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# Lessons for Radar

## [Waveform diversity in echolocating mammals]

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 existed for fewer than 100 years. Given the extraordinary capability of echolocating mammals it seems self-evident that designers of radar (and sonar) systems may be able to learn lessons that may potentially revolutionize current radar-based capability leading to truly autonomous navigation, collision avoidance, and automatic target classification. Echolocating mammals have been little studied in relation to the operation of radar and sonar systems. In this article, we introduce a range of strategies employed by bats and consider how these might be exploitable in the radar systems of tomorrow. Specifically, we concentrate on the functions necessary for autonomous navigation. Echolocating mammals are known to vary their waveforms via modification to the pulse-repetition frequency (PRF), also known to biologists as pulse-repetition rate (PRR), power, and frequency content of their transmitted waveforms. This has enabled them to evolve highly sophisticated orientation techniques and the ability to successfully forage for food. Moreover, recent developments in technology mean that it is now possible to replicate these parametric variations in synthetic sensing systems such as radar and sonar. By examining the behavior of echolocating mammals, we may gain potentially valuable insights enabling improvements in the performance of their synthetic counterparts, i.e., radar and sonar systems. This likely leads radar and sonar led robust capabilities such as autonomous navigation and automatic target classification. In this article, we examine the waveform strategies used by bats as a function of orientation and intent contrasting

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strategies adopted for waveform design with those currently employed by radar systems. In particular, techniques and metrics typically employed in the design and analysis of radar systems are employed to help translate observations into a radar-meaningful context. This enables an understanding as to how bats are exploiting waveform diversity and how this can be exploited in future radar and sonar systems for applications.

Finally, we review how bats control and vary their emitted waveforms. This provides valuable insights as to how such parametric variations may be exploited in synthetic systems. Mammals such as bats use echolocation to perform autonomous navigation (or more strictly orientation), detection, and classification of targets and often in highly cluttered environments. The properties of the transmitted and received waveforms are quite wide ranging but can be easily replicated in synthetic sensing systems (such as sonar and radar) using currently available technology. 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 echolocating mammals. This is inhibiting the development of capabilities such as autonomous navigation and hence preventing their gainful exploitation. We investigate the very able autonomous orientation performed by bats in an attempt to identify the key aspects that can help move towards truly autonomous systems on a much more reliable and robust basis. Initial investigations suggest that a combination of flight profile, waveform diversity, and multialgorithmic nonlinear processing are all important ingredients to success. We have concentrated on these aspects here, quantifying their properties and evaluating their role in determining navigation and obstacle avoidance methodologies. 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 leads to a much wider variety of applications in areas as diverse as robotics, remote sensing, counter terrorism, sensor networks, and transportation.

The signals exploited by bats take a variety of forms having evolved over an immense period of time. Fossil bats found around 53 million years ago (Mya) are thought to have possessed at least basic echolocation, although a fossil bat found recently in deposits of a similar age was hypothesized to be unable to echolocate because its cochlea was not especially enlarged. It is currently hypothesized 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 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]–[4]. All bat species in the remaining 18 families of bats currently recognized (>800 species) are known to use laryngeal echolocation, at least for orientation and often for the detection, localization, and classification of prey. This wide variety of species together with their wide geographic distribution also suggests that we would expect to see a wide range of techniques employed when examined in detail.

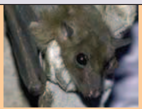
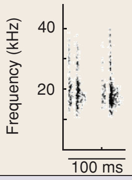
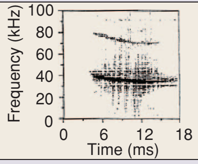
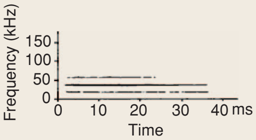
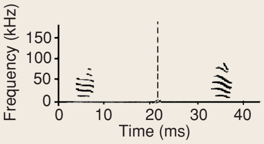
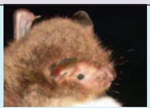
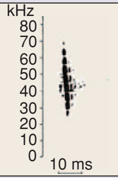
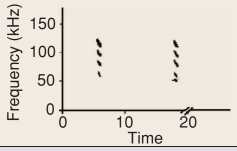
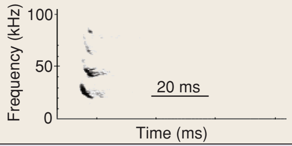
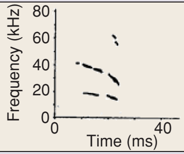
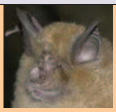
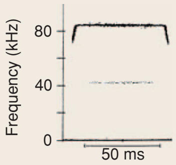
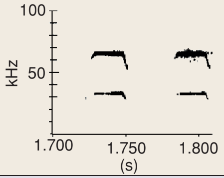
Signal designs as categorized by [4] are shown in Figure 1, with illustrations of their occurrence in selected families in the two major divisions of bats currently recognized. Figure 1, although not exhaustive, is illustrative of the diversity of waveforms used by bats in echolocating and this will be examined in more detail later in the article. The categorization is based around signals emitted when bats are searching for prey: intraspecific (and indeed intra-individual) variation in call design can be substantial, and the scheme was introduced to illustrate patterns of convergent evolution. Some physical factors that determine call design are: call intensity, harmonic structure, call frequency, bandwidth, call duration, pulse interval, and repetition rate and duty cycle. These are all parameters that could be varied on a pulse-by-pulse basis in a radar system but up to this time, have not. Indeed, the spectrograms shown in Figure 1 exhibit a wide variety of waveform types indicative of the wide variation one might expect to observe in practice. These waveforms range from an unmodulated pulse to a very wideband hyperbolic modulation and often contain two or three harmonic components. As such they are quite different to waveforms typically employed by radar systems of today (although some sonar systems do use the hyperbolic modulation).

In the next section, we examine the waveform calls and their variation with orientation in more detail seeking to establish a relationship with the tasks necessary for autonomous navigation.

## RELATIONSHIPS BETWEEN FLIGHT, ECHOLOCATION, AND AUTONOMOUS NAVIGATION

Echolocation and flight occur simultaneously in bats, and flight performance feeds back to influence echolocation signal design. While the former might be true of airborne radar systems, the latter aspect (i.e., feedback) most certainly is not. However, such feedback is part of a truly intelligent system and probably represents one of the major sensor research challenges for the future. It certainly seems to be a key component in determining total system performance. Bats typically produce one call per wing beat when searching for prey or commuting as this minimises the cost of producing energetically expensive sound pulses [5]. 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.

