Biologically Inspired Waveform Diversity for Synthetic Autonomous Navigation Sensing

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SUMMARY

Echolocating mammals such as bats, whales and dolphins have been using waveform diversity for over 50 million years. Synthetic systems such as sonar and radar have been in existence for less than 100 years. Echolocating mammals vary their Pulse Repetition Frequency (PRF), power and frequency content of their transmitted waveforms. This has enabled them to evolve highly sophisticated orientation techniques and the ability to forage for food. Moreover, recent developments in technology mean that it is now possible to replicate all of the above methods in synthetic sensing systems such as radar and sonar. Thus echolocating mammals potentially offer valuable insights that might allow improvements in the performance of their synthetic counterparts. This may enable capabilities such as autonomous navigation and automatic target classification which have hitherto proved elusive. We examine the waveforms used by bats as a function of orientation and intent. In particular we carry out this examination using techniques and metrics typically employed in the design and analysis of radar systems. By conducting the analysis in this way we are able to derive an understanding as to how bats are exploiting waveform diversity and how this can be exploited in radar and sonar systems for applications such as autonomous navigation and target classification.

1. INTRODUCTION

We begin by reviewing the ways in which bats control and vary their emitted waveforms. This is described in the first four sections of the paper. Understanding signal diversity in bats provides valuable insights as to how such design may be exploited in synthetic systems and is an important foundation given the multi-disciplinary approach that we have adopted. Mammals such as bats use echolocation to perform autonomous navigation (or more strictly orientation), detection and classification of targets (sometimes in cluttered environments). The properties of the transmitted and received waveforms are quite variable but can be easily replicated in synthetic sensing systems (such as sonar and radar) using the technology of today. However, there is a huge shortfall in autonomous navigation performance that can be achieved with such synthetic sensor systems when compared with that of bats and other mammals. This is now inhibiting the development of capabilities such as autonomous navigation and preventing their commercial exploitation. Thus, in this research we have investigated the very able autonomous navigation performed by bats in an

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attempt to identify the key aspects that can help move towards either autonomous air or underwater vehicles on a much more reliable basis. Initial investigations suggest that a combination of flight profile, waveform diversity and multi-algorithmic (and possibly non-linear) processing are all important ingredients to success. We have concentrated on these aspects here, aiming to quantify their properties and evaluate their role in determining navigation and obstacle avoidance methodologies.

If we can understand how bats exploit echolocation for autonomous navigation and collision avoidance we can then begin to build this into synthetic systems and hence, potentially, provide a step function change in the utility of unmanned systems. The key is to create systems that will be able to react to their local environment and cater for unexpected and unpredictable navigation hazards. If sonar and radar sensors can be used in this way then system performance will be independent of daylight conditions and 24 hour, all weather operation is entirely feasible. This should subsequently lead to a much wider variety of applications in areas as diverse as robotics, remote sensing, counter terrorism, sensor networks and transportation.

In the next section we introduce and summarise echolocation as observed in the natural world and highlight how this is exploited by bats for orientation and selection and attack of prey. This leads naturally into an analysis of the waveforms emitted by a variety of species of different bats in terms of their construction, spectral composition and ambiguity function properties. The results allow us to derive conclusions as to how bat echolocation can be exploited for autonomous navigation.

2. ECHOLOCATION IN BATS

It is currently hypothesised that laryngeal echolocation (calls produced in the larynx) evolved in the ancestor of all extant bats although some scientists argue that laryngeal echolocation may have evolved at least twice independently. Assuming one evolutionary event, laryngeal echolocation may then have been lost in Old World fruit bats (family Pteropodidae), only to evolve secondarily (by tongue clicking) in one genus (*Rousettus*) in this family [1-3]. All bat species in the remaining 18 families of bats currently recognised (>800 species) are known to use laryngeal echolocation, at least for orientation and often for the detection, localisation and classification of prey. This wide variety of species also suggests that we would expect to see a wide range of techniques employed when examined in detail.

Signal designs categorised by Jones and Teeling [3] are shown in Fig. 1, with illustrations of their occurrence in selected families in the two major divisions of bats currently recognised. The categorisation is based around signals emitted when bats are searching for prey: intra-specific (and indeed intra-individual) variation in call design can be substantial, and the scheme was introduced to illustrate patterns of convergent evolution. The following eight signal design categories may be summarised as follows:

(a)   Most *Old World fruit bats* (Pteropodidae) do not use echolocation for orientation, and instead appear to rely largely on vision.

(b)   *Brief, broadband tongue clicks* are produced by cave-dwelling bats in the genus *Rousettus* (family Pteropodidae) [4]. The clicks are produced in pairs (one from each lip) by raising the tongue from the floor of the mouth. The clicks are of short duration (typically < 1 ms) and the mechanism of their production is quite different from that used in laryngeal echolocation by all other echolocating bats. Although the performance of these clicks has traditionally been considered poor, it has recently been argued that echolocation in *Rousettus* may be more sophisticated than previously realised [5].

(c)   *Narrowband signals dominated by the fundamental harmonic* are produced by bats in the families Vespertilionidae, Miniopteridae and Molossidae that fly in open spaces. These calls have narrow bandwidths, and are relatively long (often > 5 ms).

(d)   *Narrowband multiharmonic signals* are emitted by bats from a range of families that hunt in open spaces. Each harmonic is narrowband, but several prominent harmonics feature in the call. The dominant harmonic is usually not the fundamental.

(e)   *Short, broadband calls with a dominant fundamental harmonic*. These calls are the typical 'chirps', or frequency-modulated (FM) calls that have dominated research on broadband echolocation.

(f)   *Short, broadband multiharmonic signals* are produced by bats in at least six families. Bat species that emit these calls characteristically fly in cluttered situations.

(g)   *Long duration broadband calls* are presently described only for the Malagasy sucker-footed bat *Myzopoda aurita* (family Myzopodidae) [6]. Most energy is in the second harmonic.

(h)   *Pure constant frequency (CF) signals are long duration signals* whose dominant component has zero bandwidth. CF calls emitted by rhinolophids and by *P. parnellii* can be long in duration (> 30 ms), and these bats compensate for Doppler shifts induced by their own flight speed [7]. Hipposiderids emit shorter signals (often < 10 ms), and show partial, or sometimes complete Doppler shift compensation (DSC) [8].

Call design also varies within species and even within individual bats. For example, bat calls may change radically during insect capture. Prey in the air are searched for, detected and located by a series of echolocation pulses that ultimately ends in a 'terminal buzz'. During a terminal buzz, calls typically become shorter, are repeated at a higher rate, and have shorter intervals between them. In most bats, pulse-echo overlap is usually avoided during prey capture (because the calls become shorter as the prey is approached). We will now examine some of the physical factors that determine call design.

A.   Call intensity

Many aerial feeding bats produce calls of intensities > 120 dB peak equivalent sound pressure level (peSPL) at 10 cm when searching for prey, and measurements of 135 dB peSPL at 10 cm have been recorded for some fast flying species that fly in open spaces [18,19]. Such values are among the highest intensities documented for airborne vocalizations by any animal. Bats that fly in confined areas (such as in woodland) may produce calls < 75 dB peSPL. Relationships between call intensity, target distance and hearing sensitivity have been studied in depth. Most bats reduce call intensity when approaching prey (intensity compensation). Hearing sensitivity also increases when bats approach targets to compensate for increases in echo strength as target range shortens (automatic gain control (AGC)). If Patheiger's values for distance-dependent hearing sensitivity are assumed to hold bats may experience a constant sensation level during target approach [12]. Target size was found not to affect call intensity during approach to targets of varying size in *M. daubentonii* [12].

In synthetic sensing terms this equates to maintaining a constant and relatively high signal to noise ratio that matches the transmitted waveform to the target scenario. Additionally bats use an equivalent signal to noise ratio that is typically around 25dB higher than used in radar and sonar. The significance of this is not yet understood but may indicate that important information is contained in lower levels of echo that would otherwise be swamped by noise.

B.   Harmonic structure

Bat calls often show complex frequency spectra that comprise a harmonic series. Signals often consist of a harmonic series where frequencies are integer multiples of the lowest, or fundamental (also known as the first) harmonic. Some bats emit signals that are dominated by the fundamental harmonic. Bats in many families emit multiharmonic signals, and the fundamental may not be the dominant harmonic. Bats in the families Rhinolophidae and Hipposideridae that emit long, constant frequency signals channel most energy into the second harmonic, though detection of the fundamental harmonic is vital for echo processing [13]. The presence of multiple harmonics in a call is also believed to improve ranging and discriminative performance [14]. This is examined later in section 6 via the ambiguity waveform of real bat calls.

C.   Call frequency

Bat echolocation calls vary in their dominant frequency between about 11 kHz (e.g. *Euderma maculatum* [15]) and 212 kHz (*Cloeotis percivali* [16]). The vast majority of insectivorous bats use calls with dominant frequencies between 20-60 kHz [17]. In general, however it is likely that two features constrain the frequencies used by bats: atmospheric attenuation and target strength. Because of the two-way travel of sound in echolocation, and because weak echoes are reflected from most targets, atmospheric attenuation will limit the effective range of echolocation at high frequencies. Although the relationship between target strength and frequency was developed for spheres by Lord Rayleigh over a century ago, the theoretical relationship between prey size and call frequency exists for insect targets (Fig. 2). Reflectivity decreases sharply when wavelength exceeds the wing length of the insect, so that low frequencies (20-30 kHz) reflect poorly from small insects (2.5-5 mm wing length) [19].

D. Bandwidth

The ability of bats that use broadband echolocation calls to detect prey close to clutter depends much on bandwidth. Species that used calls with the highest bandwidth are most successful in capturing prey close to a clutter screen that mimics a vegetation edge. The wide range of frequencies used in broadband calls (e.g. those of *Myotis nattereri*, whose calls sweep from 135-16 kHz) spans wavelengths from about 22-2.6 mm. Many reflecting surfaces, including prey, and vegetation objects, may therefore be ensonified simultaneously. If matched filter processing is assumed (or an equivalent) this equates to a range resolution in the region of 1mm. This might provide sufficient resolution to create a range profile that can be used to identify targets. However, it is more likely that this will be augmented using a combination of multiple looks and fine scatterer location using reception on both ears.

E. Call duration

Call duration is determined partly by the proximity of obstacles for all bats except for those species that use Doppler Shift Compensation (DSC) and are therefore tolerant of pulse-echo overlap (see 'Doppler shift compensation' below). Call duration influences the minimum distance at which a target can be detected. Bats that echolocate at low duty cycles (signal 'on' for short proportion of time), reduce call duration as they approach prey in order to avoid temporal overlap of their powerful vocalizations with the returning faint prey echoes, which would cause ambiguity and make tracking of prey difficult if not impossible [20]. The zone around the bat in which target echoes overlap with the emitted call is named the Signal Overlap Zone (SOZ). Reducing call duration when approaching targets is adaptive because each 1 ms of signal duration adds 17 cm to the SOZ. Bats therefore often reduce call duration as they approach obstacles, so that the SOZ is equal to or less than the distance to the target, and so pulse-echo overlap is avoided (Fig. 3).

