Acoustical Society of America
International Student Challenge Problem in Acoustic Signal Processing 2014
Student Entry Evaluation Report by the Technical Committee on Signal Processing in Acoustics

Background

Background information on the international student challenge problem can be found in the article by B. G. Ferguson and R. L. Culver, "International Student Challenge Problem in Acoustic Signal Processing," *Acoustics Today*, Volume 10, Issue 2, pp 26-29, Spring 2014 (available online at acousticstoday.org). The article highlights the pull quote: *Students are given the opportunity to distinguish themselves by solving a challenging problem in acoustic signal processing.*

Evaluation Process

The solution notes, which provided guidance for evaluating the student entries, form Appendix A. The entries were assessed by the evaluators to be of a very high standard reflecting considerable time and effort having been expended by the students and, justifiably, a sense of pride and achievement permeated their submissions. Students who have clearly distinguished themselves by detailing their approach and reasoning in solving the problem and providing good estimates of the parameter set were selected as *Finalists*. From the entries of the Finalists, five entries were judged to be *Meritorious*. The final step required ranking the meritorious entries in order: first, second and third.

Finalists

Andrew Acquaviva *(Pennsylvania State University, USA)*
Michael Biffignani (*Pennsylvania State University, USA)*
Yuta Enomoto *(Waseda University, Japan)*
James Esplin and Matthew Shaw *(Pennsylvania State University, USA)*
Philip Feurtado *(Pennsylvania State University, USA)*
Kay (Kai) Gemba *(University of Hawaiʻi at Mānoa, USA)*
Sahar Hashemgeloogerdi *(University of Rochester, USA)*
Yasuhito Ishihara *(Waseda University, Japan)*
Aaron Lesky *(Pennsylvania State University, USA)*
Michael Muhlestein *(University of Texas at Austin, USA)*
Bernado Murta, Bruno Knebel, Gil Greco and Sergio Aguirre *(Federal University of Santa Maria, Brazil)*
Ananth Raghavendra *(Pennsylvania State University, USA)*
Rishabh Ranjan and Kaushik Sunder *(Nanyang Technological University, Singapore)*
Leandro Sebastian Rodiño *(Universidad Nacional de Tres de Febrero, Argentina)*
Yu Shiduo, Xu Lingji and Yang Long *(Northwestern Polytechnical University, China)*
Sarah Smith and Michael Heilemann *(University of Rochester, USA)*
R. Troy Taylor *(Pennsylvania State University, USA)*
Kohei Yatabe *(Waseda University, Japan)*
David Zartman *(Washington State University, USA)*

Winners

First Place: Kay Gemba *(University of Hawaiʻi at Mānoa, USA)*

Equal Second Place: Yu Shiduo, Xu Lingji and Yang Long *(Northwestern Polytechnical University, China)*;
Yuta Enomoto *(Waseda University, Japan)*

Equal Third Place: James Esplin and Matthew Shaw *(Pennsylvania State University, USA)*;
Sahar Hashemgeloogerdi *(University of Rochester, USA)*

APPENDIX A. PROBLEM AND SOLUTION NOTES

International Student Challenge Problem in Acoustic Signal Processing 2014

Background. A truck with a 4-stroke diesel engine travels along a straight road with constant speed. Near the road is a microphone that senses the radiated acoustic noise from the truck during its passage past the microphone. The output of the microphone is sampled at the rate of 12,000 samples/second and 30 seconds of data are recorded during the truck's transit which can be found in the attached *wav* file. During the recording of the data, the speed of sound propagation in air was a constant 347 m/s.

Problem: Assuming that the truck is a point source,

- Plot the spectrogram of the acoustic data *wav* file
- Given that the strongest spectral line is the *engine firing rate*, calculate the truck's:

(1) engine firing rate (in Hz),

(2) cylinder firing rate (in Hz),

(3) number of cylinders,

(4) tachometer reading (in revolutions/minute),

(5) speedometer reading (speed in km/hour),

(6) distance (in meters) of the closest point of approach of the truck to the sensor,

(7) time (in seconds) at which the closest point of approach occurs.

Right Click Here to Download file:

https://acousticstoday.org/wp-content/uploads/2014/04/truck30sec.wav

Your solution should detail your approach and reasoning to solve the problem, as well as your best estimates of the above parameters.

ASA Signal Processing in Acoustics Technical Committee Solution Notes to 2014 International Student Challenge Problem

Two approaches to solving the problem are considered below: one is based on time-frequency analysis and the Doppler Effect, the other on nonlinear least squares estimation of the parameters. A comparison of the parameters estimated using each of these two approaches (below) are found to be in close agreement.