One of the major issues facing pulse design for radar sensors on airborne platforms is the Doppler tolerance of the signal and how Doppler tolerance trades off against localization performance. The ambiguity function is routinely used to understand these relationships and has been used previously to examine the performance of broadband echolocation signals used by bats [6] but the range of analysis was limited. Wideband ambiguity functions (WAFs) of the calls of *Myotis mystacinus* have also been calculated by Lin [7]. Here we show how this approach can be used to quantify Doppler tolerance

| Echolocation Call Type | Bat Species (Family) | Spectrogram | Bat Species (Family) | Spectrogram |
|---|---|---|---|---|
| | Yinpterochiroptera | | Yangochiroptera | |
| No Echolocation |  Cynopterus Brachyotis (Pteropodidae) | | | |
| (a) | | | | |
| Brief, Broadband Tongue Clicks |  Rousettus Aegyptiacus (Pteropodidae) |  | | |
| (b) | | | | |
| Narrowband, Dominated by Fundamental Harmonic | | |  Lasiurus Borealis (Vespertilionidae) |  |
| (c) | | | | |
| Narrowband, Multiharmonic |  Rhinopoma Hardwickii (Rhinopomatidae) |  |  Taphozous Melanopogon (Emballonuridae) |  |
| (d) | | | | |
| Short, Broadband, Dominated by Fundamental Harmonic | | |  Myotis Daubentonii (Vespertilionidae) |  |
| (e) | | | | |
| Short, Broadband, Multiharmonic |  Megaderma Lyra (Megadermatidae) |  |  Mystacina Tuberculata (Mystacinidae) |  |
| (f) | | | | |
| Long, Broadband, Multiharmonic | | |  Myzopoda Aurita (Myzopodidae) |  |
| (g) | | | | |
| Constant Frequency |  Rhinolophus Ferrumequinum (Rhinolophidae) |  |  Pteronotus Parnellii (Mormoopidae) |  |
| (h) | | | | |

**[FIG1] 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 [3].**

and localization performance in a range of call designs as they evolve over a typical mission. Of special 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 detection abilities and possibly micro-Doppler classification using narrow bandwidths, to one that optimizes localization performance for aim-point selection using wide bandwidths. Such analyses may be especially important for understanding tracking or landing maneuvers 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 via the analysis of a real feeding buzz sequence. Adapting the design of the transmitted pulse has significant benefits as it can be tailored to the task to be undertaken. The parameters to be adaptively set include the central frequency $f_c$, PRF between consecutive calls in a burst, frequency modulation (FM), call duration T, its instant intensity, and power spectrum (PS).

Echolocating bats exhibit a wide range of frequency modulations. Nevertheless, they often emit calls in which at least a portion of the pulse sweeps through a range of frequencies in order to increase the range resolution and therefore, the ranging capabilities [8]. Although well known, we begin by introducing the linear frequency modulated waveform so that its properties may be compared with the hyperbolic modulation more usually employed by bats.

### LINEAR FREQUENCY MODULATION

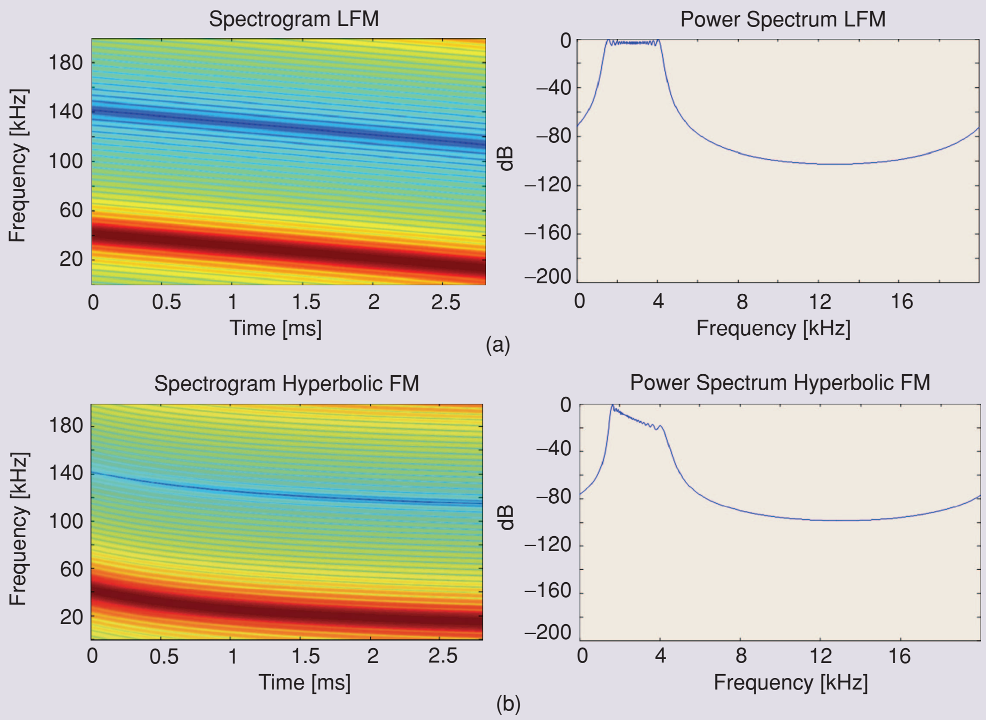
Linear frequency modulated (LFM) signals are widely used in both sonar and radar applications, since they allow for a fixed transmission energy (related to the pulse length T) and therefore sensitivity, while increasing the signal bandwidth B by changing the pulse compression rate $\gamma$ (i.e., the rate at which frequency is increased across the pulse duration):

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

where $f_c$ is the center illuminating frequency, and rect () is the rectangular or box car function such the $s(t)$ is zero for $t \le T/2$ or $t \ge -T/2$. The instantaneous frequency is defined as the derivative of the phase of the signal. Therefore, the bandwidth of the LFM signal is in the range bounded by the minimum and maximum frequencies

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

where $\varphi(t)$ is the phase of the signal s(t) as a function of time t. The spectrogram of a LFM pulse having $\gamma = -750 \times 10^6$ and a time length $T = 20$ ms is shown in Figure 2(a). The total bandwidth is $B = 30$ kHz, yielding a range resolution $\Delta = c/2B = 5.6$ mm, where c is the velocity of sound in air and is assumed to be 340 $\mathrm{ms}^{-1}$.