Masking of prey echoes by the outgoing signal (*forward masking*) therefore limits pulse duration in echolocating bats. Additionally, clutter echoes from background targets that return soon after the echo of interest may also interfere with echolocation by *backward masking* if echoes from clutter interfere with neural activity evoked by the prey echo [39, 44]. Bats are therefore predicted to use signal durations that result in echoes returning in an overlap-free window, where forward and backward masking are avoided [20]. Thus the bats generally use a waveform that avoids range ambiguity. This greatly simplifies subsequent processing and is, of course, a typical design goal in synthetic sensing systems.

F. Pulse interval and repetition rate

When searching for prey, bats often emit one pulse per wing beat. This is because the mechanics of flapping the wings, breathing, and producing sound pulses are all coupled. Because of this coupling, the pulse repetition rate is often the same as wing beat frequency when bats are searching for prey [22], though the coupling breaks down during the final stage of insect pursuit when pulse repetition rates may reach 200 Hz and calls are emitted at lower intensities. Bats sometimes batch groups of pulses into groups (*strobe groups*) with relatively stable repetition rates [23]. These strobe groups are produced more frequently during complex acoustic tasks, such as detecting prey close to a background (e.g. a plant). Pulses within strobe groups are produced more frequently in such 'cluttered' situations, increasing the bat's sampling rate of the environment under conditions where the bat experiences echoes other than those from the target of interest [24]. Again, this aspect is examined in greater detail in section 5.

G. Duty cycle

Bats operating at high duty cycles often use long signals with short pulse intervals. Low duty cycle species have short calls and relatively long pulse intervals. High duty cycle species (> 30%) use CF components in their calls and show either partial or complete Doppler shift compensation [18]. These waveforms are used for micro-Doppler classification of insects with flapping wings.

3. THE KEY TASKS OF ECHO LOCATION IN PREY CAPTURE: DETECTION, LOCALIZATION AND CLASSIFICATION

Important perceptual challenges that must be overcome by echolocation are the *detection, localization* and *classification* of targets. This categorisation has proven to be a valuable way of understanding the adaptive significance of signal design in echolocating bats [26].

A.   Detection

In flight, a bat must find prey. For many bats, the task of relevance is the detection of echoes from insects flying in open surroundings. Narrowband signals (bandwidth of only a few kHz) are well designed for detection in this context and they are often relatively long in duration, and therefore have a high probability of detecting successive 'glints' (defined here as small modulations in frequency or amplitude caused by movements of insect wings). Narrowband signals are poorly adapted for localisation since they activate only a few frequency channels, giving somewhat imprecise time markers and are poor at encoding angular cues [26].

B.   Localization

After a target has been detected, the bat must determine its location. The location of a target in three dimensions can be determined from its range and direction. Range is determined by measuring time delays between signal production and reception. A delay of 2 ms corresponds to a range of 34 cm. Broadband signals activate each of many neuronal filters for very short time periods, allowing the use of many discrete time markers that can give accurate measures of delay and hence range [26]. For determination of direction, the horizontal angle of a target is determined from binaural echo cues. The shape of the external ears (pinnae) plays an important role in determining both the sensitivity to frequencies and the directional responses of hearing [28]. Horizontal angle, or *azimuth*, is determined by analysing differences in the sounds that reach the left and right ears.

C.   Classification and discrimination of objects

Echo features can be object-specific, enabling bats to classify targets. For example, horseshoe bats that emit long constant frequency calls receive echoes that include a number of glints, with each glint caused by an insect's wing beat. The movement of the wing creates small Doppler shifts and amplitude modulations in echoes. Neither amplitude nor frequency modulation alone is sufficient for insect identification by horseshoe bats, and it seems that the bats rely on complex computations of acoustic parameters to classify insects [30]. Bats are also able to discriminate among objects of different sizes and textures.

•   *Object size*: Bats can detect small insects with a diameter of 1-4 mm at a range of about 35 cm [27]. Although wavelength constrains the size of targets that bats can detect because of Rayleigh scattering, bats can detect and avoid wires of diameter 0.06-0.1 mm because these wires have diameters 20-280 times smaller than the wavelengths of sounds used by the bats.

•   *Texture*: Bats can discriminate between different surfaces with hole depths of 8mm and 7mm. It is thought that the texture of surfaces can be determined according to interference patterns generated from 'valleys' and 'hills' in the target's surface. If sound waves are 180 degrees out of phase, cancellation of energy in the wave will create a notch in the frequency spectrum. When waves are in phase, addition of energy in the waves is maximal. Notches in a frequency spectrum occur when the distance between high and low points on a target is $\lambda/4$ or uneven multiples of this relationship, so that the notch frequency = $1c/4\lambda$, $3c/4\lambda$, $5c/4\lambda$ …, where c = velocity of sound. Recent attempts to understand how bats that emit broadband echolocation calls can classify natural targets have focussed on understanding impulse responses (IRs) from objects [31].

4. BAT ECHO LOCATION AND DOPPLER EFFECTS

A.   Doppler shift compensation (DSC)

Bats in the families Rhinolophidae and Hipposideridae produce signals with a relatively long CF component. The calls of rhinolophid bats (often > 30 ms) are typically longer than those produced by hipposiderids (often < 15 ms). Rhinolophids compensate for Doppler shifts induced by their flight speeds in echolocation, and hipposiderids show at least partial, sometimes complete DSC [9]. The hearing system of rhinolophid bats is sharply focussed to the frequency that the bat emits when it is resting. In the greater horseshoe *bat Rhinolophus ferrumequinum*, the resting frequency is close to 83 kHz.

When a greater horseshoe bat is at rest, it emits calls with a frequency of the CF component close to 83 kHz. Long CF signals are especially susceptible to Doppler effects. When the bat takes off, it lowers the frequency of the emitted pulse to compensate for the Doppler shifts induced by its flight speed. The faster

the bat flies, the more it lowers the frequency of the emitted call so that the echo returns at the frequency of the acoustic fovea (Fig. 4). Although the bats compensate for Doppler shifts induced by their own flight speed, they do not compensate for Doppler effects created by flying insects [38].

One important consequence of DSC is that call and echo are separated in frequency when the bat is flying and so the bat does not suffer the consequences of self-deafening while calling. This allows horseshoe bats to still produce calls of long duration when flying close to clutter. The long duration signals of horseshoe bats allow them to operate at high duty cycles (sometimes > 60%). This increases their chances of detecting fluttering targets. Localisation is achieved by the broadband sweeps at the end of the call. The duration and bandwidth of the terminal sweep vary systematically in relation to target range, suggesting that the terminal sweep is used for ranging [39].

B.   Doppler effects are not only important for CF bats

Recently it has been proposed that many other bats may utilise Doppler shifts in sophisticated ways to minimise localisation errors [21]. To introduce how this works, it is first necessary to consider Doppler tolerance and signal design in bat echolocation. Doppler effects compress the time between the emission and reception of signals, and elevate echo frequencies. The pulse design that minimises Doppler effects is one that has a period which increases linearly over time (linear period modulation [42]). Such calls also show hyperbolic frequency modulation.

Echo analysis by bats is often quantified by using Cross Correlation Functions (CCFs). The CCF is representative of how bats might measure the delay between the call and the echo. The time-shift of optimal alignment is indicated by the peak in the CCF, and represents the optimal measure of delay (and hence range) between call and echo. Doppler shifts increase the frequency of echoes, and shifts the position of CCF peaks so that time delays between call and echo tend to increase, resulting in a perceived overestimate of target range (Fig. 5). Such Doppler ranging errors are minimised by using hyperbolic frequency sweeps. Because these sweeps also show a narrow CCF envelope, ranging acuity is also maximised by this type of signal.

Although Doppler shifts may cause bats to overestimate target range, bats also experience another ranging error during flight. A bat approaches a target between calling and receiving the echo. Because the distance that the bat flies reduces the distance that sound travels, the time of the echo delay is shortened. Consequently, when the echo is received, the target's range can be closer by half the distance flown than it was at the time of calling.

C.   Distance of focus

Bats therefore have the possibility of mutually cancelling these two ranging errors. In theory, bats could adjust signal design so that the Doppler-related range overestimation exactly compensates for the range underestimation caused by the bat's movement in flight. Whiskered bats *Myotis mystacinus* appear to modify call design in the ways predicted by the distance of focus theory. Calls were emitted that gave more distant DOF values when bats were flying further from a hedge (Fig. 6). The DOF in general underestimated the hedge distance slightly, perhaps as a safety precaution because an overestimation of range might increase collision risk. The bats clearly adjust call design in a range-dependent manner to minimise localisation errors at the distance of the target of interest. Analysis of call design showed that calls with lower bandwidths and longer durations had greater DOFs, and that bandwidth and duration affected DOF independently, as predicted in [40]. Doppler effects are relevant to bats that emit broadband echolocation calls as well as to CF bats. The two ranging errors only cancel at one distance, termed the 'distance of focus' (DOF) [43]. The DOF forms a sphere in front of the bat, and as shown in Fig. 7, depends critically on signal design. Steeper, more broadband calls have a short DOF, while more narrowband calls of longer duration have a greater DOF. Thus bats go to some lengths to ensure ranging accuracy under unambiguous conditions, an approach considered equally important in radar and sonar systems.

5. RELATIONSHIPS BETWEEN FLIGHT, ECHO LOCATION AND AUTONOMOUS NAVIGATION

Echolocation and flight occur simultaneously in bats, and flight performance feeds back to influence echolocation signal design. This seems to be a key component in total system performance and one not always exhibited in synthetic sensors. As described in the section on 'Pulse interval and repetition rate', bats typically produce one call per wing beat when searching for prey or commuting, because this minimises the cost of producing energetically expensive sound pulses. Autonomously-guided vehicles can obviously be free of this constraint, but must still solve the challenges of separating pulse and echo, either in time (as used by many bats), or in frequency (as used by species that use DSC).

One of the major issues facing pulse design for flying vehicles will be to consider the Doppler tolerance of the signal, and how Doppler tolerance might trade off against localization performance. One method to better understand this is to use ambiguity functions. Ambiguity functions have been used by radar and sonar engineers to better understand the performance of broadband echolocation signals used by bats (e.g. [41]). Wideband Ambiguity Functions (WAFs) of the calls of *Myotis mystacinus* were calculated by Lin [51]. Here, we show how this approach can be used to quantify Doppler tolerance and localization performance in a range of call designs. Of especial interest is the change in call design used by bats as they approach targets. During these 'feeding buzzes' the bat might be interested in changing its call design from one that gives good Doppler tolerance to one that optimises localization performance. Such analyses may be especially important for understanding tracking or landing manoeuvres by autonomously-guided vehicles.

