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Jerome Helffrich; Sean Fulop

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The phase-locked loop as a tool for signal analysis

Jerome Helffrich
Southwest Research Institute, San Antonio, TX; jhelffrich@swri.org

Sean Fulop
Linguistics, California State University Fresno, Fresno, CA, 93740; sfulop@mail.csufresno.edu;

Tracking of signal frequency and/or phase is made much more challenging by the presence of "rapid" frequency or phase changes in a signal—occurring in a time short compared to the amount of frequency shift. In these scenarios, the usual Fourier decomposition does not provide detail sufficient to tell what is going on. Although there are time-frequency tricks one can use (such as the reassigned spectrogram), these do not provide simple answers to the question of what is the phase as a function of time, and they do not track the instantaneous frequency as effectively as is wanted. An interesting solution from the realm of electrical engineering is provided by the phase-locked loop (PLL) detector: a construct that takes the input signal and tries to phase lock an on-board oscillator to it. It turns out that this process is surprisingly effective at tracking instantaneous frequency/phase while discarding noise if an initial estimate of the target signal frequency is known. We present examples of the superior frequency and phase tracking provided by a PLL approach, including the extremely brief chirps produced by electric fish, and the forensic detection of editing cuts in audio samples.

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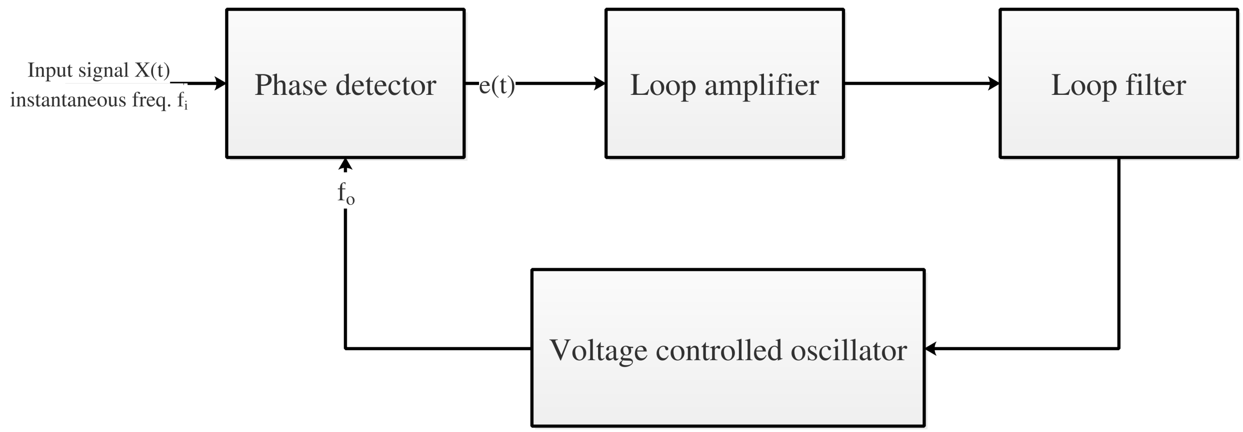

Figure 1: Basic phase-locked loop consists of a* phase detector *with output $e(t)$ proportional to the phase error between signal input $X(t)$ and VCO output, a low-pass filter with a specified gain, and a* voltage-controlled oscillator *whose frequency f_o is controlled by the filtered phase detector signal.

1. INTRODUCTION

Modern time-frequency analyses such as the reassigned spectrogram[1–3] enable the instantaneous frequency of signals to be accurately tracked. These representations are imperfect because of the necessity of time-windowing, and thus can be problematic for extremely brief changes to the frequency. Moreover, they also don't represent signal phase, so a phase change which causes an apparent change of instantaneous frequency can be obscured. The time-honored technology of the phase-locked loop[4,5] invites a new approach to the problem of instantaneous frequency tracking, and because it uses the signal phase, it provides information on the instantaneous frequency and phase at once. In this paper we will analyze two different kinds of signals which have frequency/phase changes taking place. The purpose will be to show how a phase-locked loop analysis can complement and clarify a more typical time-frequency analysis, in the effort to understand the apparent changes of the instantaneous frequency which may ultimately stem from changes to the signal phase.

2. PROCEDURE

Referring to the block diagram in Figure 1, first, we transform the signal to be tracked using an imposed sinusoidal frequency:

1. Sine and cosine function are created at a target frequency to be tracked.
2. Original signal is bandpass filtered around the target, then decimated by a sequence of windowed frames and multiplied by the sine function and the cosine function separately.
3. Results are combined into a new complex analytic signal $X(t)$ that is now a downsampled and bandlimited version of the original that is also modulated to the target frequency.