**[FIG2]** **(a) Spectrogram and power spectrum of an LFM, and (b) HFM pulses, having T = 20 ms, bandwidth is B = 30 kHz, and yielding _r = 5.6 mm.**

### HYPERBOLIC FREQUENCY MODULATION

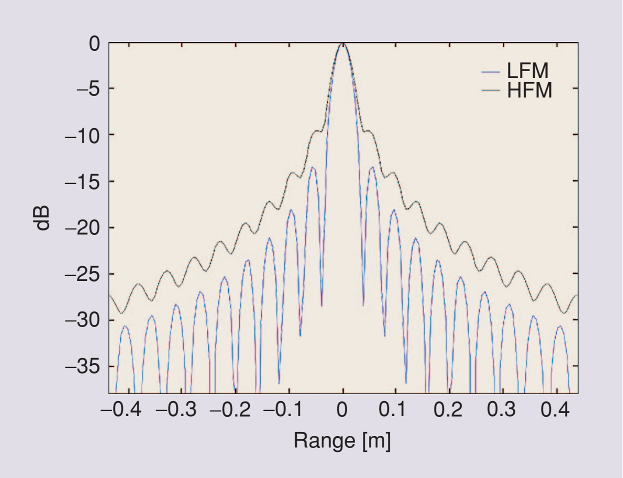
The hyperbolic frequency modulation (HFM) is often used by echolocating bats and has some significant difference to the LFM more normally employed in radar systems. The transmitted waveform depends on the initial and final frequencies ($f_1$, $f_2$) as follows:

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

The synthesized bandwidth after pulse compression is then calculated as

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

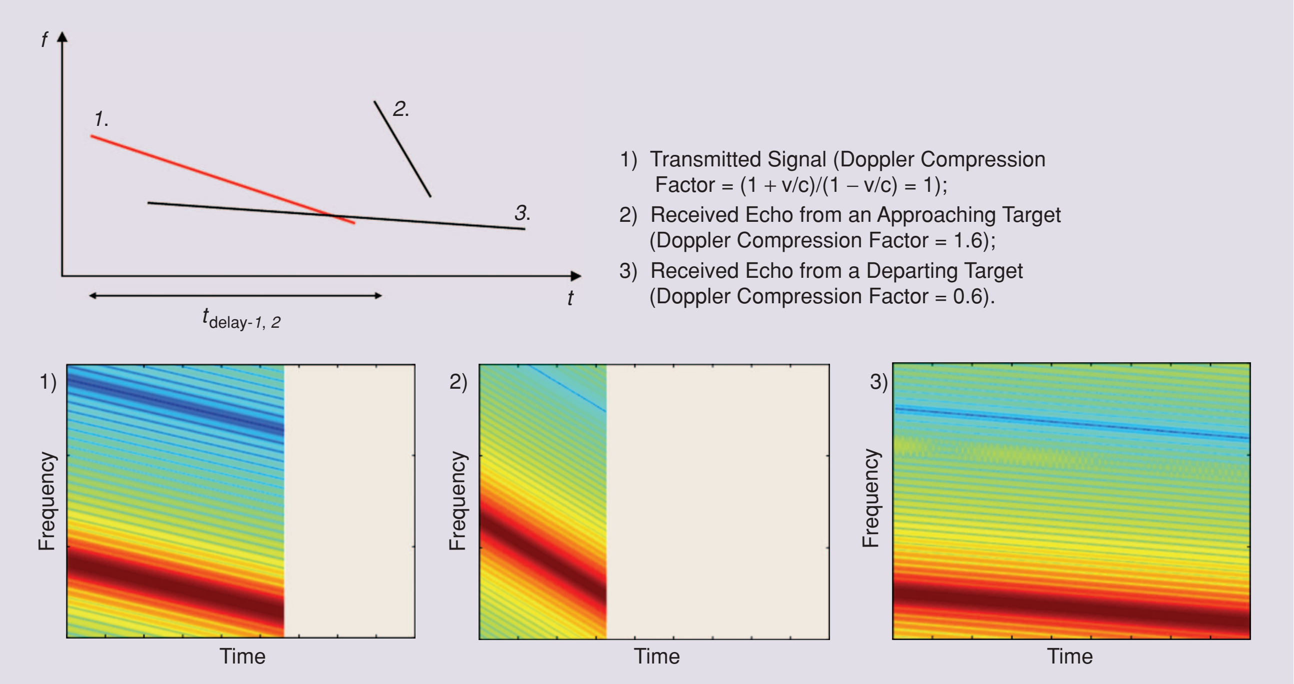
In Figure 2(b), the spectrogram and power spectrum of a HFM pulse are shown. Differences in the signal constricts are immediately apparent although their significance is less clear. This is now examined in further detail. As can be observed from Figure 3, the side-lobe levels (SLL) of the HFM are inferior to those of to the LFM pulse. In fact, the potential advantage of nonlinear frequency modulation (NLFM) resides in being Doppler tolerant. The effects of Doppler shifts when treating narrowband signals can be assumed as a frequency shift and the narrowband ambiguity function can be corrupted [9]. For wideband signals, the effect is a compression or expansion of the transmitted signal, depending on the value of the Doppler compression factor defined as follows:



**[FIG3] Point-spread functions after matched filtering for LFM and HFM signals. The SLL levels are deteriorated using nonsymmetrical nonlinear frequency modulations, although the resolution (-3 dB points) remain unaltered.**

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

where v is the relative speed between the system and the target. When the system is homing towards the target the relative speed is conventionally assumed positive and $\eta$ greater than one. In Figure 4, the Doppler effects on a LFM pulse are shown, highlighting the worsening cross correlation function (CCF) properties as represented by resolution and side lobe levels. Conversely, when HFM signals are transmitted, the CCF