Solution Method 1. Doppler Effect Approach

1. Generate a spectrogram for the digital time series output of the microphone during the truck's transit (*.wav* file) using the fast Fourier transform (FFT) with parameters: FFT size = 256*1024 samples, window length = 8*1024 samples, frequency bin width = fs/FFTsize ≈0.048 Hz, where fs is the sampling rate (12,000 samples/s) – see Fig. 1. The strongest line corresponds to the engine firing rate (EFR), which is observed at a frequency of about 120 Hz. The EFR is observed to change systematically with time due to the acoustical Doppler Effect. There is a harmonic series with a fundamental frequency of about 20 Hz, which corresponds to the cylinder firing rate (CFR). The Doppler Effect is more readily observed on the higher frequency harmonics. The number of cylinders is given by the EFR/CFR=6. The number of cylinders (6) is confirmed by visual inspection because every sixth harmonic of the CFR is a strong spectral line.

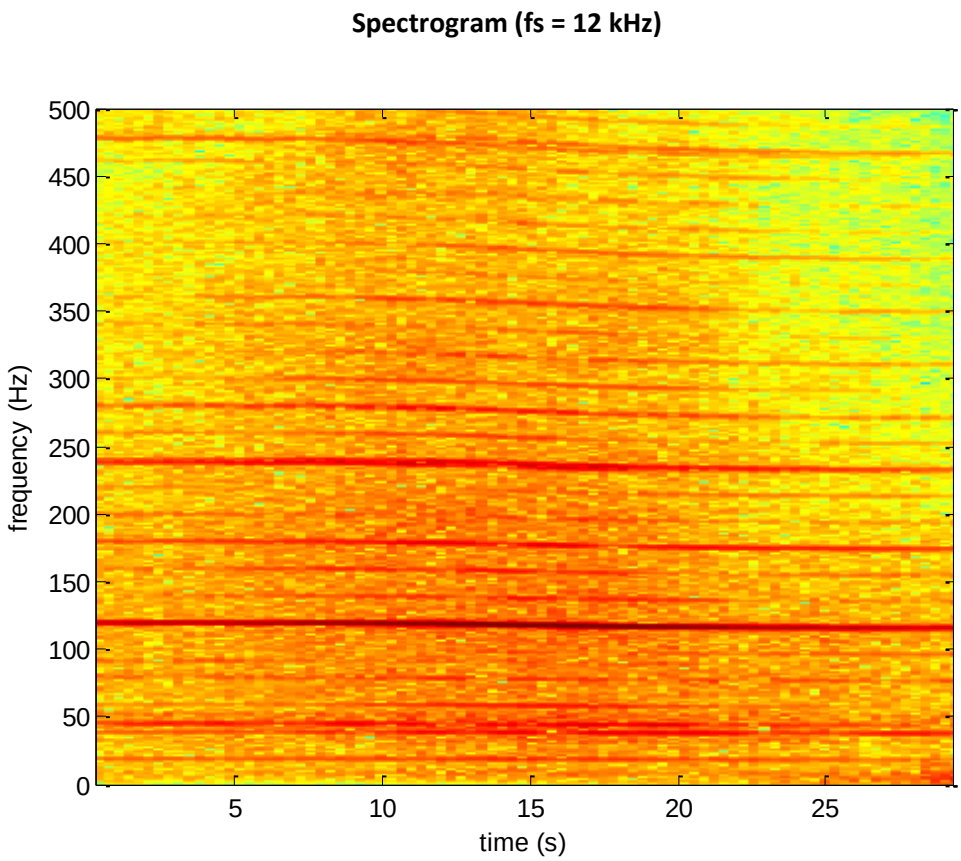

FIG. 1 Spectrogram showing the variation with time of the spectral components of the signal.