This signal preparation results in better signal-to-noise ratio in the transformed signal, and the phase will be tracked with relative ease at the target frequency.

The next step is to feed our transformed signal into the phase-locked loop, which is a fairly standard second-order loop design.

1. Initialize the phase using the seed frequency.

2. Voltage-controlled oscillator (VCO) is set up with this frequency.
3. Error signal $e(t)$ is computed with the "phase detector" which tries to match the VCO frequency with the tracked signal.

There are important parameters of the PLL which set the gain of the loop filter. We refer to the snippet of Matlab code in the appendix for details of the PLL implementation. In general, the VCO phase should be an estimate of the input phase, and so the PLL system should drive the phase error towards zero when it is operating within expected ranges.[6]

The illustrations of the outcomes in this paper show three plots: a time-frequency analysis which is a reassigned spectrogram; the cumulative phase error from the PLL; and the instantaneous frequency relative to the PLL seed, subjected to a moving average filter. We will observe how the simultaneous tracking of instantaneous frequency using a TF analysis on the one hand, and the PLL on the other, provides a wealth of information about what is happening with the subject signals.

3. APPLICATION TO FORENSIC AUDIO

A problem in forensic audio analysis is that the editing of audio recordings can be very hard to detect. However, if a tonal frequency is present in the background, a phase-locked loop can track the phase of this tone and be used to detect interruptions, which can provide evidence of tampering with or splicing the audio recording.

The subject signal for this application is a speech recording which has a "hard" edit at 2.1 s—the signal had a chunk cut out of it with no other processing performed. There is a helpful 60 Hz power hum in the background. We use a bandpass filter tight around 60 Hz, which eliminates most of the signal, however there are many ways of filtering and they do affect the outcomes to some extent.

Figure 2 shows one analysis which bandpasses the signal using a Hann window in the frequency domain. The reassigned spectrogram tracks the instantaneous frequency but no phase information is preserved, so what causes the change remains obscured. The cumulative phase error plot, by contrast, shows the sudden change in the phase that results from the editing of the recording. Finally, the PLL relative frequency tracks the instantaneous frequency more smoothly than the reassigned spectrogram can.

Figure 3 shows a second analysis of the signal, only this time the bandpass filtering was performed with a finite impulse response time-domain filter. It can be seen that the method of bandpass filtering can have an effect on the specific outcomes of the phase-locked loop, however this second approach has the advantage that it could be done in real time.