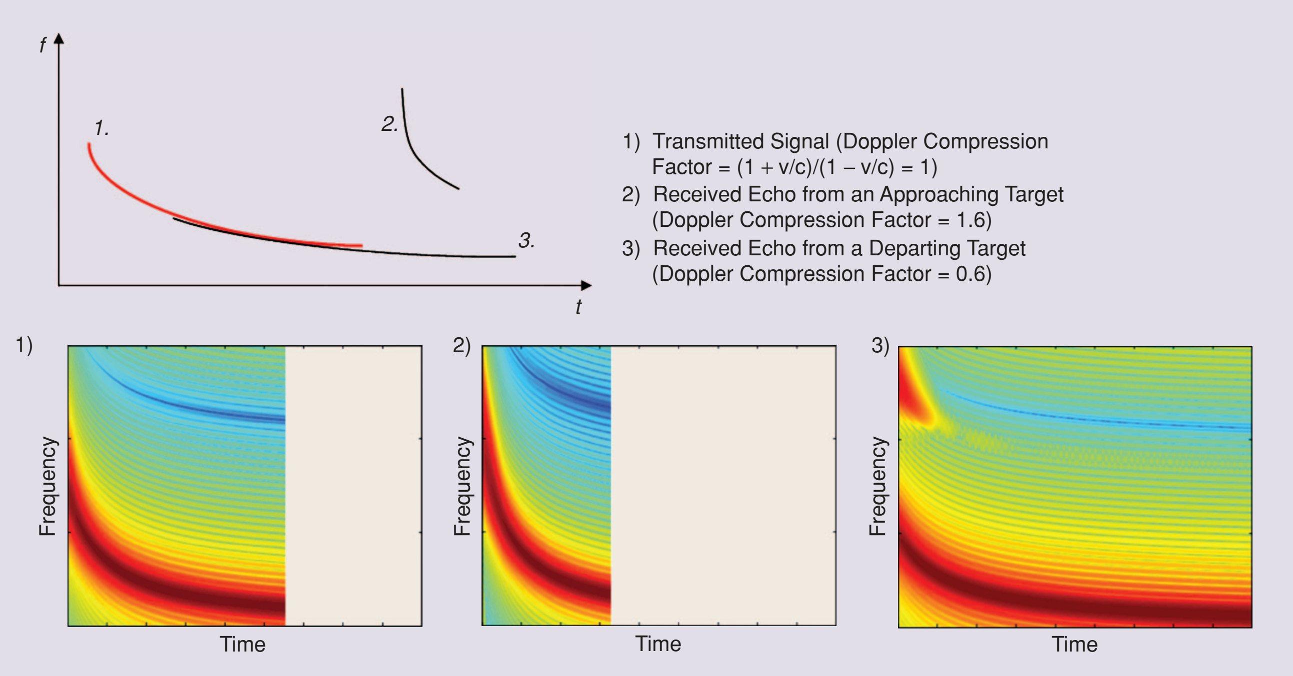
**[FIG4] Two received signals from LFM illuminated point-scatterers at different velocities. The relative velocity changes the slope of the pulse, reducing the cross correlation between transmitted and received pulses, and therefore the output of the matched filter.**

properties are considerably more stable over a variety of different compression factors as shown in Figure 5.

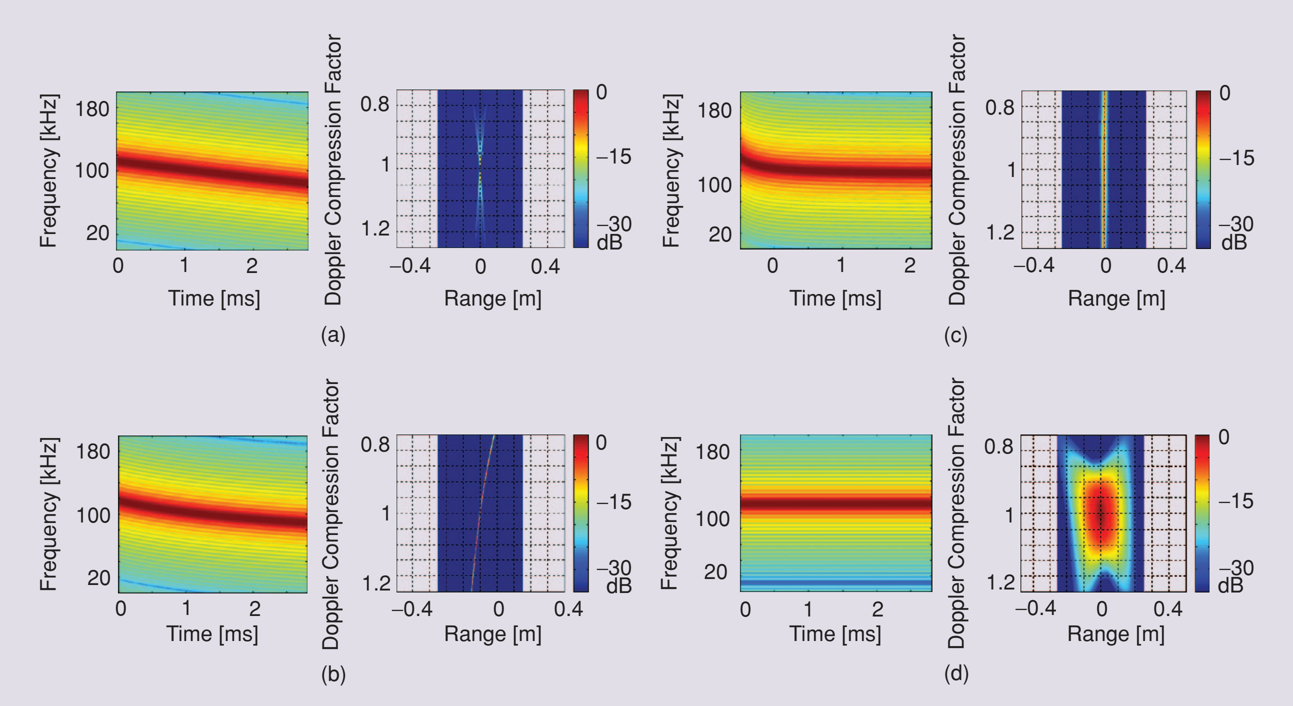
To understand the effects of the Doppler compression factor on the cross correlation properties between the transmitted and received signals in more detail, the WAF is introduced [10]

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

In Figure 6, (a) the WAF of a LFM chirp is compared with the WAF of two HFM (b) and (c), and (d) CF pulses. The WAF is