The truck's transit past the sensor is represented diagrammatically in Fig. 2(a), where v is the (assumed constant) velocity of the truck and R_s is the distance of the closest point of approach (CPA) of the truck to the sensor. As noted above, the instantaneous frequency of the EFR spectral line is observed to change with time due to the Doppler Effect, which can be modelled by the curve in Fig. 2(b). The up-Doppler and down-Doppler asymptotes are denoted by $f(-\infty)$ and $f(+\infty)$, respectively. The time τ_c is the time when the source is at the CPA and $f(\tau_c)$ is the instantaneous frequency (IF) of the signal received at the sensor at this time. Similarly, t_c is the time when the IF of the received signal is equal to the constant source (or rest) frequency f_0. Note that at this time (t_c), the source is *past* CPA. In other words, the IF of the received signal is equal to the source frequency f_0 at a later time $t_c = \tau_c + R_c / c$, where R_c/c is the time delay for the sound to propagate at a constant speed c from the source to the sensor when the source is at CPA. The IF of the signal received at the sensor is given by[1]

$$f(t) = \alpha + \beta p(t;\tau_c, s), \tag{1a}$$

where

$$\alpha = f_0 c^2 / \left(c^2 - v^2\right), \tag{1b}$$

$$\beta = -f_0 c v / \left(c^2 - v^2\right), \tag{1c}$$

$$s = \frac{R_c (c^2 - v^2)^{1/2}}{vc}, \tag{1d}$$

and

$$p(t;\tau_c, s) = \frac{t - \tau_c}{\left[s^2 + (t - \tau_c)^2\right]^{1/2}} . \tag{1e}$$

The asymptotic expressions for $f(t)$ are given by

$$f(-\infty) = \frac{f_0}{1 - v/c}, \tag{2a}$$

$$f(+\infty) = \frac{f_0}{1 + v/c}. \tag{2b}$$

The frequency estimates of the two asymptotes can be used to provide estimates of the source (or rest) frequency $\hat{f}_0$ and the source speed $\hat{v}$:

$$\hat{f}_0 = \frac{2\hat{f}(-\infty)\hat{f}(+\infty)}{\hat{f}(-\infty) + \hat{f}(+\infty)} \tag{3a}$$

$$\hat{v} = c\frac{\hat{f}(-\infty) - \hat{f}(+\infty)}{\hat{f}(-\infty) + \hat{f}(+\infty)} \tag{3b}$$

where the ˆ symbol denotes estimation of the parameter.