The bat's ability to dynamically modify its call parameters in order to accomplish different goals is now discussed more in detail through the analysis of real feeding buzz sequences. As previously mentioned, the adaptive transmitted pulse design has significant benefits depending on the nature of the task to be undertaken. The parameters to be adaptively set include the central frequency f_c, the Pulse Repetition Frequency PRF between consecutive calls in a burst, the frequency modulation FM, the call duration T, its instant intensity and power spectrum PS.

A. Frequency modulations

Echolocating bats exhibit a wide range of frequency modulations. Nevertheless they have in common a portion of the pulse which sweeps a range of frequencies in order to increase the range resolution and, therefore, the ranging capabilities [52] Although well known we begin by introducing the linear frequency modulated waveform so that it may be compared with the hyperbolic modulation more usually employed by bats.

1)   Linear Frequency Modulation

Linear Frequency Modulated (LFM) signals are widely used in both sonar and radar applications, since they allow for a fixed transmission energy (related to the pulse length T), and therefore sensitivity, while increasing the signal bandwidth B by changing the pulse compression rate γ:

$$s(t) = rect\left(\frac{t}{T}\right)\exp\left[j2\pi\left(f_c t + \gamma t^2\right)\right] \tag{1}$$

where t is time and j is the imaginary unit. The instantaneous frequency is defined as the derivative of the phase of the signal. Therefore, the bandwidth (B) of the LFM signal is in the range delimited by the minimum and maximum frequencies spanned:

$$B = \left.\frac{\partial\varphi(t)}{\partial t}\right|_T = 2\gamma T \tag{2}$$

The spectrogram of a LFM pulse having $\gamma = -5\cdot10^6$ and a time length T = 20 ms is shown in Fig. 8.a. The total bandwidth is B = 30 kHz, yielding a range resolution $\Delta r = c/2\cdot B$ = 5.6 mm.

2)   Hyperbolic Frequency Modulation

The Hyperbolic Frequency Modulation (HFM) is often used by echolocating bats most likely because of the significant Doppler tolerance. The transmitted waveform depends on the initial and final frequencies (f_1, f_2) as follows:

$$s(t) = rect\left(\frac{t}{T}\right)\exp\left[j2\pi\left(\frac{-f_1 f_2 T}{(f_2 - f_1)}\right)\ln\left(1 - \frac{(f_2 - f_1)}{f_2 T}t\right)\right] \tag{3}$$

The synthesised bandwidth after pulse compression is then calculated as:

$$B = (f_2 - f_1) \tag{4}$$

In Fig. 8.b, the spectrogram and power spectrum of a HFM pulse are shown.

B. Doppler Tolerance and Wideband Ambiguity Function

As observed in Fig. 9, the Side-Lobe Levels (SLL) of the HFM are inferior to those of to the LFM pulse. The advantage of Non-Linear Frequency Modulation (NLFM) resides in the Doppler tolerance. The effects of Doppler shifts when considering narrowband signals can be treated as a frequency shift and the Narrowband Ambiguity Function can be corrupted [53]. For wideband signals, the effect is a compression or expansion of the transmitted signal, depending on the value of the Doppler compression factor η defined as follows:

$$\eta = \frac{c + v}{c - v} = \frac{1 + v/c}{1 - v/c} \tag{5}$$

where v is the relative speed between the system and the target. and c is speed of sound?

When the system is homing towards the target the relative speed is conventionally assumed positive and η greater than one. In Fig. 10, the Doppler effects on a LFM pulse are shown, describing the deteriorating CCF properties. Conversely, when HFM signals are transmitted, the CCF properties are significantly stable at different compression factors as shown in Fig. 11.

To understand in more detail the effects of the Doppler compression factor on the cross correlation properties between the transmitted and received signals, the Wideband Ambiguity Function (WAF) is introduced [54]:

$$\chi(\eta, \tau) = \sqrt{\eta}\int s(t)s*(\eta(t - \tau))dt \tag{6}$$

where η is the Doppler compression factor defined above and τ is time delay (which is easily converted to range). In Fig. 12, the WAF of a LFM chirp (*a*) is compared with the WAF of two HFM (*b, c*) and CF (*d*) pulses. The WAF is plotted in dB scale over range and Doppler compression factors. The range (Doppler) resolution can be evaluated by taking a cut at a fixed Doppler compression factor (range) and measuring the distance between the -3 dB points. For the LFM pulse, the range resolution deteriorates at low compression factors (i.e. low Doppler tolerance). Small and constant curvatures for the HFM pulse (e.g. Fig. 12.b) exhibit a higher range resolution although there is a higher Doppler ranging error of the actual position of the point-scatterer as explained in Section 4. The hyperbolic curvature effect on range resolution can be observed in Fig. 13, where a series of HFM pulses has been simulated synthesising the same bandwidth.

The choice of the curvature is therefore adapted depending on the flight conditions and must be taken into account when the object is a fixed obstacle for instance (high η) and high Doppler tolerance is required, or if the goal is accurate ranging measurement of a target.

C. Stepped-Frequency Techniques and Multiharmonic Calls

The information that can be derived from the higher harmonics leads to high range resolution and can be successfully used to attempt target shape classification. Indeed this may form part of the strategy used by bats for recognition of very small targets or fine target features [48]. In radar technology, to achieve high range resolution the Stepped-Frequency technique is used [55]. The procedure consists of transmitting a burst of compressed pulses at different centre frequencies. The received signals are subsequently shifted in the Frequency Domain and finally combined synthesising a wider bandwidth. Multiharmonic signals have

the property that each frequency swept by a harmonic is replicated by the higher order harmonic and spaced by an octave. Since the second order harmonics generated by bat calls often only slightly overlap in frequency with the fundamental it might be possible that harmonics are used to refine range resolution and reduce range ambiguities.

D.   Real 'feeding buzz' analysis

The analysis is now extended to real data measurements from feeding buzz sequences. The time series spectrogram of the *Eptesicus nilssonii* is shown in Fig.14. The dynamic PRF changes between the search, detection and recognition phases. The curvature of the HFM also changes from being dominated by a long, almost CF component to a more LFM shape. The single pulse WAFs have been processed for each call, showing the range and Doppler resolution at different phases. In particular, as soon as the bat gets closer to the target, it is clear that the waveform is adapted in order to emphasise either range or Doppler information.

In Fig. 15, an example of a pulse from the search phase prior to the final stage of the feeding buzz from *Eptesicus nilssonii* is shown. The fundamental harmonic contains most of the energy as can be seen from the spectrogram. The hyperbolic frequency modulation is used for ranging, while the long CF component can be exploited to perform moving target detection of and subsequently recognition. The WAF exhibits high range tolerance and Doppler accuracy. During this phase, large Doppler shifts are not tolerated. After detection and classification, the pulse length is progressively reduced as the bat approaches the prey. This is due to the ambiguity constraints imposed by the SOZ. The PRF also decreases as a consequence of the need to iteratively refine range information with increasing temporal rate. The resulting rise of multi-pulse range ambiguities has no effects since the prey has already been located.

As the position in the 'mission' progresses (Fig. 16), the prey is recognised as a potential target and the approach phase commences. The third harmonic energy is attenuated, and the fundamental and second harmonics overlap for a small range of frequencies. The range resolution increases while the Doppler resolution is significantly reduced (as the classification phase has been completed). The waveform subsequently becomes highly Doppler tolerant to allow very accurate ranging for a wide range of Doppler compression factors since the distance between the bat and prey is low enough that even slight trajectory changes would produce large Doppler ranging errors between consecutives pulses.

During the terminal phase, the power and PRF are sensibly reduced to minimise energy expenditure. The resolution is maintained in range only and very high Doppler tolerance obtained (as a consequence of the reduced pulse length, since the frequency modulation is rather linear). The fundamental and second harmonics are separated in frequency as can be observed from the power spectrum, where the two centre frequencies can be isolated (Fig. 17).

Similar results and trends have been found in a feeding buzz for the *Pipistrellus pygmaeus* feeding buzz series (Fig. 18). As can be seen from the spectrogram, the pulse is hyperbolically modulated and the energy is mostly concentrated on the fundamental harmonic. As observed for the *Eptesicus nilssonii*, the central frequency is progressively reduced during the terminal phase, as well as the PRF and the call intensity. The quasi CF component is also gradually removed while the HFM pulse duration reduced, leading to a fast linear frequency sweep.

The wideband ambiguity analysis of the first four pulses (Fig. 19) of the time series shows that the resolutions in range and Doppler are equally of interest during the detection and classification phases. Nevertheless, the first WAF suggests that the bat is attempting to detect moving targets by exploiting the Doppler and micro-Doppler effects, information difficult to be retrieved when Doppler tolerant waveforms are used. As soon as the prey is detected, the recognition phase still requires significantly detailed Doppler information and, meanwhile, the target has to be accurately located with progressive increase of range resolution in order to prepare the approach and terminal phases. As a consequence, the WAF plots rotate towards the Doppler compression factor direction. When the bat is close enough to the prey that any minimal change in the prey trajectory produces significant Doppler compression variations, the information about the target velocity is no longer required because of possible ambiguities.

During the approach phase, the WAF contour shows that the waveform is designed in order to obtain high matched filtering response for a wide range of Doppler compression factors, so that the range-Doppler coupling is consistently reduced. The call duration reduction, necessary to reduce the SOZ, has the effect of strengthening the Doppler tolerance resulting from HFM.

E.   **Target Recognition**

The wing beat of the prey produces glints in amplitude and regular oscillations in the time-frequency domain (micro-Doppler effects). The recognition of the target is therefore attempted using both the spatial separation of glints in range and the periodicity and amplitude of the micro-Doppler effects on the received echo. The multiplicity and diversity of backscattering analysis is exploited by echolocating bats by also processing other diversity sources such as:

• Binaural echo processing: as well as azimuth positioning through time difference of arrival, the echoes scattered towards slightly different directions provide different features to discriminate targets. The procedure is similar to the principles of bistatic radar systems and bistatic target classification [56] for relatively small bistatic angles.

• Multiple perspectives: the multiplicity of aspect angles sensing the prey are a source of target information which has recently been investigated for sonar and radar systems [57].

• Multiple frequencies: the use of a multiharmonic signal allows for the illumination of the prey with different ranges of frequencies. The backscattering description is therefore more detailed since the texture and elementary scattering structures behave differently when the target is illuminated with different wavelengths. In radar and sonar these aspects have also been investigated [58].