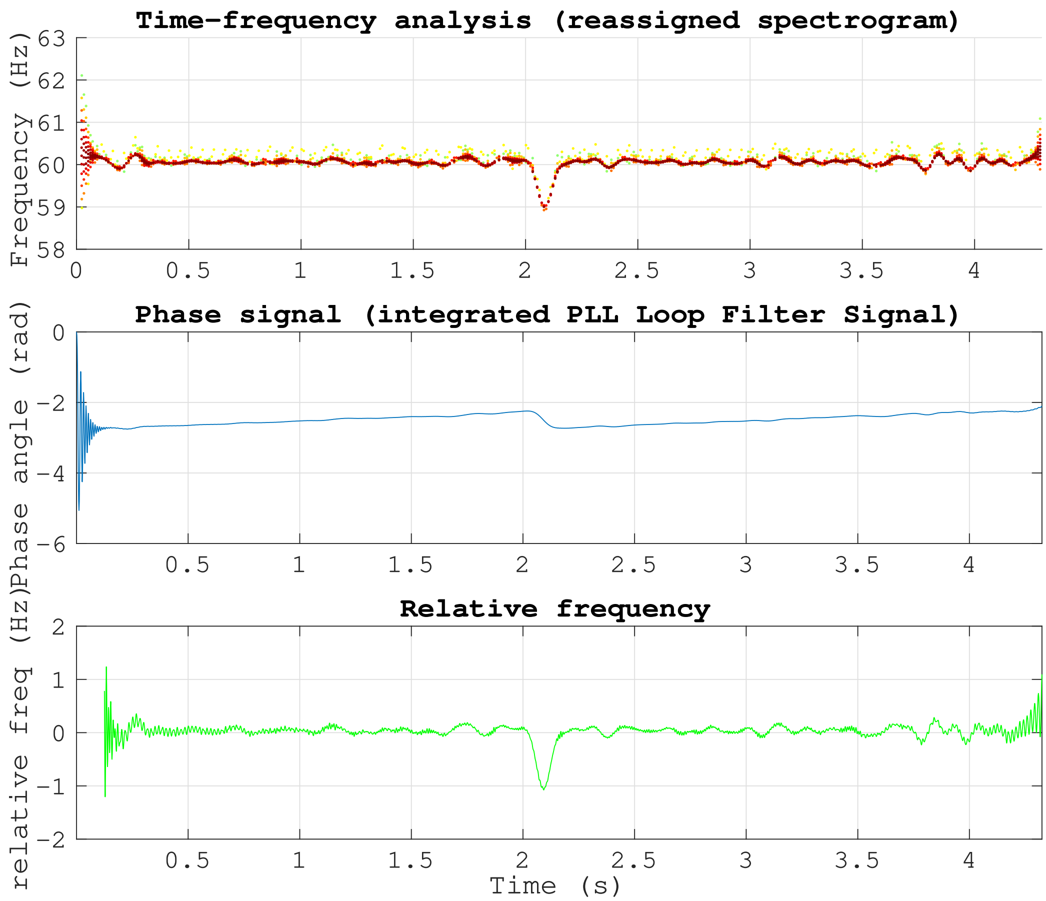

Figure 2: A bandpassed audio recording with a hard edit causing a phase shift; filtered with a frequency-domain Hann window

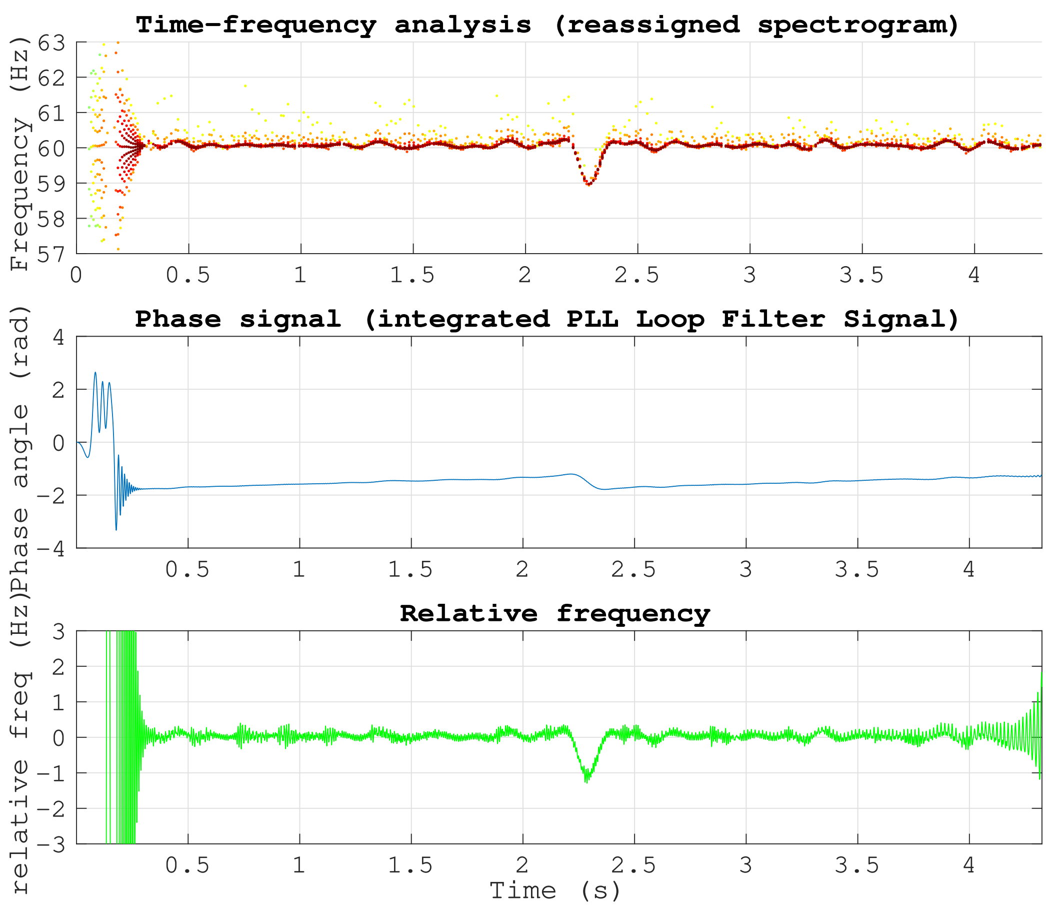

Figure 3: The same signal as the previous figure, but instead using a FIR time-domain filter