**[FIG5]** The correlation between transmitted and received pulses from a point-like scatterers at different velocities.



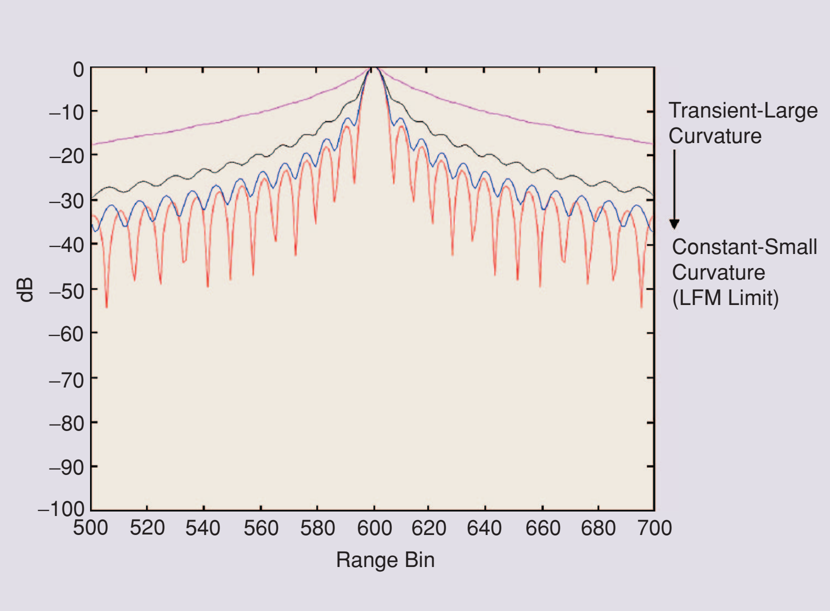
**[FIG6]** Spectrograms and WAF computed for different frequency modulations. The LFM (a) and (b), (c) HFM synthesize the same bandwidth, while the (d) CF is a pure tone. The two HFM pulses differ for the different curvature: a transient curvature followed by a CF component show more robust Doppler tolerance although lower range resolution.

plotted in decibel scale over range and Doppler compression factors. The range resolution can be evaluated by taking a cut at a fixed Doppler compression factor 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 HFM pulses [e.g., Figure 6(b)] exhibit a higher range resolution although there is a higher Doppler ranging error of the precise position of the point-scatterer. The effect of the degree of hyperbolic curvature on range resolution can be observed in Figure 7, where a series of HFM pulses have been simulated whilst maintaining the same bandwidth. The choice of the curvature is adapted according to the flight conditions and previous echoes and is taken into account when the object is a fixed obstacle (high $\eta$) and high Doppler tolerance is required or if the goal is accurate ranging measurement of a target. Thus, we begin to see how the hyperbolic waveform and adjustments to its degree of curvature and bandwidth extent can be exploited as the conditions demand in an evolving mission.

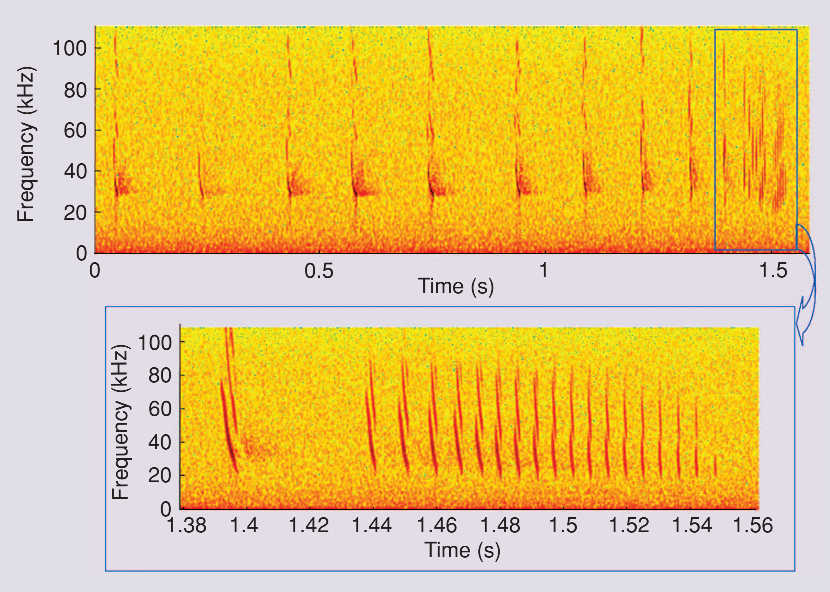
The information that can be derived from harmonics leads to high-range resolution and can be subsequently used to attempt target classification. Indeed, this may form part of the strategy used by bats for recognition of very small targets or fine target features [11]. In radar, high-range resolution may be achieved using the stepped-frequency or stepped-chirp techniques [12]. 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 synthesizing 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 bats calls often only slightly overlap in frequency with the fundamental, it is possible that, collectively, the harmonics are used to refine range resolution and reduce range ambiguities as they are transmitted within a single pulse.

We now examine data from a real bat feeding buzz sequence. The sequence is shown as a time-series spectrogram for *Eptesicus nilssonii* in Figure 8. The PRF increases markedly as the bat changes task from detection to localization. The curvature of the HFM also changes from being dominated by a long narrowband component to a exhibiting a greater degree of curvature. The single pulse WAFs have been processed for each call, showing the range and Doppler resolution at different positions in the feed. In particular, as soon as the bat gets closer to the target, it is clear that the waveform is adapted in order to emphasise range rather than Doppler information.

In Figure 9, an example of a pulse from the search phase, prior to the final stage of the feeding buzz is shown. The fundamental



**[FIG7]** **Large and transient curvatures in HFM give deteriorated range resolution and SLL but significant Doppler tolerance. Vice versa, small, and constant curvatures yield high-range resolution, although higher Doppler range migration.**