It appears that the target recognition task should not be thought as a set of different sources of information separately contributing to the target classification goal but as a group of parameters that are tuned interactively depending on the environment condition (distance and relative trajectories) and on the features of the prey (size, wing beat, behaviour).

6. AUTONOMOUS NAVIGATION STRATEGIES

The adaptive call design of mammals seems to have significant implications for improvements in autonomous navigation strategies and obstacle avoidance algorithms using synthetic systems such as sonar and radar.

Autonomous Navigation Systems (ANSs) comprise Autonomous Underwater Vehicles (AUVs) and Unmanned Aerial Vehicles (UAVs) which are not remotely controlled. The main applications of unmanned vehicles are remote sensing, reconnaissance, imaging, attack and, for AUVs, the interaction with undersea objects. The affinity between such tasks with the tracking and capture phases of bats and the similarities between the principles of sonar and radar systems with biological echolocation motivate the idea of investigating bat's calls and behaviour in order to understand possible key aspects to be potentially replicated and navigation capabilities improved.

ANS can be seen as the combination of positioning and steering behaviours also identified as *global* and *local positioning*. The former can be accomplished using satellite navigation systems (i.e. GPS, GLONASS and NAVSTAR) and aided by Inertial Measurement Units (IMUs). When the ANS is underwater, the microwave satellite signals do not propagate, a surface support reference will act as beacon while the UAV measures its position acoustically using Baseline (BL) systems. Conversely, steering behaviours are related to a local scenario and require the perception and the interaction with the environment through the use of multiple sensors. Although ANS are often investigated using Control Theory, here we try to combine it with an artificial intelligence analysis inspired by human and animal behaviours. The list of steering behaviours made by Reynolds [59] in the field of autonomous character motion can be applied to a number of ANS applications. These include:

•   **Seek and Flee**: the system moves towards or away from a fixed goal point. Therefore, accurate ranging has to be performed. Time delay ranging would provide for along-track resolution, while a binaural inspired system measuring the time difference of arrival would give cross-track resolution. This function can also be combined with "sequential-lobing" (an azimuthal alternation of the antenna mainlobe with respect to the boresight line) or monopulse operations (amplitude or phase difference of arrival). The waveform for these tasks may be a wideband short HFM pulse which guarantees significant Doppler tolerance, necessary because of the high system-target relative velocity.

– **Seek**: the pulse length, when seeking, needs to be progressively reduced in order to decrease the SOZ. Moreover, the Distance of Focus (DOF, see section 2) has to be taken in consideration. The effects of backward masking (see Section 2) from clutter in radar systems (from ground or sea) and reverberation in underwater sonar systems (from surface, seabed or volume scattering) has also to be taken into account although possibly attenuated by high directivity antennas for the seek behaviour.

– **Flee**: the signal intensity for this task needs to be gradually increased because of the propagation spreading loss (reduction in power density associated with spreading of the power over a sphere of radius equal to the target-system range).

• **Pursue and Evade**: similar to seek and flee with the difference that the target is moving and its location at the moment of capture has to be predicted on the basis of the previous motion and position parameters of the target. The ranging capability has to be therefore integrated with enough Doppler resolution in order to retrieve the three rotational motion parameters of the target (roll, pitch and yaw).

• **Offset pursuit**: the system pursues the target and stays at a specified distance without eventually colliding. This steering behaviour requires an accurate Doppler and range information acquisition. Since the system-target relative velocity must be maintained close to zero, a low Doppler tolerance would be acceptable in this case. The offset distance is a key parameter for the waveform design since it affects the SOZ, therefore the pulse length, the signal intensity and the process to obtain Doppler information: the pulse length (mostly the CF component of HFM pulse) may be increased in order to refine Doppler information, bearing in mind the limits given by forward masking, strictly dependent on the offset distance. The waveform needs to be designed also to give a DOF equal to the system-target distance. Moreover, the need of updating the target rotational and position parameters will increase the PRF enough to avoid range ambiguities since the *a priori* knowledge of the expected target position from previous measurements.

• **Random Steering – wandering – exploring**: these behaviours are related to scenarios where the goal has not been specified yet. Wandering behaviour is a type of random steering, exhibiting smoothed trajectories. This behaviour can be associated with detection. As a consequence, as seen for the bats, the waveform might have to be characterised by a high intensity long duration HFM pulse for ranging and a CF component for moving target detection. The PRF needs to be tailored to the maximum range where a target can be detected.

• **Arrival**: the target is stationary and the goal is to seek the target whilst progressively reducing speed. This steering behaviour requires the same considerations of seeking a target from a perceptual perspective. The only difference is that the system needs a reliable measure of its own velocity which could be provided by global positioning.

• **Obstacle and Collision Avoidance**: the system needs to avoid fixed (Obstacles) or moving targets (Collision). The concept is similar to flee and evade behaviours with the exception that that the system has to avoid collisions instead of steering away from the object. This task is often combined with other steering behaviours. As a consequence, the waveform has to be designed as a compromise between different requirements. If, for instance, the obstacle avoidance is combined with offset pursuit, since the stationary obstacle is stationary, the system will have to discriminate between the two Doppler compression factors transmitting a waveform allowing for the optimal compromise between Doppler resolution and Doppler tolerance. The problem of different objects' DOF while focusing a single distance may constrain the system to alternate between different waveform designs.

• **Containment**: the goal is to keep the system confined in a particular region, so that obstacle avoidance is involved. As soon as the region is sufficiently explored, the system will preserve a rough 3-D "image" which is only refreshed by a few references after its acquisition as the human behaviour would suggest.

• **Path Following**: is a type of containment, where the goal is to follow a defined route, maintaining a minimum distance from it.

• **Wall Following**: similarly to the offset pursuit, the system steers in order to keep a constant distance from a wall. This is done by predicting the system position and steering depending on it. Pulse length and duty cycle, PRF, DOF, SOZ and call intensity are tuned depending on the system relative

velocity and the distance from the wall. This last measurement needs to be updated again with respect to the system relative velocity and its prediction evaluated through recursive filters widely used in Control Theory (i.e. Kalman filter).

This list of steering behaviours only represent a set of primitives that in a typical real environment are combined in order to represent a more complicated task.

7. CONCLUSIONS

The behaviour and performance echolocating bats in terms of detecting, locating, tracking and capturing prey have been investigated. The most significant key aspects for autonomous navigation have been identified that relate to the design of the transmitted waveform and their dynamic adjustment as a function of flight trajectory. This is also evident through the wide range of frequency modulations used by different bat species (CF, LFM, HFM), a number of parameters are set depending on the particular task to be carried out. The facility for changing the bandwidth of the transmitted call within a feeding buzz sequence, reducing the illuminating frequency, modifying the pulse repetition interval, the call intensity and pulse length is undoubtedly a sign of important waveform diversity design which may provide insights into the development of more reliable autonomous systems. It should also be noted that this analysis has only considered transmitted calls whereas, of course, the real information will be embedded in the received calls. Additionally the received calls a re processed via two ears (receivers). These aspects will be the subject of future studies.

8. ACKNOWLEDGEMENTS

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**Biologically Inspired Waveform Diversity
for Synthetic Autonomous Navigation Sensing**

Echolocation call type	Bat species (Family)	Spectrogram	Bat species (Family)	Spectrogram
	Yinpterochiroptera		Yangochiroptera	
(a) No echolocation	Cynopterus brachyotis (Pteropodidae)			
(b) Brief, broadband tongue clicks	Rousettus aegyptiacus (Pteropodidae)			
(c) Narrowband, dominated by fundamental harmonic			Lasiurus borealis (Vespertilionidae)	
(d) Narrowband, multiharmonic	Rhinopoma hardwickii (Rhinopomatidae)		Taphozous melanopogon (Emballonuridae)	
(e) Short, broadband, dominated by fundamental harmonic			Myotis daubentonii (Vespertilionidae)	
(f) Short, broadband, multiharmonic	Megaderma lyra (Megadermatidae)		Mystacina tuberculata (Mystacinidae)	
(g) Long, broadband, multiharmonic			Myzopoda aurita (Myzopodidae)	
(h) Constant frequency	Rhinolophus ferrumequinum (Rhinolophidae)		Pteronotus parnellii (Mormoopidae)	
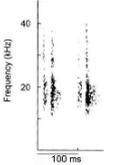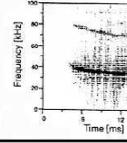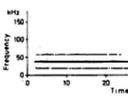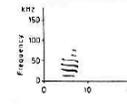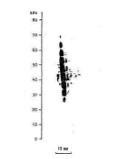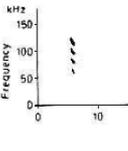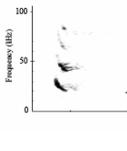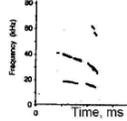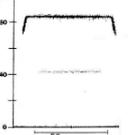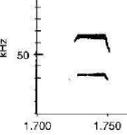
Figure 1 The diversity of echolocation calls in bats. Bats are divided into the suborders Yinpterochiroptera and Yangochiroptera, as supported by the emerging molecular consensus. As well as illustrating the adaptive radiation of call types within these clades, examples of convergence can be seen for narrowband, multiharmonic; short, broadband, multiharmonic; and constant frequency signals, with bats in both clades producing these calls. Taken from Jones and Teeling [3].
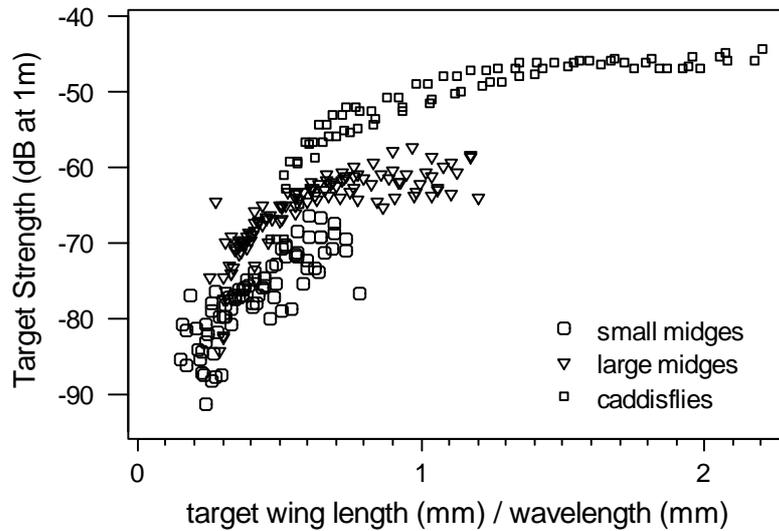
Figure 2 Insect target strength when ensonified by tone pulses at frequencies between 20 kHz and 85 kHz. The x-axis shows the ratio between an arbitrary linear dimension of the target (wing length) and the wavelength of ultrasound. 'Small midges' (chironomids): wing length 2.6–3.1 mm, 'large midges' (chironomids): 4.0–5.0 mm, caddis flies: 8.0–9.0 mm [19].
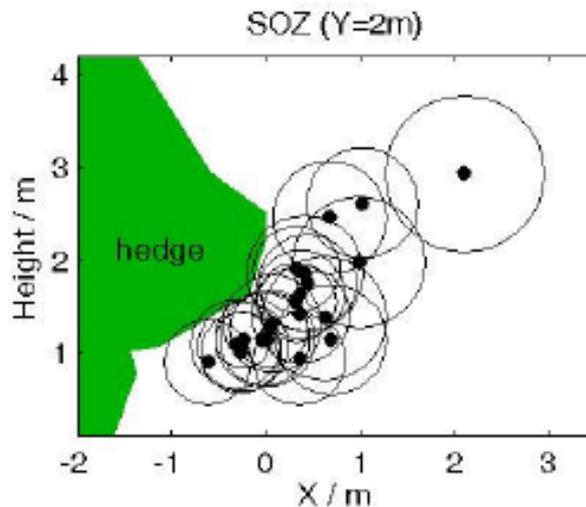