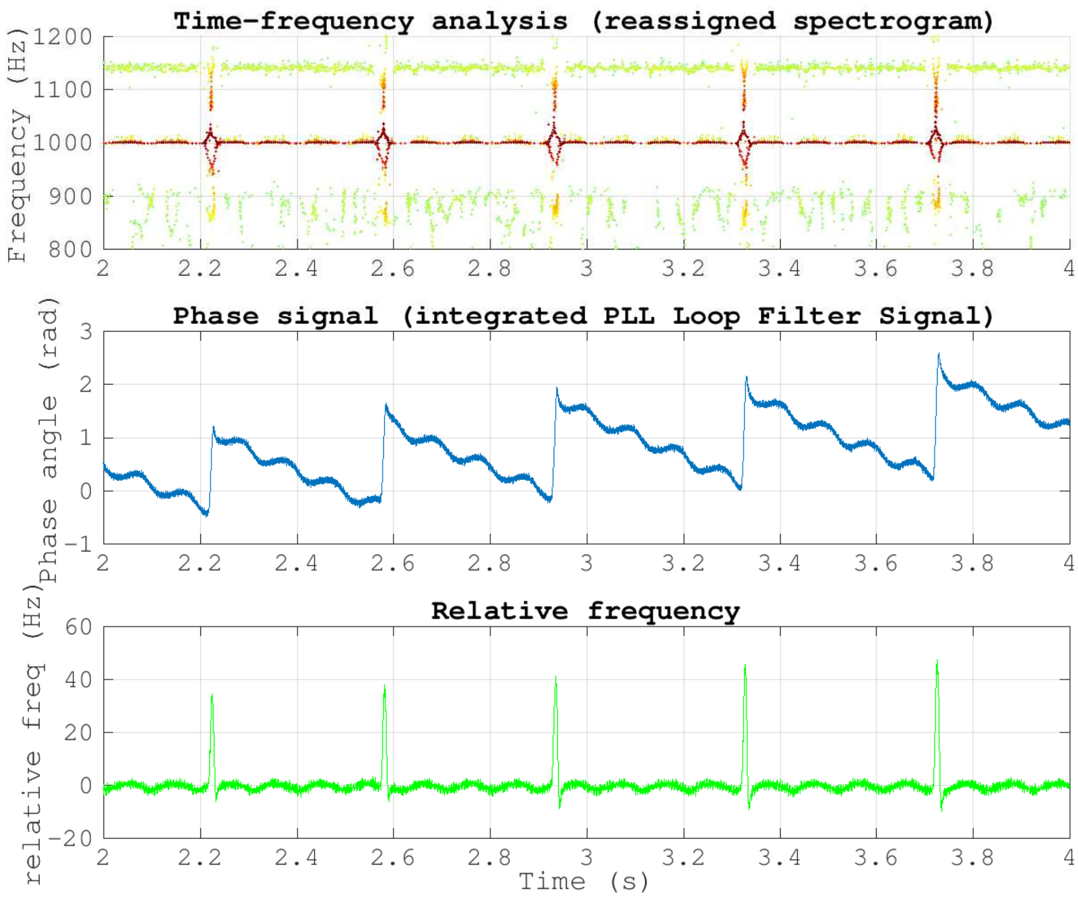

Figure 4: A single fish emitting a 1 kHz EM signal and chirping throughout

4. APPLICATION TO ELECTRIC FISH SIGNALS

Weakly electric fish (order *Gymnotiformes*) emit tonal EM frequencies that are extremely steady, but interrupted by a variety of brief chirp-type events.[7] The precise nature of these events is the subject of continuing study. There is some debate as to whether phase changes in the signal generation by the fish are a cause of the frequency chirps.[8,9] Here we show a few examples of the fish signals, in which brief frequency excursions can be observed at numerous points in time. We also observe a number of phase-reversal events, which possibly do not involve a frequency shift per se, although this is hard to determine because of the intimate relationship between phase and frequency. All of these events are poorly resolved by time-frequency analysis, but are better observed by our phase-locked loop analysis.

Figure 4 shows a single fish emitting a 1 kHz tone and chirping throughout. Figure 5 shows the single "chirp" at 2.9 s, which is verified by our analysis to be a brief frequency chirp of 40 Hz up and down. The PLL signal shows the frequency shift as a phase change. The poor view in the reassigned spectrogram is clearly improved upon by the PLL analysis, and in particular the smoothed relative frequency plot shows the instantaneous frequency with unparalleled precision.

Figures 6 and 7 show emitted frequencies from two different fish. The two fish were emitting at the same time, one at 860 Hz and the other at 941 Hz. This is a common type of interaction that appears to serve