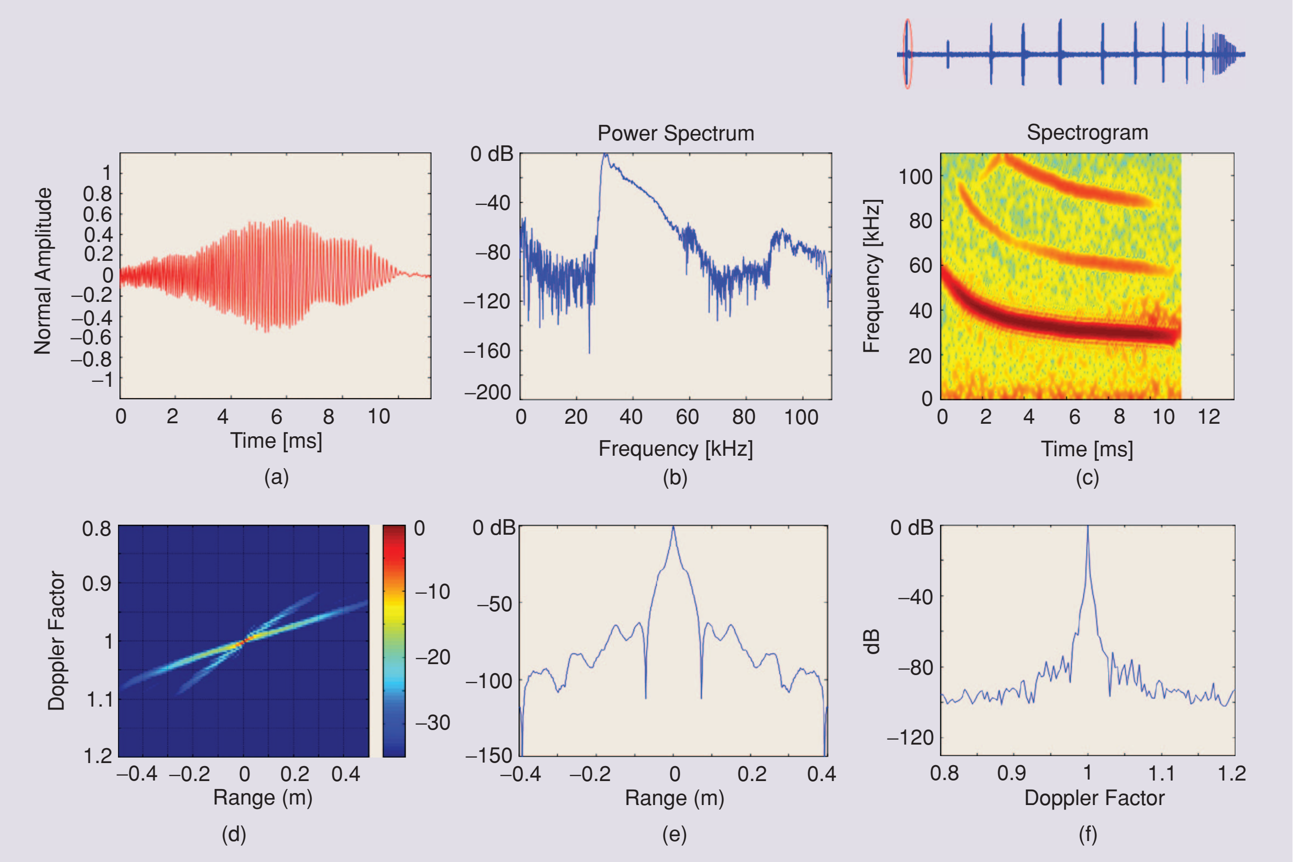
**[FIG8]** ***Eptesicus nilssonii*** **time-series spectrogram. A drop of the central frequency can been observed during the Buzz II part of the terminal phase (blue box). Moreover, the call intensity is progressively reduced as the bat approaches the prey (AGC) and the multiharmonic structure becomes a single wideband signal.**

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 and potentially micro-Doppler recognition via observation of the wing beat frequency of the intended prey. The traditional view of the utility of narrowband signal components in search phase calls is that they enhance detection because they evoke neural activity in the response range of auditory neurons, and activity is increased at longer signal durations [13]. The WAF exhibits good range and Doppler resolution. During this phase, Doppler shifts are not well catered for. Further into the feeding buzz sequence, after detection and classification, the pulse length is progressively reduced as the bat approaches the prey, as can be seen in Figure 10. This avoids range ambiguities which is, of course, always preferable in radar operation. The PRF increases as a consequence of the need to iteratively refine range information with an increasing temporal rate.

As the position in the mission progresses, the prey is confirmed 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 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 transmitted and the pulse length are reduced to minimize energy expenditure and to minimize echoes from background clutter. The resolution is maintained in range only and very high Doppler tolerance obtained and as a consequence of the reduced pulse length, the frequency modulation is now near linear. The fundamental and second harmonics are separated in frequency as can be observed from the power spectrum shown in Figure 11, where the two center frequencies can be isolated.

The first WAF suggests that the bat is attempting to detect moving targets by exploiting the Doppler and micro-Doppler effects. Clearly, Doppler information is difficult to retrieve when Doppler tolerant waveforms are used. As soon as the prey is detected, the recognition phase still requires sufficiently detailed Doppler information and the target has to be accurately located using progressive increases in range resolution in order to prepare for the approach and terminal components of the mission. As a consequence, the WAF plots rotate towards the Doppler compression factor direction. When the bat is close enough to the prey, any minimal change in the prey trajectory produces significant Doppler compression variations. However, the information about target velocity is no longer required.



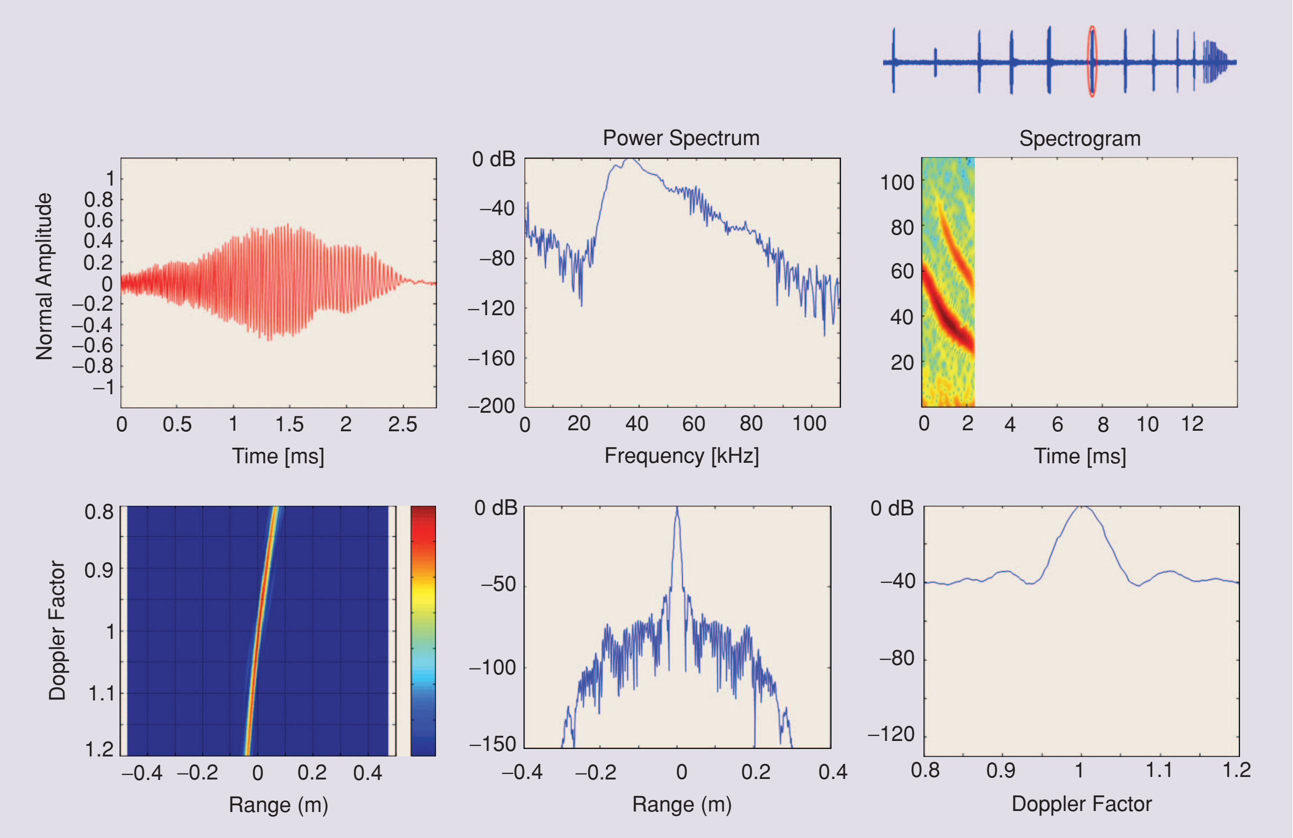
**[FIG9]** ***Eptesicus nilssonii:*** **Search phase pulse analysis. The first chirp of the time series is analyzed in its (a) time domain representation, (b) power spectrum, (c) spectrogram, (d) WAF, (e) range, and (f) Doppler profiles.**