Figure 3 Signal overlap zones (SOZ) from calls emitted by whiskered bats *Myotis mystacinus* flying along a hedgerow. The SOZ is always less than or close to the target of interest (the hedge), so that the bats avoid overlap between outgoing pulse and the returning echo. If the SOZ extended into the hedge, the echo would be masked by the outgoing call [21].
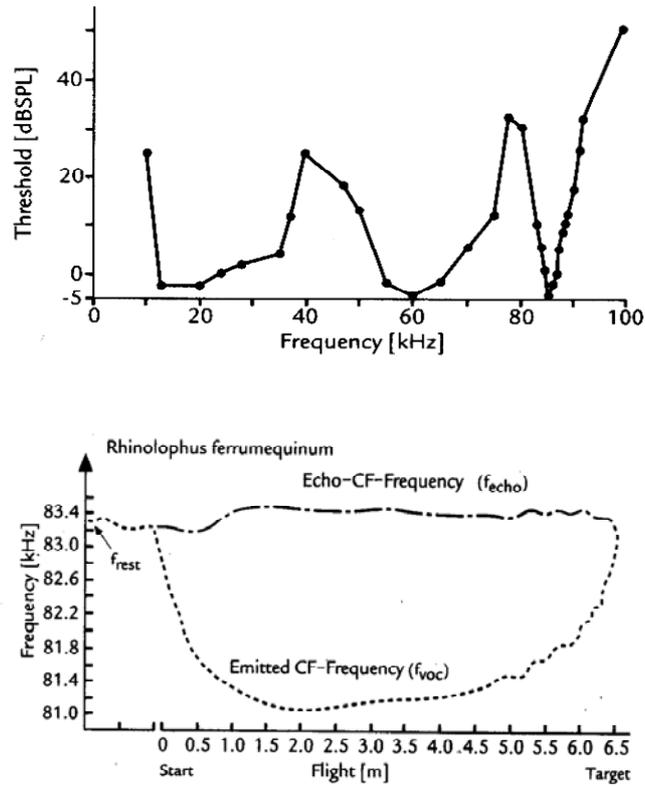
Figure 4 Top- behavioural audiogram of a greater horseshoe bat *Rhinolophus ferrumequinum*. Note the focused sensitivity at 83 kHz, the 'acoustic fovea' [36]. Bottom – Doppler shift compensation by *Rhinolophus ferrumequinum*. The graph shows the emitted frequency (dotted line) and the frequency heard by the bat (dashed line) as it flies from its starting position to a target. During flight, the emitted frequency is lowered as the bat flies faster so that the bat compensates for Doppler shifts induced by its flight speed, and hence the frequency returning to the bat is relatively constant at the frequency of the acoustic fovea [37]. (f_{rest} ≡ frequency emitted before takeoff.)
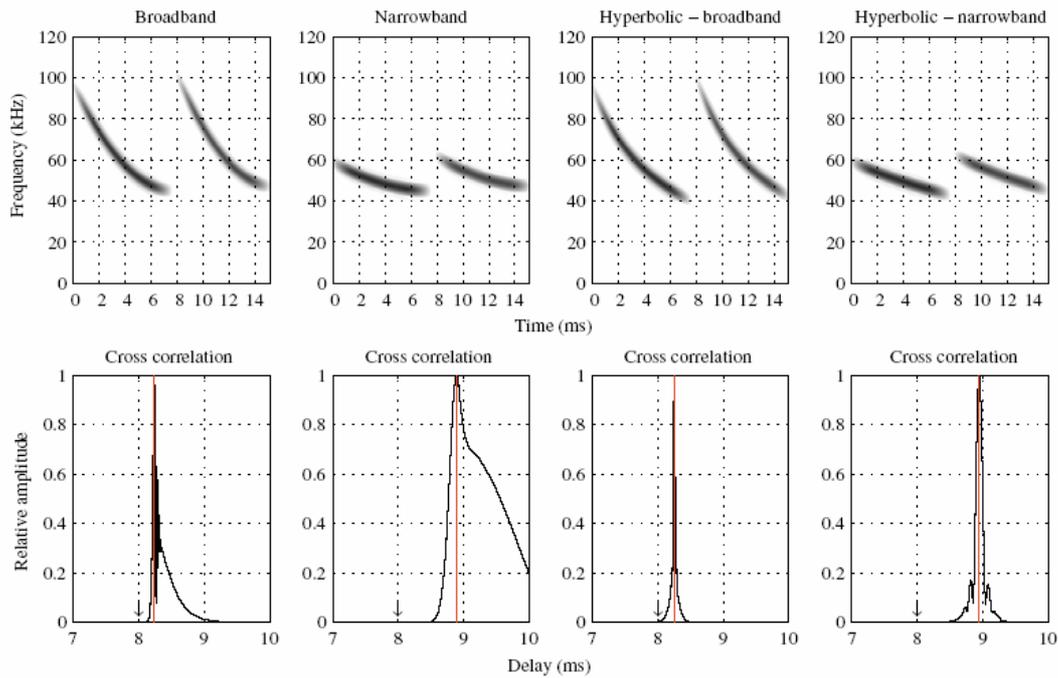
Figure 5 The influence of signal design on Doppler-related ranging errors at a flight speed of 8 m/s. The upper row shows spectrograms of pulse-echo pairs. The lower row shows the cross correlation function (CCF) between call and echo. Arrows indicate the actual time delay of 8 ms between call and echo. Red vertical lines show the peak of the CCF. Note how in each case the delay is overestimated by the CCF. This difference (the Doppler ranging error) is minimised in the call with hyperbolic-broadband modulation. The narrow CCF envelope for this signal also shows that the pulse has high ranging acuity [21].