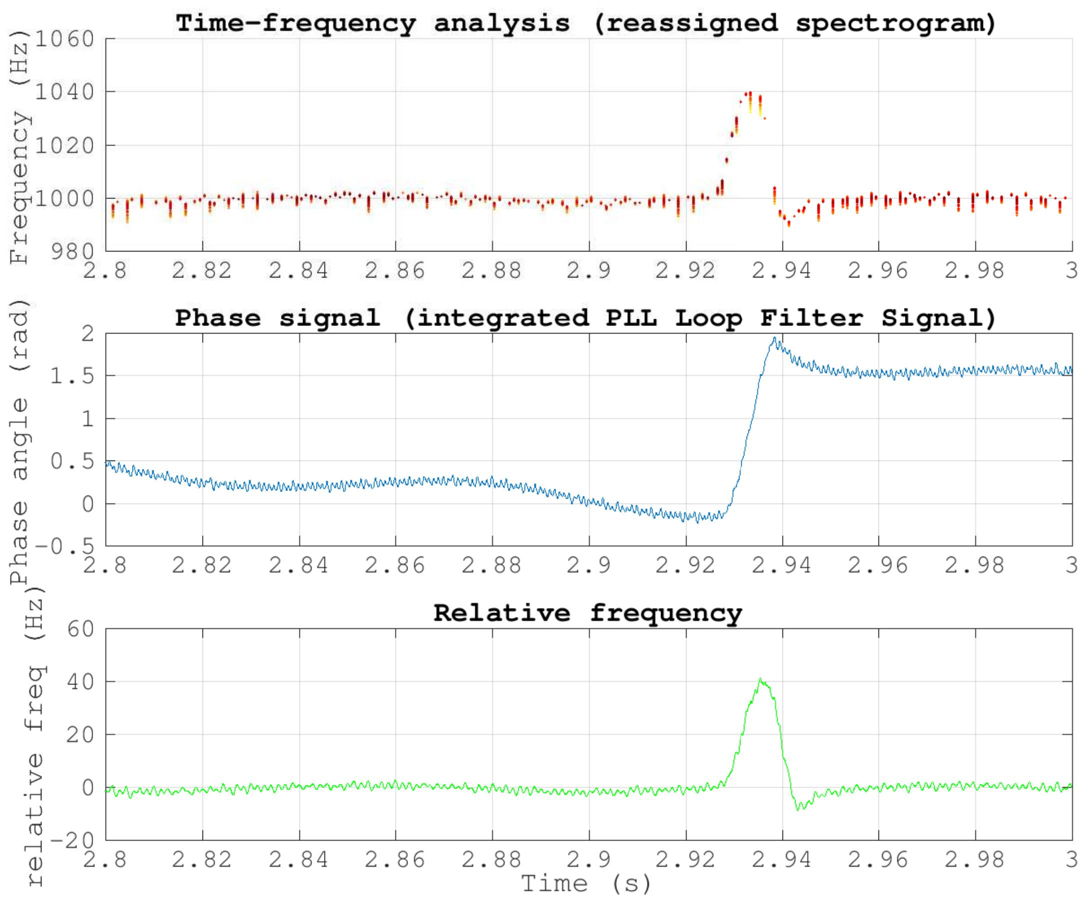

Figure 5: A single chirp which occurs at 2.9 s in the previous figure

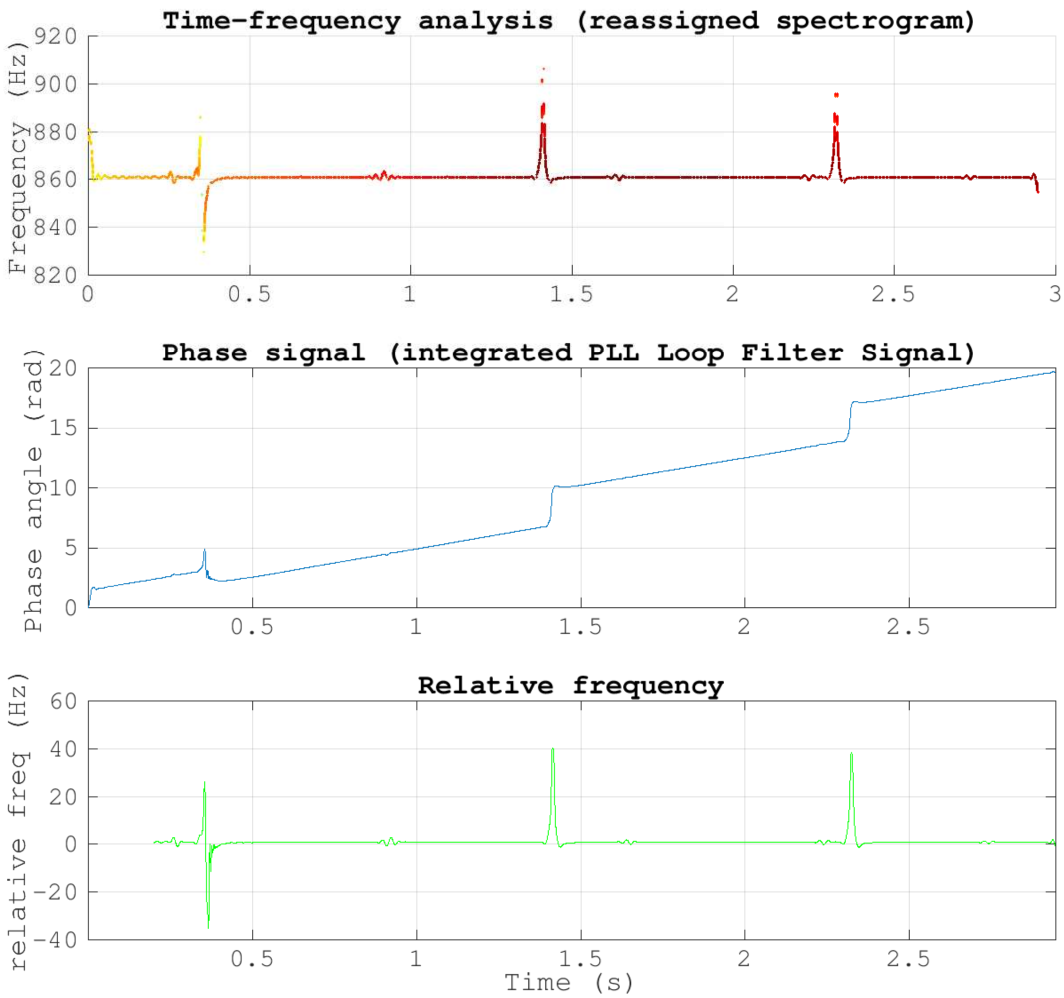

Figure 6: One fish emitting at 860 Hz, communicating with another fish shown in the next figure.

a communicative function. In each emission we observe a number of up-down frequency shifts, an example of which is magnified for analysis in Figure 8. Each signal also shows examples of a different kind of shift, which appears to involve a phase-reversal that is not present in the first kind of chirp. Figure 9 magnifies one example of this sort.

5. CONCLUSION

This paper has attempted to demonstrate the utility of tracking instantaneous frequency using a phase-locked loop. The information available combines the instantaneous frequency with information about the signal phase, which can be important in applications where the phase itself may be manipulated. The first application was in the realm of edit detection in forensic audio analysis, and a method to use the PLL for this detection has already been deployed.

The second application was the investigation of electric fish signalling. These signals have been widely documented as a mostly steady tone with rapid chirps, however some authors have opened the possibility