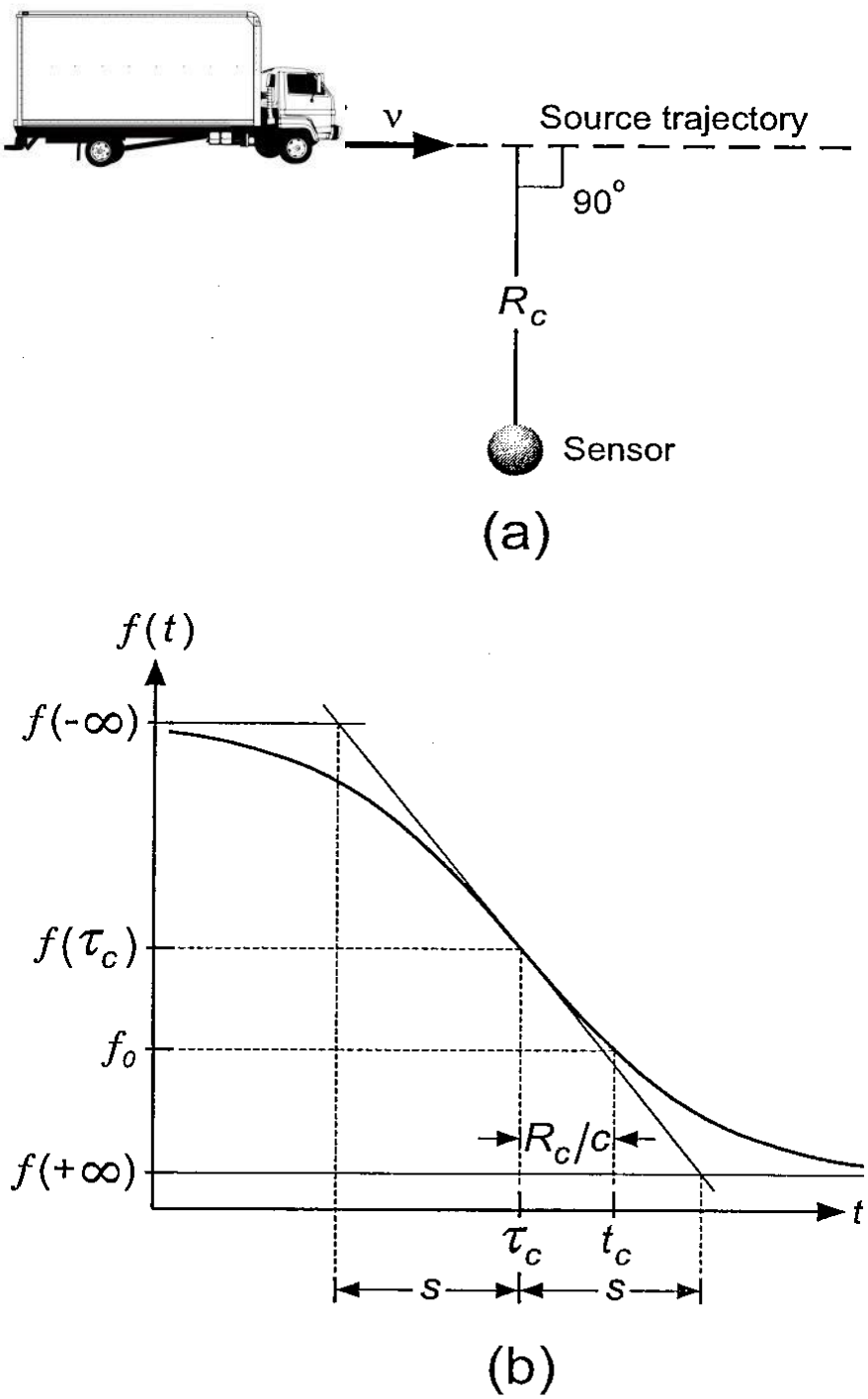

FIG. 2. (a) Geometry of a stationary sensor and a moving source traveling in a straight line at constant speed. (b) A typical time-frequency curve

Now Fig. 1 indicates that the variation with time of the IF is negligible during the first and last 5 s of data, so process these two time frames to estimate the up Doppler frequency asymptote $f(-\infty)$ and the down Doppler frequency asymptote $f(+\infty)$, using the fast Fourier transform (FFT) with parameters: FFT size = 256×1024 samples, window length = 64×1024 samples, frequency bin width = fs/FFTsize ≈0.048 Hz, where fs is the sampling rate (12,000 samples/s) – see Fig. 3.

Frequency spectra (fs = 12 kHz)

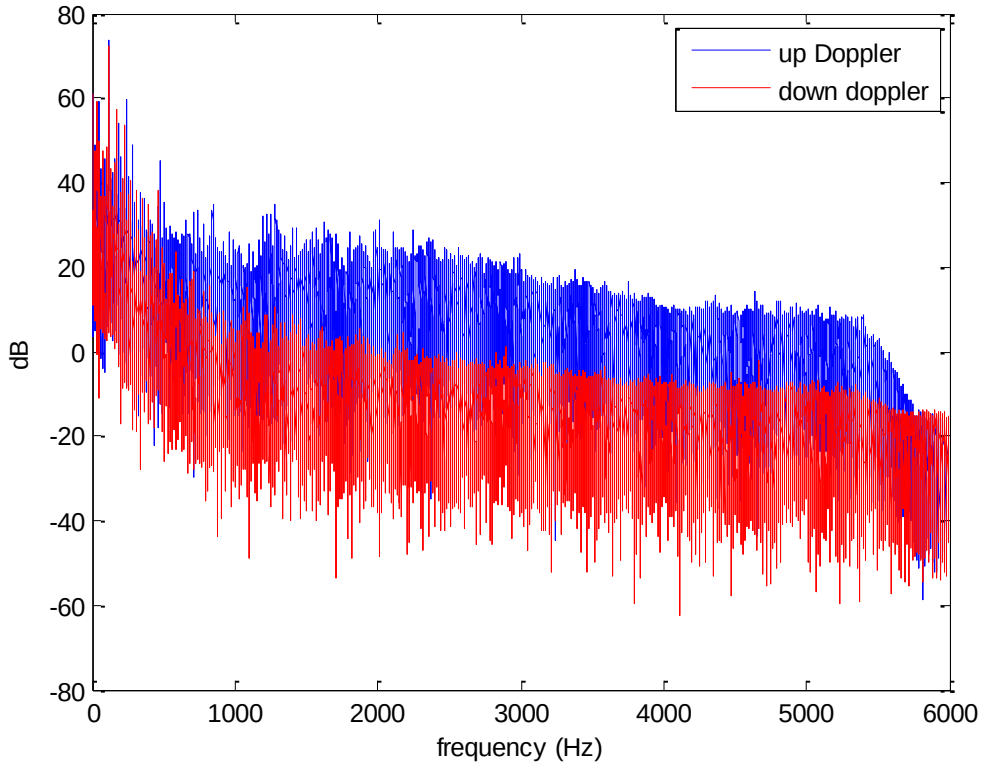

FIG. 3. Frequency spectra of the initial and final 5 s of microphone output data.