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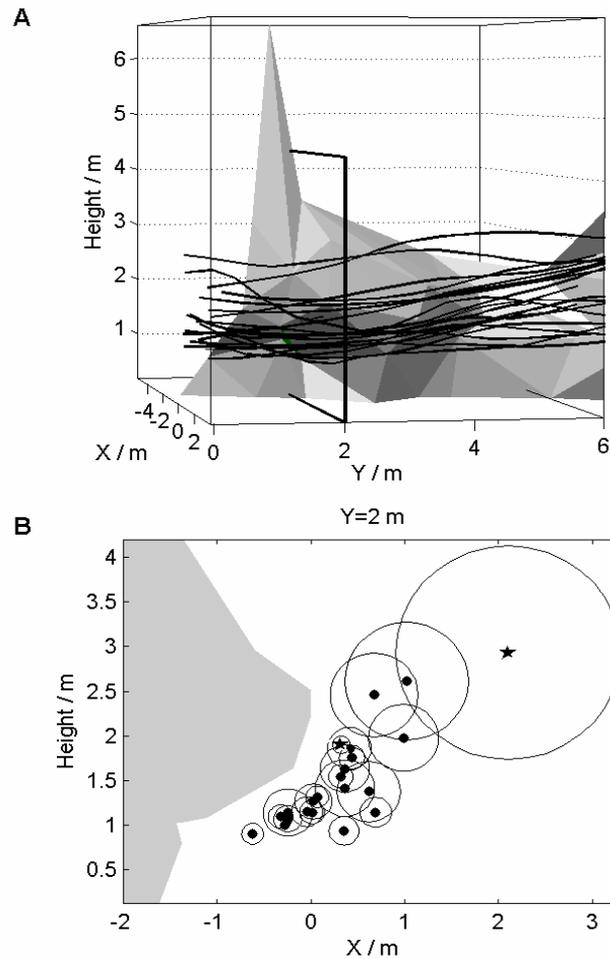
Figure 6 Distance of focus in relation to distance from a hedge: data for *Myotis mystacinus*. A: three-dimensional representation of the flight paths of 22 bats and of the hedge they were flying along. The rectangle at Y=2 m indicates size and position of the cross section shown in B. B: cross section through hedge and flight paths as indicated by the rectangle in A. Symbols show where each individual bat has passed the cross sectional plane. Circles around symbols have a radius that equals the distance of focus of the call emitted by the particular bat closest to the cross sectional plane. Stars indicate where the two calls shown in greater detail in Fig. 7 (A and C) were emitted [21].
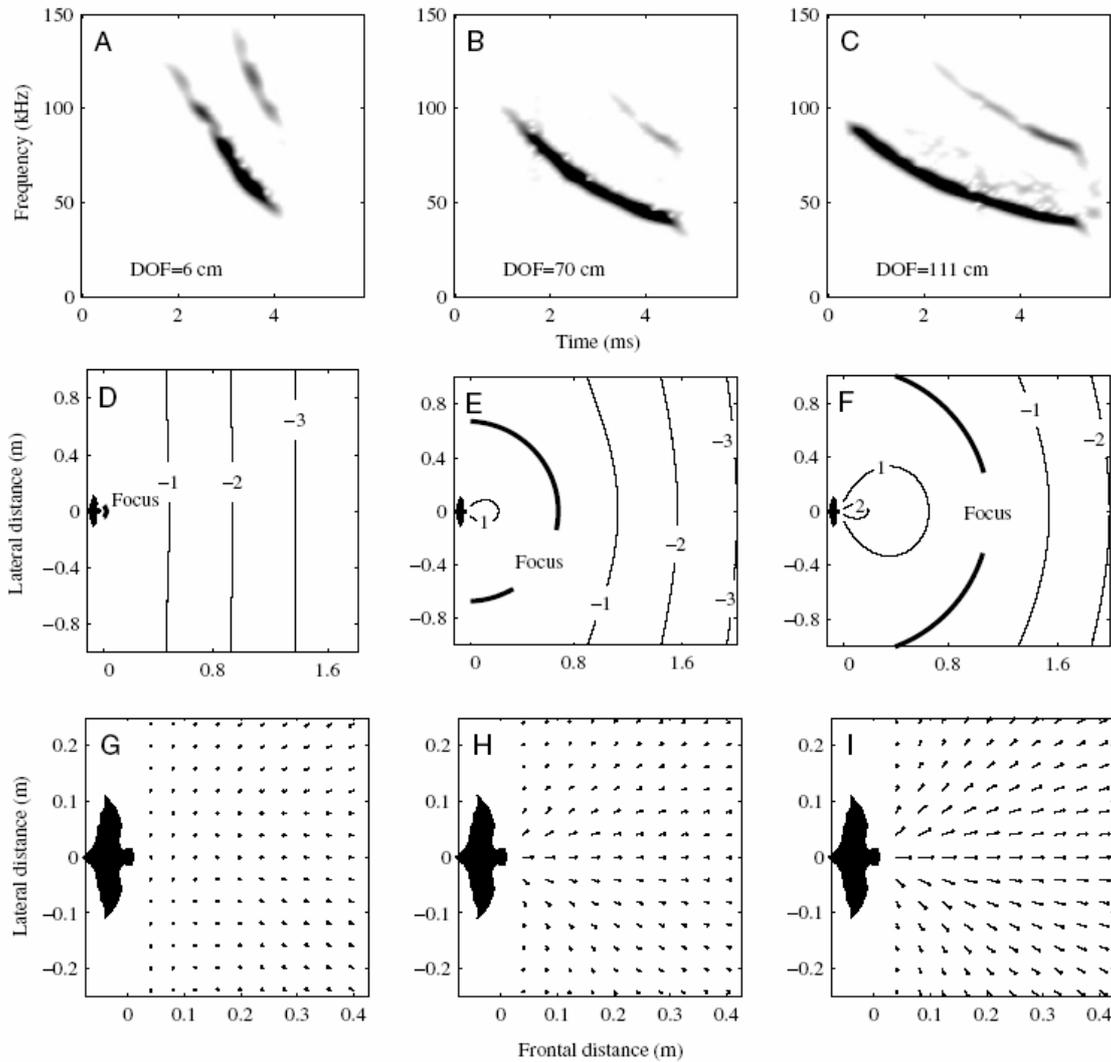
Figure 7 Three examples of the effect of call design on ranging errors for *Myotis mystacinus*. (A–C) Spectrograms (FFT size 512, 256·points Hanning window, 240 points overlap). DOF indicates the distance at which overall ranging errors were zero. (D–F) Ranging errors calculated for these calls and indicated as lines of identical error. Labels on lines indicate size of ranging error in centimetres (>0 represents overestimation and <0 represents underestimation of distance). The thick line labelled 'focus' indicates locations where the overall ranging error is zero. (G–I) Ranging errors as in D–F but for a smaller distance range. 'Pinheads' indicate perceived positions and 'pin tips' the actual positions of targets [21].
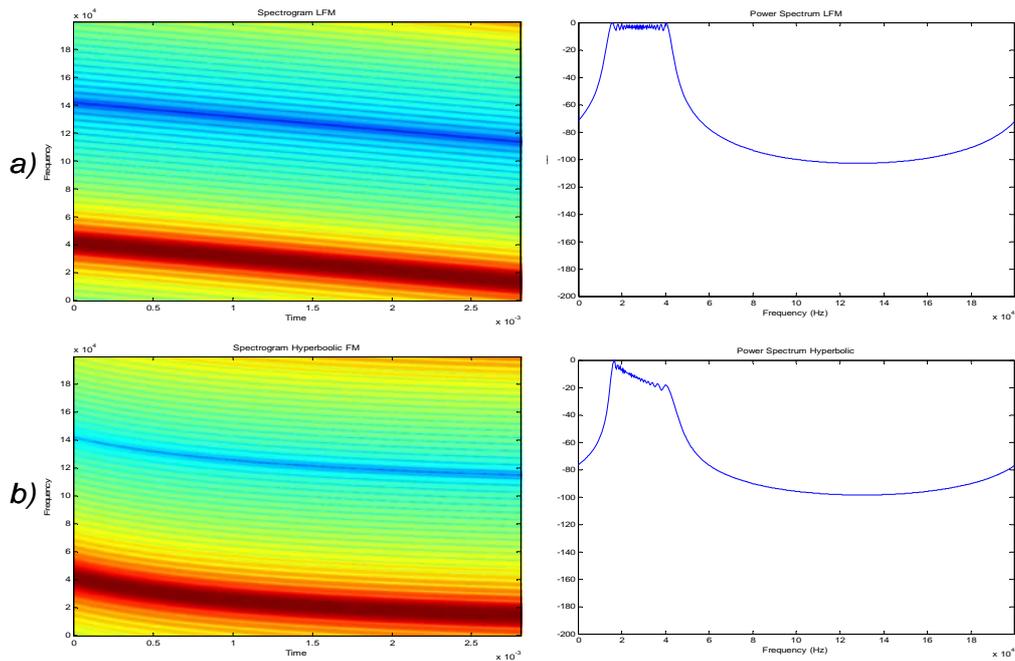
Figure 8 (a) Spectrogram and power spectrum of a Linear Frequency Modulated (LFM), and (b) Hyperbolic Frequency Modulated (HFM) pulses, having T = 20 ms, bandwidth is B = 30 kHz, and yielding Δr = 5.6 mm.
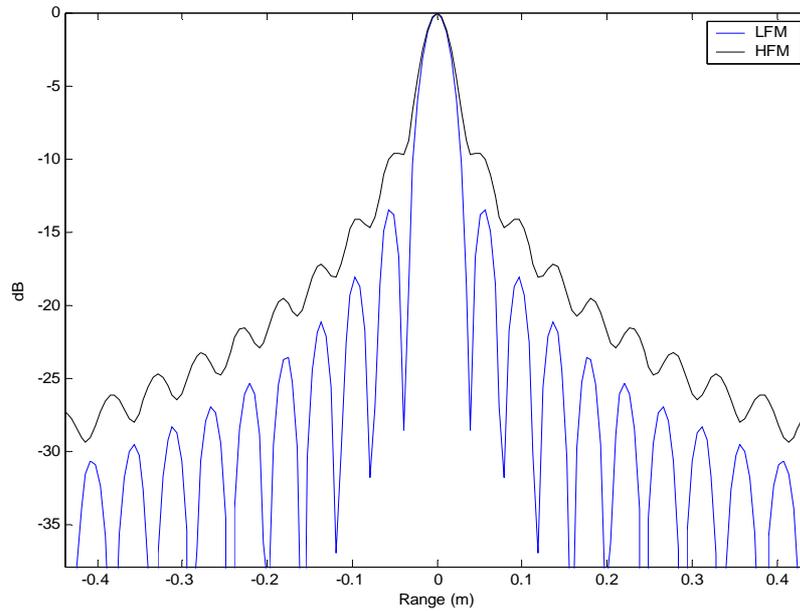

Figure 9 Range profiles after matched filtering for LFM and HFM signals. The SLL levels are deteriorated using non-symmetrical non-linear frequency modulations, although the resolution (-3dB points) remain unaltered.

1. Transmitted signal (Doppler Compression Factor = (1+v/c)/(1-v/c) = 1)
2. Received echo from an approaching target (Doppler Compression Factor = 1.6)
3. Received echo from a departing target (Doppler Compression Factor = 0.6)
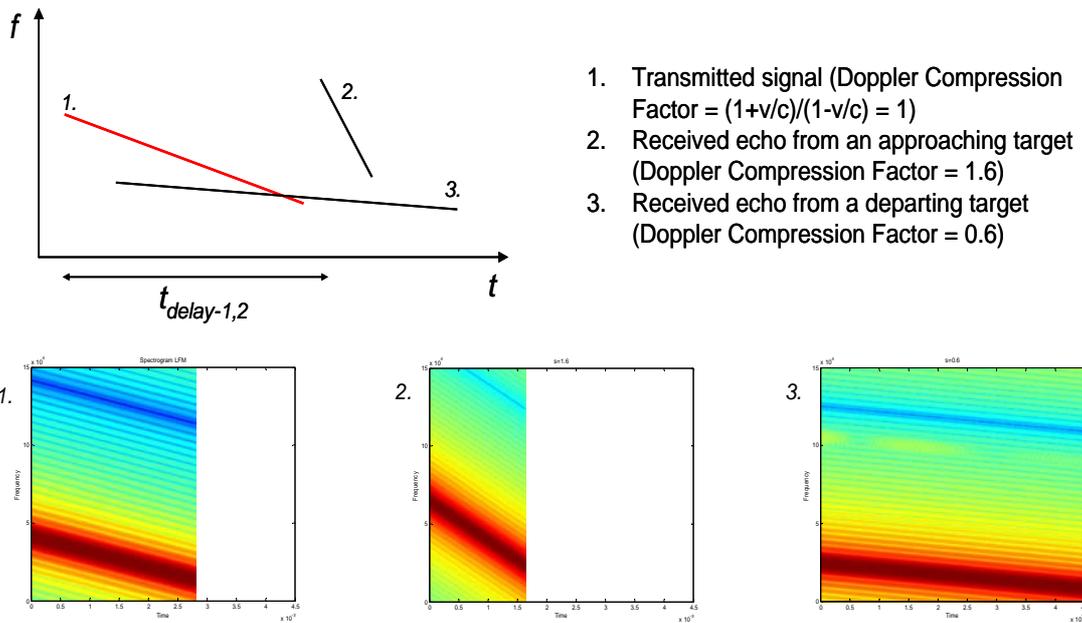
Figure 10 Two received signals from LFM illuminated point-scatterers at different velocities. The relative velocity changes the slope of the pulse, reducing the cross-correlation between transmitted and received pulses, and therefore the output of the matched filter.