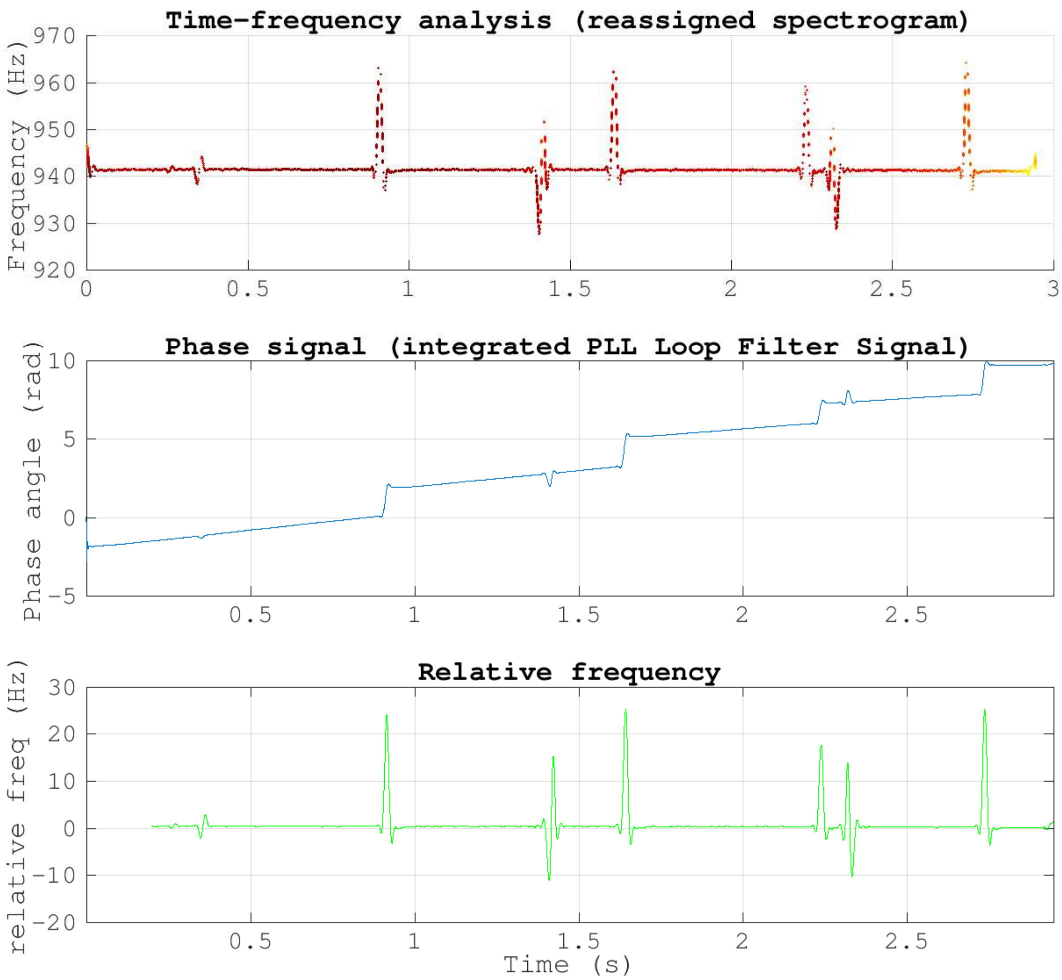

Figure 7: A second fish emitting at 941 Hz, communicating with the fish shown in the previous figure.