Zoom the spectra to localise the asymptotes of the EFR – see Fig. 4. Hence, the IF estimates $\hat{f}(-\infty) \approx 120.53$ Hz and $\hat{f}(+\infty) \approx 116.78$ Hz. Substituting these values into (3a) and (3b), where $c = 347$ m/s, gives:

$$\hat{f}_0 = \frac{2\hat{f}(-\infty)\hat{f}(+\infty)}{\hat{f}(-\infty) + \hat{f}(+\infty)} = 118.62 \text{ Hz} \qquad (4a)$$

$$\hat{v} = c\frac{\hat{f}(-\infty) - \hat{f}(+\infty)}{\hat{f}(-\infty) + \hat{f}(+\infty)} = 5.49 \text{ m/s} = 19.76 \text{ km/hr} \qquad (4b)$$

So the source (or rest) frequency of EFR is 118.62 Hz and the source frequency of the CFR is 19.77 Hz.

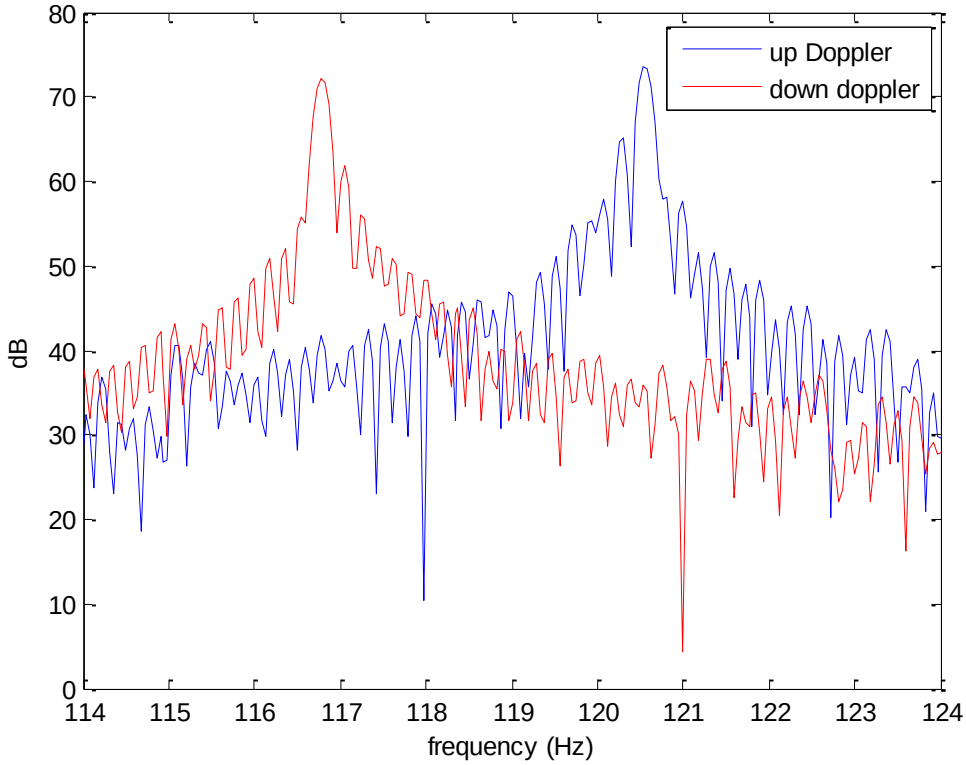

FIG. 3. Zoom spectra to estimate the frequency asymptotes of the Doppler shifted EFR. Note FFT size is 256*1024 samples, window lengths are 64x1024 samples from which the frequency asymptotes are 120.53 Hz and 116.78 Hz.

{f1 = 120.5292 Hz, f2 = 116.7755 Hz, v = 5.4888 m/s, f0 = 118.6227 Hz}

When the truck is near the CPA, the IF of the received signal decreases rapidly with time – see Fig. 2(b). The maximum magnitude for the rate of change of $f(t)$, which occurs when $t = \tau_c$, is given by

$$g_{\max} = \left| \frac{df(t)}{dt} \right|_{t=\tau_c} = \frac{f_0 c^2 v^2}{R_c \left(c^2 - v^2\right)^{3/2}}. \qquad (5)$$

The corresponding IF of the received signal at $t = \tau_c$ is

$$f(\tau_c) = \alpha = \tfrac{1}{2}\left[f(-\infty) + f(+\infty)\right], \qquad (6)$$

which is larger than the source frequency f_0. Reiterating, when the source is at the CPA ($t = \tau_c$), the IF of the *received* signal is $f(\tau_c)$, *not* f_0. Owing to the propagation delay R_c / c, the IF of the *received* signal is equal to f_0 at a later time $t_c = \tau_c + R_c / c$ - see Fig. 2(b).