During the approach phase, the WAF contour shows that the waveform is designed in order to obtain a 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 ambiguity also has the effect of strengthening the Doppler tolerance resulting from HFM. Thus, we can see that there is careful and continuous adjustment of the transmitted waveform such that it is able to derive the correct type of information at the appropriate juncture as the nature of the mission unfolds. By gaining a more complete understanding of these continuous alterations in the design of the transmitted waveform and how the bat is extracting informing to aid this process, we can exploit this to hugely improve the performance and the realm of capability in synthetic sensors such as radar (and sonar) systems. In the next section, we consider such waveforms and their adjustments in the context of behavioral types that might make up a complex autonomous mission.

## AUTONOMOUS NAVIGATION STRATEGIES

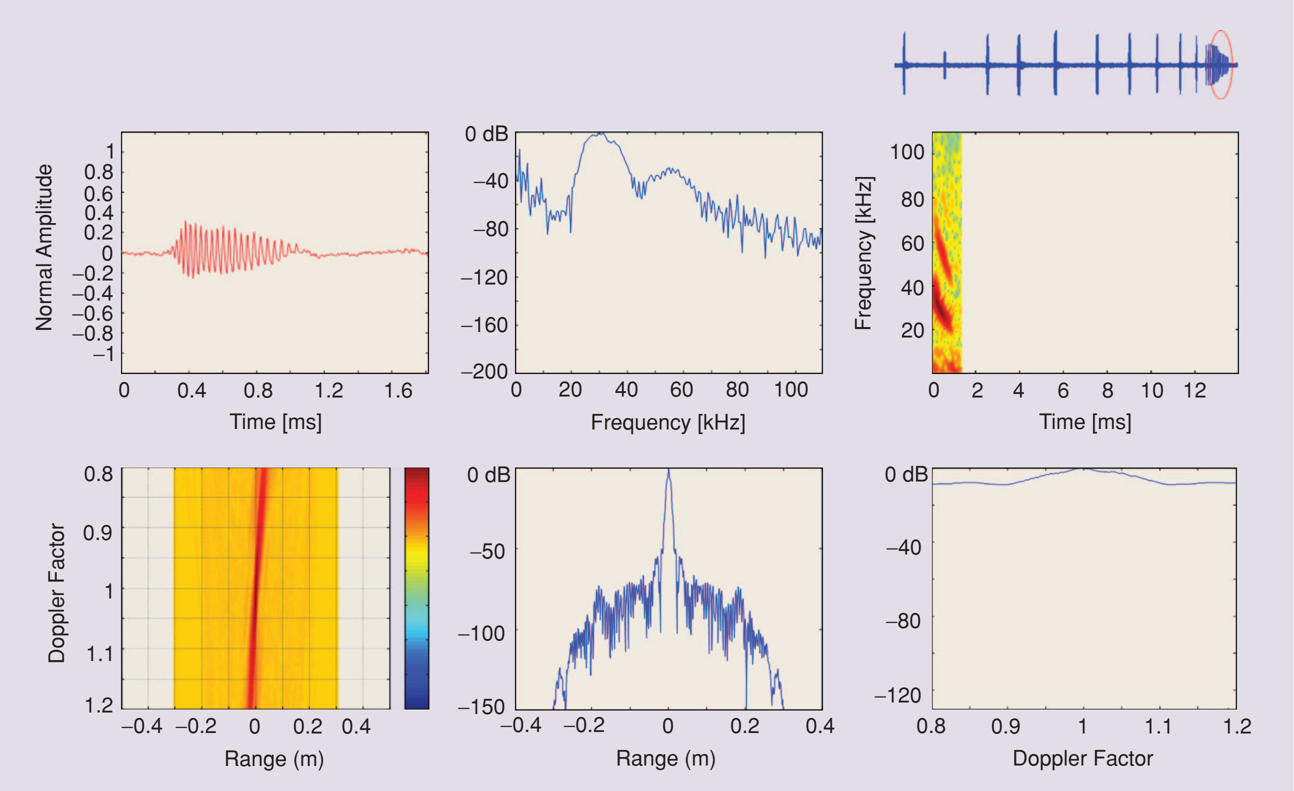
As stated above, the adaptive call design of bats has potentially significant implications for improvements in autonomous navigation strategies (ANS) and obstacle avoidance by synthetic sensor systems such as sonar and radar. ANS are often investigated using control theory. Here, we suggest a series of waveform strategies that are based on observations of the behavior of bats of the type outlined in the previous sections. Specifically, we combine them with an artificial intelligence approach inspired by the behaviors of echolocating bats. The list of steering behaviors made by Reynolds [14] 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 which requires accurate ranging to be performed. Time delay ranging provides for along-track resolution, while a binaural inspired system measuring the time difference of arrival can 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 bat sequence described here includes a short wideband HFM pulse which guarantees significant Doppler tolerance, necessary to cope with a high system-target relative velocity.
- *Pursue and Evade:* This is 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). This is likely to require a waveform with a narrowband or a constant frequency component for high-accuracy Doppler measurement.