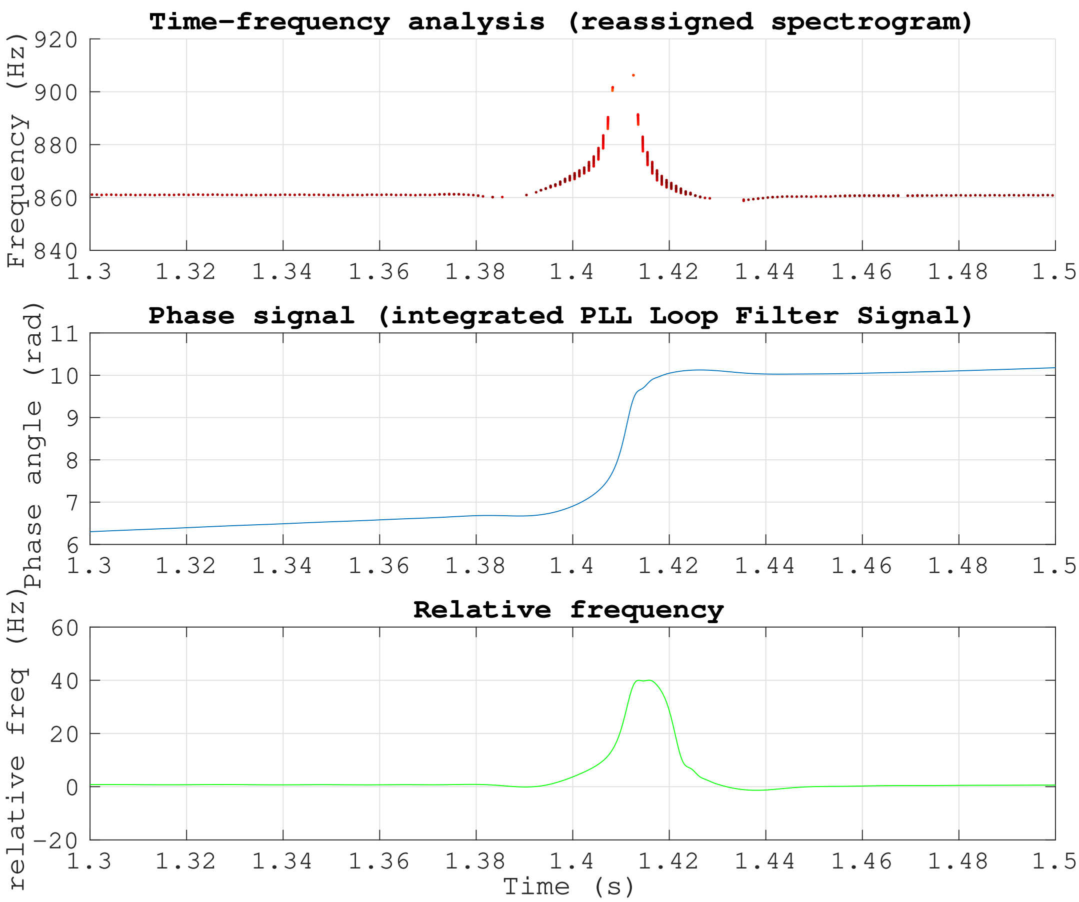

Figure 8: Close-up view of one chirp in Figure 6

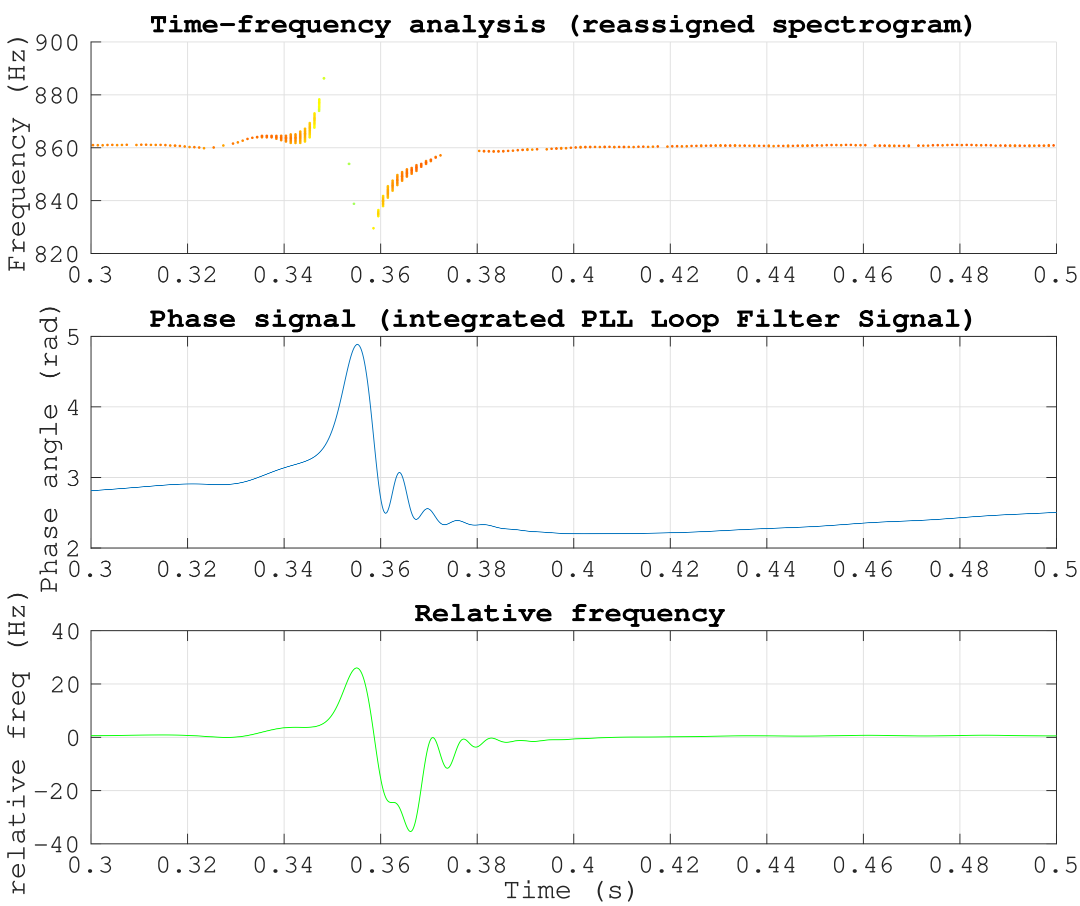

Figure 9: Close-up view of a "phase-reversal event" of unknown cause in Figure 6

that there are direct phase shifts in addition to frequency chirps. With a usual spectrum or time-frequency analysis it is virtually impossible to resolve the frequency changes adequately, and the story of the phase remains unknown by this analysis. The analyses presented here have demonstrated a greater precision which reveals at least two different types of events in the fish signals, whose distinctive phase shifting can be observed with the aid of a phase-locked loop.

APPENDIX

Here we provide a bit of Matlab code with comments, to show precisely the way we implemented our phase-locked loop. It may be seen that we apply the complex envelope concept to simulate the PLL in the digital domain. The filtering is performed using trapezoidal integration. For a useful textbook treatment we may refer to Tranter et al.[6] Appendix A.

```
% Signal is a discrete analytic signal associated to the input real signal
% fs is the sampling frequency of the signal
% Initialize PLL Loop
phi_hat(1)=30;
e(1)=0;
phd_output(1)=0;
vco(1)=0;
% Define Loop Filter parameters (Sets damping)
kp=0.15; %Proportional constant
ki=0.5; %Integrator constant
% PLL implementation
for n=2:length(Signal)
vco(n) = conj(exp(j*(2*pi*n*f/fs+phi_hat(n-1))));%Compute VCO
phd_output(n) = imag(Signal(n)*vco(n));%Complex multiply VCO x Signal input
e(n) = e(n-1)+(kp+ki)*phd_output(n)-ki*phd_output(n-1);%Filter integrator
phi_hat(n) = phi_hat(n-1)+e(n);%Update VCO
relfreq(n) = phi_hat(n) - phi_hat(n-1); %Track frequency relative to seed
relfreq(n) = relfreq(n)*fs/(2*pi);
end;
```


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We wish to thank John Lewis and Ginette Hupé for sharing so many signals from their brown ghost knifefish at the University of Ottawa.

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