1. Transmitted signal (Doppler Compression Factor = (1+v/c)/(1-v/c) = 1)
2. Received echo from an approaching target (Doppler Compression Factor = 1.6)
3. Received echo from a departing target (Doppler Compression Factor = 0.6)
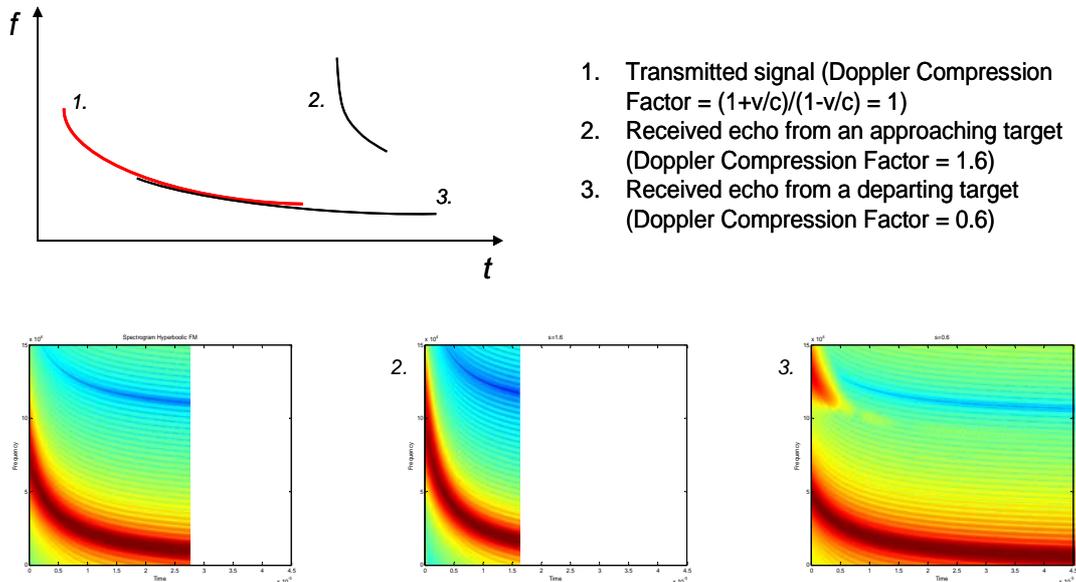
Figure 11 The correlation between transmitted and received pulses from a point-like scatterers at different velocities.

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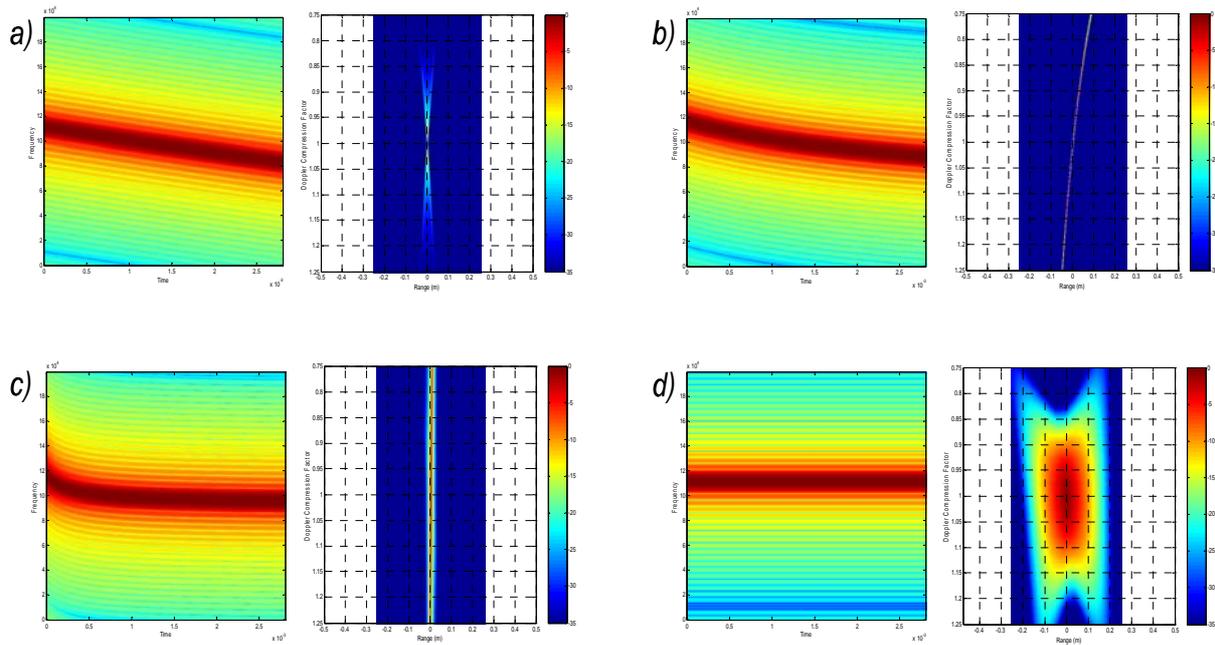
Figure 12 Spectrograms and WAF computed for different frequency modulations. The LFM (a) and HFM (b, c) synthesize the same bandwidth, while the CF (d) a pure tone. The two HFM pulses differ for the different curvature: a transient curvature followed by a CF component show more robust Doppler tolerance although lower range resolution.
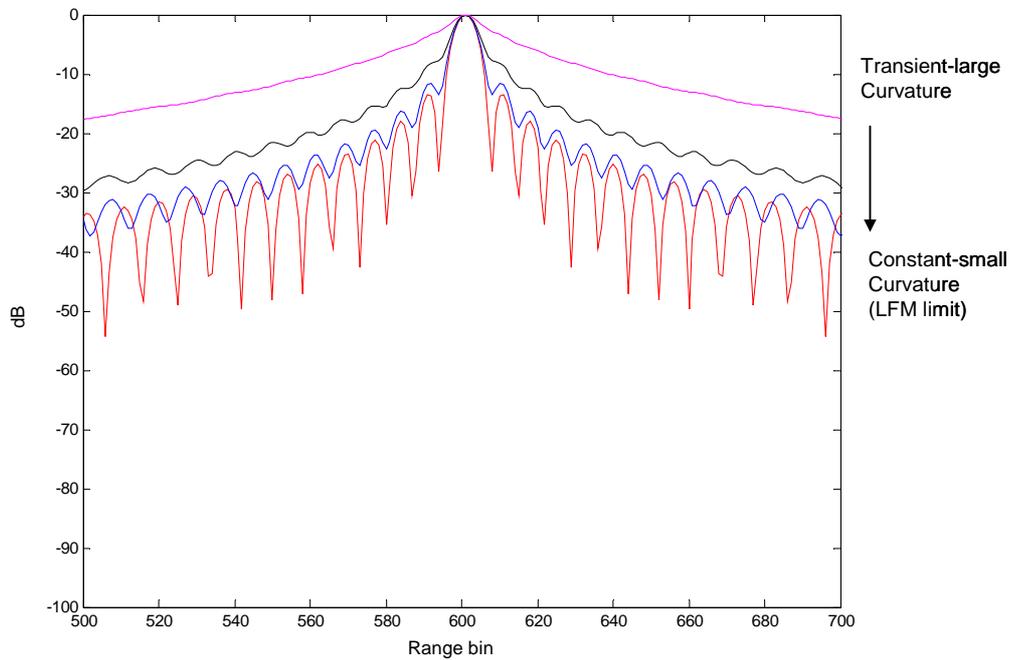
Figure 13 Large and transient curvatures in HFM give deteriorated range resolution and side-lobe level but significant Doppler tolerance. Vice versa, small and constant curvatures yield high range resolution, although higher Doppler range migration
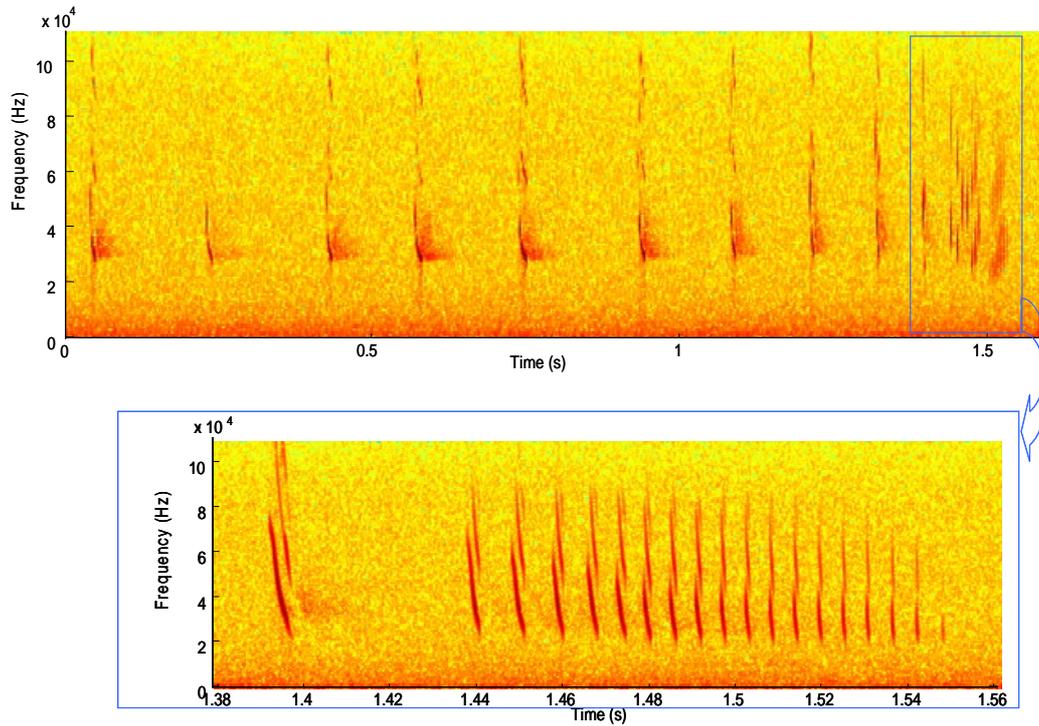
Figure 14 *Eptesicus nilssonii* time series spectrogram. As explained in Section 2.6 a drop of the central frequency can been observed during the Buzz II part of the terminal phase (blue box). Moreover, the call intensity is progressively reduced as the bat approaches the prey (AGC) and the multiharmonic structure becomes a single wideband signal.
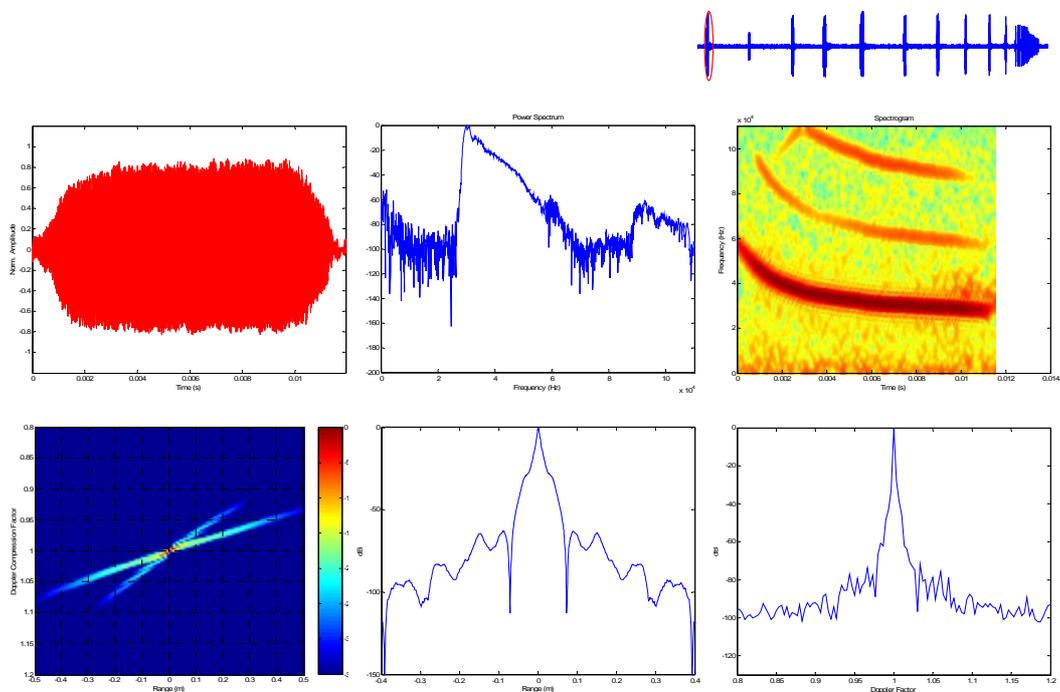
Figure 15 *Eptesicus nilssonii*: search phase pulse analysis. The first chirp of the time series is analysed in its Time Domain representation, power spectrum, spectrogram, WAF, range and Doppler profiles.