**[FIG10]** ***Eptesicus nilssonii*: Approach phase pulse analysis.**

- *Offset Pursuit*: The system pursues the target and stays at a specified distance without interception. This steering behaviour requires accurate Doppler and range information. Since the system-target relative velocity must be maintained close to zero, a low Doppler tolerance is utilized. The offset distance is a key parameter for design of the waveform since it affects the maximum unambiguous range. Therefore, the pulse length, signal intensity, and PRF may be adjusted to refine the Doppler information. The need to update the target rotational and position parameters will necessitate an increase in the PRF and range ambiguities can be avoided since a priori knowledge of the expected target position exists from previous measurements.
- *Random Steering, Wandering, and Exploring*: These behaviors are related to scenarios where the goal has not yet been specified. Wandering behavior is a type of random steering, exhibiting smoothed trajectories. This behavior can be associated with detection. As a consequence, for the bats, the waveform might be characterized 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 without needing to deal with ambiguity.
- *Arrival*: The target is stationary and the goal is to seek the target while progressively reducing speed. This steering behavior 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. A wideband hyperbolic modulation can be used to provide precise positioning information.
- *Obstacle and Collision Avoidance*: The system needs to avoid fixed (obstacles) or moving targets (collision). The concept is similar to flee and evade behaviors with the exception that that the system has to avoid to collisions instead of steering away from the object. This task is often combined with other steering behaviors. 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. This may require 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 three dimensional (3-D) image that is only refreshed by a few references after its acquisition as the human behavior would suggest. This task requires a waveform with a constant frequency term combined with a degree of frequency modulation for ranging. The process of memory storage for subsequent exploitation is not well understood in the context of synthetic sensing but appears to play a vital role in carrying out this form of task successfully.



**[FIG11]** ***Eptesicus nilssonii*: Terminal phase pulse analysis.**

- *Path Following*: This is a type of containment, where the goal is to follow a defined route, maintaining a maximum distance from all boundaries for the safest passage.
- *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, maximum unambiguous range, and call intensity are tuned depending on the system relative velocity and the distance from the wall. Measurements are updated with respect to the system relative velocity and predictions are evaluated through recursive filters (such as the Kalman filter).

This list of steering behaviors represents a hypothesized set of primitives that in a typical real environment would be combined in order to represent a more complicated task. However, they may provide a basis for more intelligent sensing and system design for autonomous applications.

## CONCLUSIONS

The behavior and performance of echolocating bats (in terms of detecting, locating, tracking, and capturing prey) have been investigated. The most significant aspects for autonomous navigation have been identified as the transmitted waveform and its dynamic adjustment as a function of flight trajectory. This is evident through the wide range of frequency modulations used by different bat species (CF, LFM, and HFM) whose parameters are set depending on the particular task to be carried out and are continuously varied. The facility for changing the bandwidth of the transmitted call within a feeding buzz sequence, reducing the illuminating frequency, modifying the pulse repetition interval, call intensity, and pulse length is undoubtedly a sign of the importance of waveform design is providing insights potentially leading to the development of more reliable autonomous systems, perhaps when combined with the strategy primitives outlined above. It should also be noted that this analysis has only considered transmitted calls whereas, of course, the information is really embedded in the received echoes. Equally, it should be recognized that this analysis is just a beginning and there are a number of aspects such as binaural techniques and neural processing that have not been examined. However, the waveforms and waveform adjustments used are significantly different from anything employed in radar systems and seem to offer scope for significant new capability.

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## REFERENCES

[1] N.B. Simmons, K.L. Seymour, J. Habersetzer, and G.F. Gunnell, “Primitive early eocene bat from wyoming and the evolution of flight and echolocation,” *Nature*, vol. 451, pp. 818–821, Feb. 2008.

[2] E.C. Teeling, M. Scally, D.J. Kao, M.L. Romagnoli, M.S. Springer, and M.J. Stanhope, “Molecular evidence regarding the origin of echolocation and flight in bats,” *Nature*, vol. 403, no. 6766, pp. 188–192, 2000.

[3] M.S. Springer, E.C. Teeling, O. Madsen, M.J. Stanhope, and W.W. de Jong, “Integrated fossil and molecular data reconstruct bat echolocation,” in *Proc. Nat. Academy of Sciences United States of America*, 2001, vol. 98, pp. 6241–6246.

[4] G. Jones and E.C. Teeling, “The evolution of echolocation in bats,” *Trends Ecology Evol.*, vol. 21, pp. 149–156, Feb. 2006.

[5] J.R. Speakman and P.A. Racey, “No cost of echolocation for bats in flight,” *Nature*, vol. 350, pp. 421–423, Apr. 1991.

[6] R.A. Altes and E.L. Titlebaum, “Bat signals as optimally Doppler tolerant waveforms,” *J. Acoust. Soc. Amer.*, vol. 48, Feb. pp. 1014–1020, 1970.

[7] Z. Lin, “Wideband ambiguity function of broadband signals,” *J. Acoust. Soc. Amer.*, vol. 83, pp. 2108–2116, Oct. 1988.

[8] R.J. Sullivan, *Radar Foundations for Imaging and Advanced Concepts*. Perth, Australia: SciTech Publishing, 1994.

[9] P.M. Woodward, *Probability and Information Theory, with Applications to Radar*. New York: McGraw-Hill, 1953.

[10] E.J. Kelly and R.P. Wishner, “Matched-filter theory for high-velocity, accelerating targets,” *IEEE Trans. Military Electron.*, vol. 9, pp. 56–69, Feb. 1965.

[11] I.E. Dror, M. Zagaeski, and C.F. Moss, “Three-dimensional target recognition via sonar: A neural network model,” *Neural Netw.*, vol. 8, pp. 143–154, May 1995.

[12] A.J. Wilkinson, R.T. Lord, and M.R. Inggs, “Stepped-frequency processing by reconstruction of target reflectivity spectrum,” in *IEEE Proc. CONFIG'98*, 1998, pp. 101–104.

[13] H.-U. Schnitzler, C.F. Moss, and A. Denzinger, “Trends in ecology and evolution,” vol. 18, pp. 386–394, Aug. 2003.

[14] C.W. Reynolds, “Steering behaviors for autonomous characters,” in *Proc. 1999 Game Developers Conf.,* 1999, pp. 763–782.