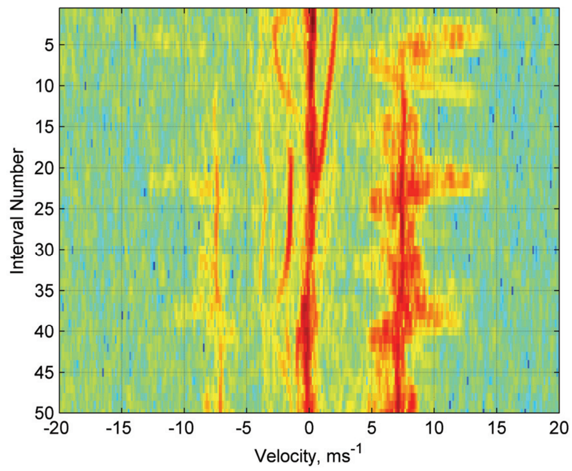

Figure 7: STFT image showing section of Peregrine take-off and flight data with the bird approaching and then passing over the top of the radar, passing at approximately at velocity of 6.5m/s. Each interval is of 10ms sample duration. The period between wing beat events is 17 sample intervals which corresponds to 170ms between beats and therefore a wing-beat frequency of 5.9Hz. Many traces from insects that are close to the radar are also visible in the image as near continuous lines weaving around in the velocity space.

Figure 8 shows a section of data recorded from a Serotine bat (*Eptesicus serotinus*) flying through the radar beam. The radar was pointing vertically and the bat flew horizontally through the beam. The transit time through the beam that provided useful data was approximately 200ms. The intervals on the vertical axis are in 10ms segments, with the most recent results at the top of the image at interval zero.

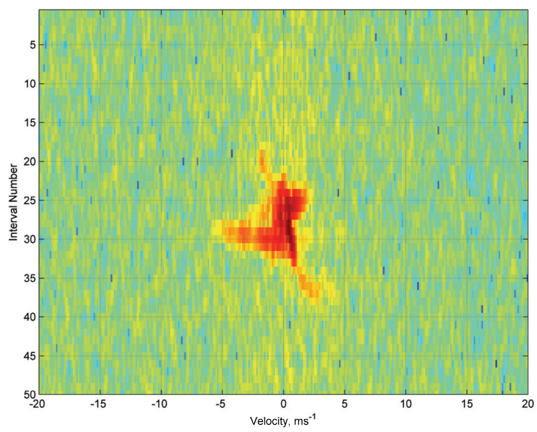

Figure 8: STFT image showing data recorded from a Serotine bat flying horizontally through a vertical radar beam. Each interval on the vertical axis is of 10ms sample duration with an overlapped CPI per interval of 50ms.

The horizontal axis shows the Doppler returns but scaled to produce a direct velocity reading. The data show the bat approaching (positive overall body velocity) at the bottom of the figure and receding at the top of the image (negative body velocity) with the point of being directly over the radar providing a zero Doppler return from the animal body. Feint returns of a wing up-stroke are apparent at approximately interval 36, followed by a down-stroke at approximately at interval 29, then a second clear upstroke at interval 25 and finally a very feint down-stroke at interval 19. Two wing cycles have therefore been estimated at 36-19=17 intervals which is approximately 0.085s for one cycle, therefore a wing beat rate of 11.8Hz.

Further radar trials have been conducted against much smaller bats, probably Pipistrelle bats (*Pipistrellus pipistrellus*), hunting over water, in which the radar was elevated at approximately 45^0 over the water surface. Data was captured of bats passing through the radar beam at an estimated range of 8 metres. The duration of the radar returns indicate that the bats transit through the beam in around 150ms. Figure 9 illustrates the raw I and Q channel data from the radar of the transit. A strong AM is clearly visible with a periodicity of around 47ms indicating a wing beat frequency of 21.3Hz.

The spectrum of the AM envelope of this data was derived using the method previously described and is shown in Figure 10. This reveals a broad peak centred on 26Hz, although it has to be borne in mind that the duration of the data burst processed here was just 227ms leading to a relatively coarse frequency resolution of 4.4Hz. The two measurements of the amplitude modulation from this data are in broad agreement with one another, bearing in mind the poor SNR of the time domain data of Figure 9 and the coarse frequency resolution data of Figure 10.

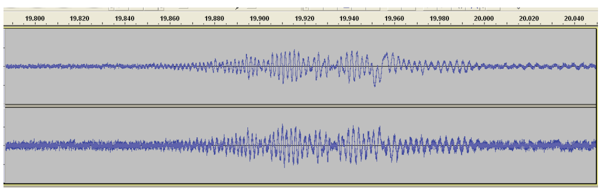

Figure 9: I/Q channel radar data on the transit of a suspected Pipistrelle bat through the radar beam. An amplitude modulation with a periodicity of approximately 47ms is clearly seen.

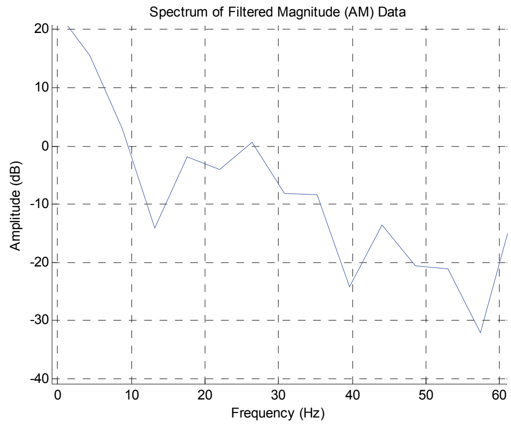

Figure 10: Spectrum of the AM envelope of the transit of a suspected Pipistrelle bat. The data indicates a broad peak centred at 26Hz.

Future work in support of ecological research requires a rapid reaction time between the detection of a target and the triggering of a camera to capture its image. The speed and agility of bat flight coupled with the requirement to operate at short ranges results in very short illumination times and provides a stern test of our equipment. We estimate that a reaction time of 100ms, or less, is required to capture images of bats, which our system can achieve.

Figure 11 shows an image of a Serotine bat that has been captured using the radar-triggered camera system. The image of the bat has been cropped as a section of the full image, the size of which covers almost 38 times the crop area. The detail remaining in the cropped section illustrates how high resolution camera systems are needed in order to allow sufficient detail to be present in the captured image for visual target identification.

Figure 11: Bat image captured using radar triggered camera system. This image is a crop of the full captured image which is nearly 38 times the area of this cropped section.

III. CONCLUSIONS

In conclusion, we have observed that animal targets impart some interesting modulations on a returning radar signal which can be exploited by coherent Doppler processing and offers improved detection and discriminations of wildlife for target recognition and ecological purposes. In particular, the wing beat of birds and bats in flight gives rise to amplitude and frequency modulations which can be observed and measured in the data. It would seem that the wing beat from the Peregrine Falcon flying towards the radar imparts a weak amplitude modulation but a more clearly discernable frequency modulation whereas the wing beat of bats gives rise to a far stronger amplitude modulation component. Although the waveform issues that arise in the study are just the sampling interval and degree of overlap of the STFT, the impact on the quality of the micro-Doppler information and the response time of the camera trigger system is critical.

IV. FUTURE WORK

Work is progressing to automate the processing to extract the wing beat modulation. Our aim is to drive towards recognition of the class of the animal and its approximate size. We hope to apply this for target recognition for both military and ecological purposes. Furthermore, work is on-going in support of ecological research into surveying of lizards and mammals and monitoring the activity of pollinating insects.

ACKNOWLEDGMENT

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