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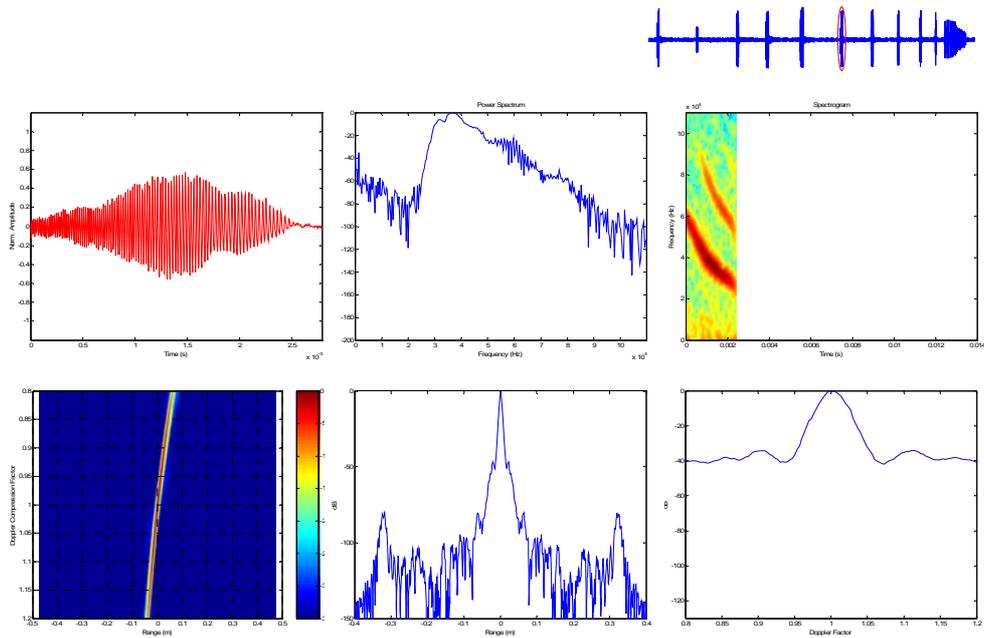
Figure 16 *Eptesicus nilssonii*: approach phase pulse analysis.
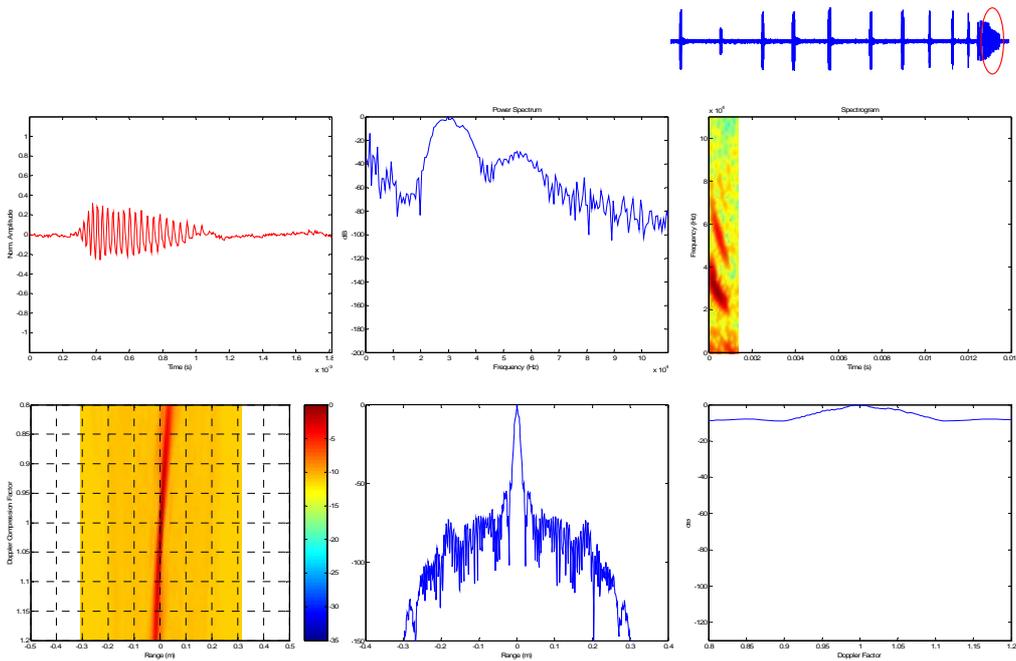
Figure 17 *Eptesicus nilssonii*: terminal phase pulse analysis.
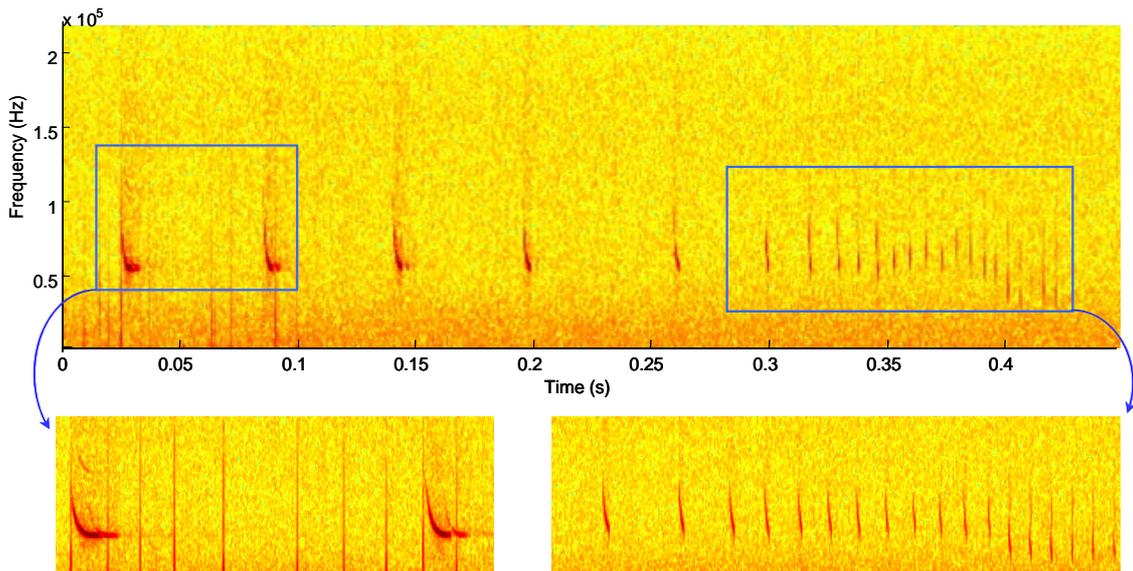
Figure 18 *Pipistrellus pygmaeus* time series spectrogram. The hyperbolic modulation becomes a fast linear chirp during the terminal phase. Strong echoes (possibly due to stationary clutter) can be distinguished after the first and second pulses. Vertical clicks on the spectrogram are heterodyne signals from the other channel of recording.
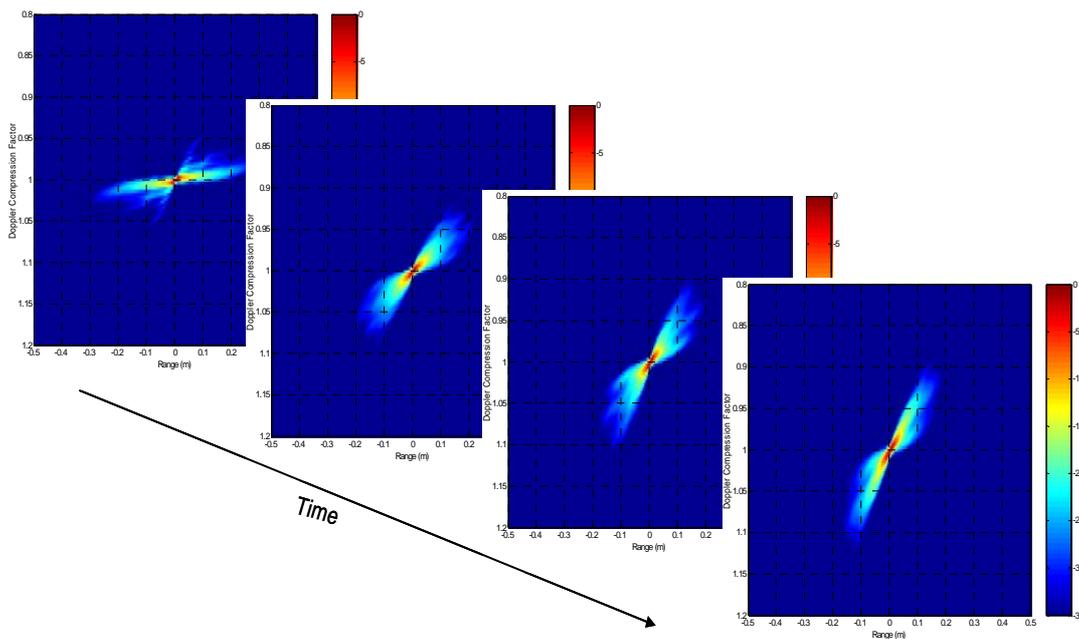
Figure 19 WAF analysis of the first four pulses from the *Pipistrellus pygmaeus* feeding buzz sequence. The range resolution is gradually increased to the detriment of the Doppler information.