The IF of the EFR can be estimated using the fast Fourier transform (FFT) with parameters: FFT size = 256×1024 samples, window length = 2×1024 samples, frequency bin width = fs/FFTsize ≈0.048 Hz, where fs is the sampling rate (12,000 samples/s). Figure 5 shows the variation with time of the raw IF estimates of the EFR as blue circles with a 5 sample smoothed version represented by the red line. Using the smoothed IF estimates, the parameter R_c can be estimated using either:

$$\hat{R}_c = \left(\hat{t}_c - \hat{\tau}_c\right)c \approx 34.3 \text{ m} \tag{7}$$

where $c = 347$ m/s, and from Fig. 5, $\hat{t}_c = 15.7392$ s with $\hat{\tau}_c = 15.6404$ s.

{tauc = 15.6404 s, tc = 15.7392 s, Rc = c*(tc-tauc) = 34.2920 m}

or:

$$\hat{R}_c = \frac{\hat{f}_0 c^2 \hat{v}^2}{\hat{g}_{\max}\left(c^2 - \hat{v}^2\right)^{3/2}} \approx 34.9 \text{ m} \tag{8}$$

where, from Fig. 5. $\hat{g}_{\max} = 0.2950$

{gmax = 0.2950, Rc = f0*(cv)^2/(c^2-v^2)^1.5/gmax = 34.9199 m}

Instantaneous frequency estimates (fs =12 kHz)

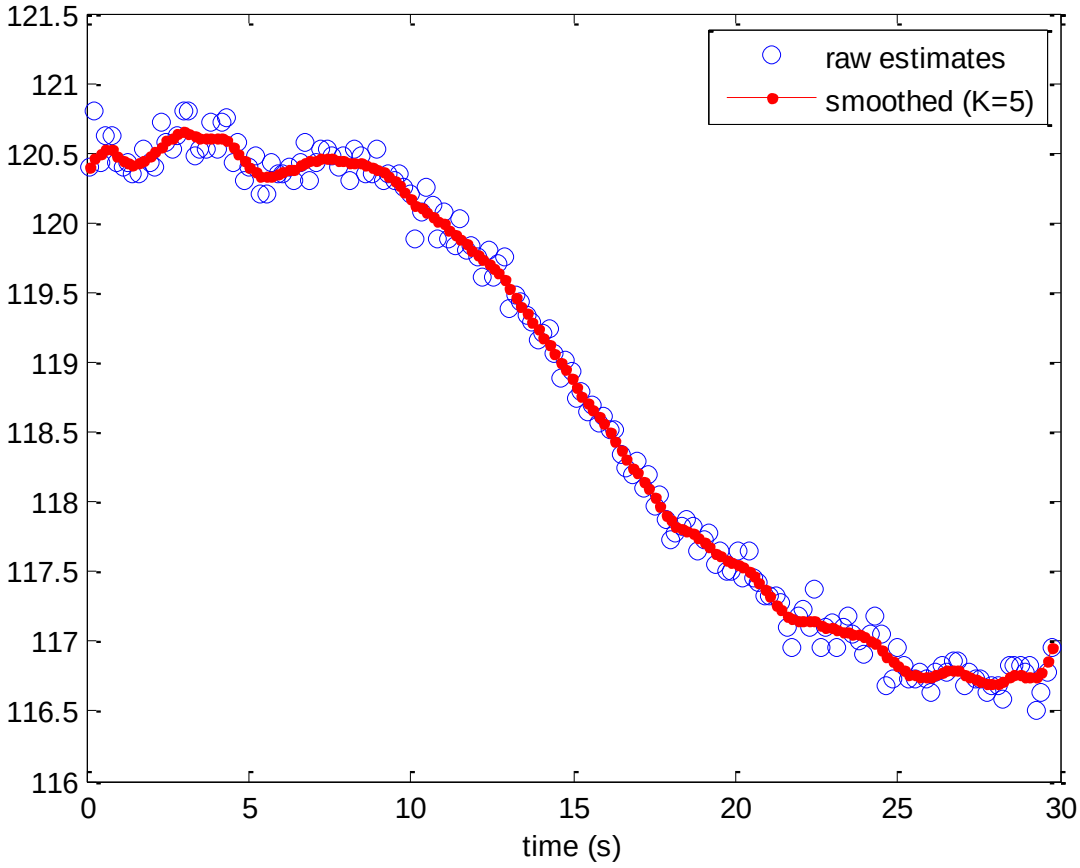

FIG. 4. Variation with time of the instantaneous frequency estimates of the EFR

Finally, by using this approach, the estimates of the parameters are:

(1) engine firing rate (in Hz): EFR= $\hat{f}_0 \approx 118.6$ Hz

(2) cylinder firing rate (in Hz): CFR ≈ 19.8 Hz

(3) number of cylinders: 6

(4) tachometer reading (in revolutions/minute), The tachometer reading is the crank shaft rate, which for a 4 stroke engine, is equal to $2 \times \text{CFR} \times 60 \approx$ 2370 rpm

(5) speedometer reading (speed in km/hour): $\hat{v} \approx 19.8$ km/hr

(6) distance (in meters) of the closest point of approach of the truck to the sensor:

$$\hat{R}_c = \left(\hat{t}_c - \hat{\tau}_c\right)c \approx 34.3 \text{ m}; \quad \hat{R}_c = \frac{\hat{f}_0 c^2 \hat{v}^2}{\hat{g}_{\max}\left(c^2 - \hat{v}^2\right)^{3/2}} \approx 34.9 \text{ m}$$

(7) time (in seconds) at which the closest point of approach occurs: $\hat{\tau}_c = 15.64$ s

The truck driver advised that the speedometer dial reading of the truck was 20 km/hr and the tachometer dial reading was 2350 Hz.

Solution Method 2. Nonlinear Least Squares (NLS) Estimation of the Parameters

The parameters $\{f_0, v, \tau_c, R_c\}$, or equivalently $\{\alpha, \beta, \tau_c, s\}$, can be estimated using a NLS approach, i.e., by minimizing the sum of the squared deviations of the noisy IF estimates from their predicted values[1]. This approach has been applied to the same truck transit previously but for a 45 s (rather than 30 s) observation interval. Also the data were downsampled to 1 kHz.

Figure 6 shows the variation with time of the *raw* IF estimates of the EFR in blue and the time-frequency curve computed using (1a) – (1e) with the NLS-optimized parameters in red. The estimated values of the source parameters were:

$$f_0 = 118.64 \text{ Hz}$$

$$v = 21.29 \text{ km/hr}$$

$$\tau_c = 20.81 \text{ s}$$

$$R_c = 34.75 \text{ m.}$$

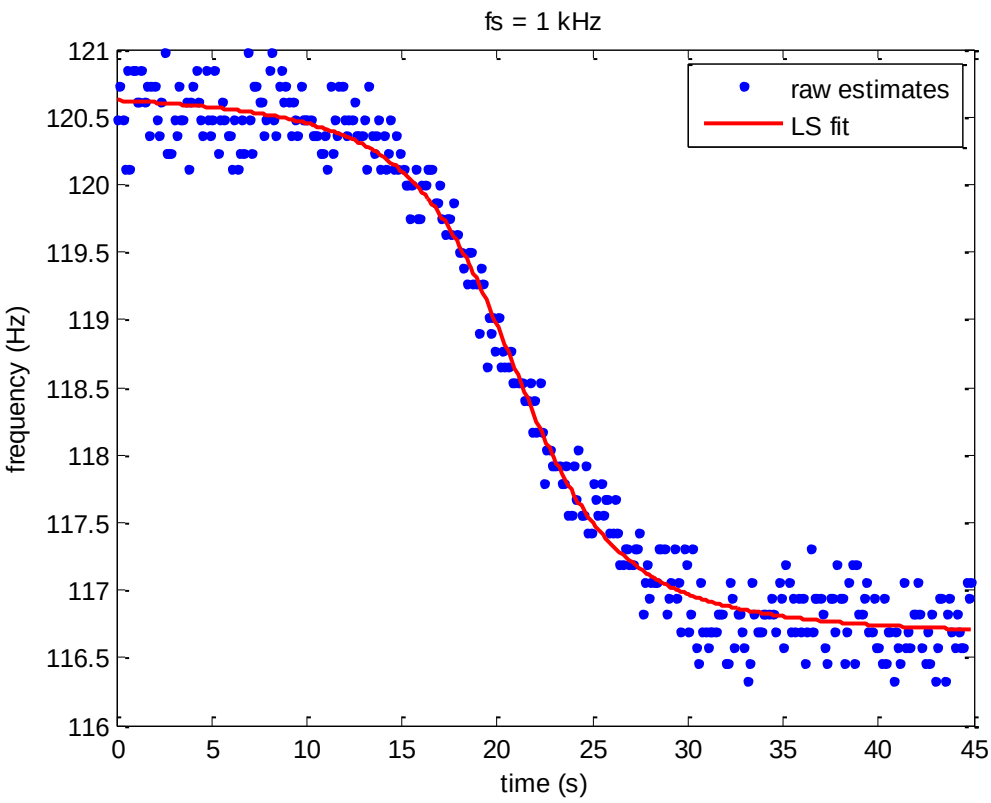

FIG. 6. Variation with time of the instantaneous frequency estimates (blue-filled circles) of the signal received by a microphone during the truck transit, and the nonlinear least squares fit (solid red line) to the observations.

{f0 = 118.6402 Hz, v = 5.9143 m/s, tauc = 20.8102 s, Rc = 34.7549 m}

Similarly, Fig. 7 shows the variation with time of the *smoothed* IF estimates of the EFR in blue and the time-frequency curve computed using (1a) – (1e) with the NLS-optimized parameters in red. The estimated values of the source parameters were:

$$f_0 = 118.64 \text{ Hz}$$

$$v = 21.29 \text{ km/hr}$$

$$\tau_c = 20.81 \text{ s}$$

$$R_c = 34.85 \text{ m.}$$

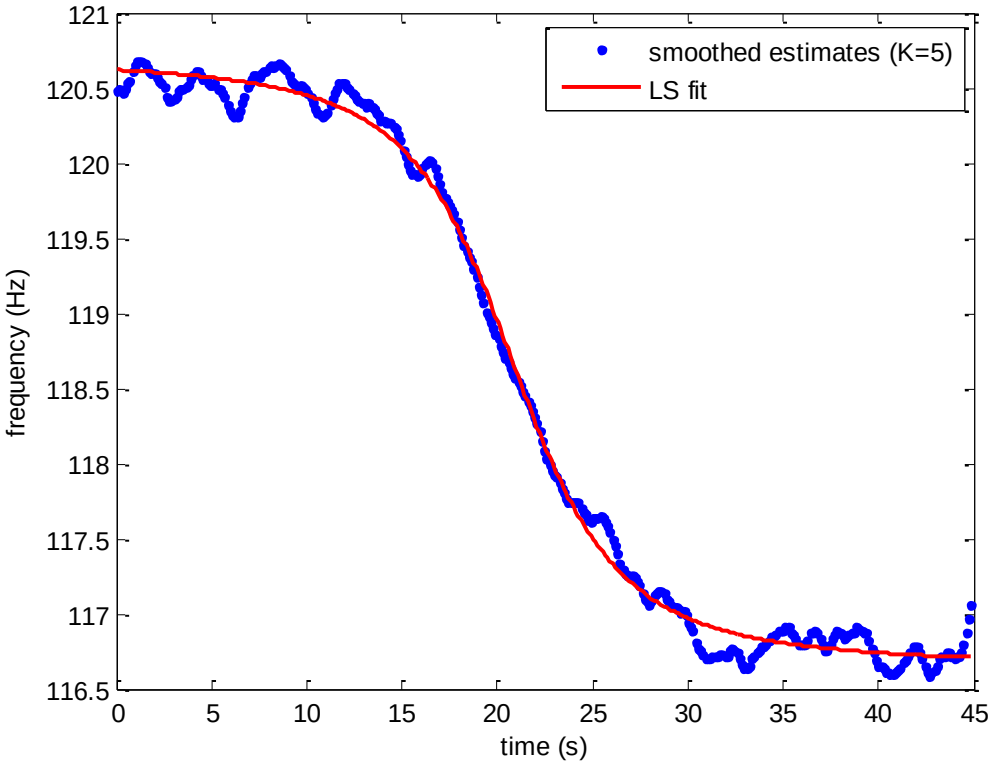

FIG. 7. Variation with time of the *smoothed* instantaneous frequency estimates (blue-filled circles) of the signal received by a microphone during the truck transit, and the nonlinear least squares fit (solid red line) to the observations.

{f0 = 118.6404 Hz, v = 5.9132 m/s, tauc = 20.8098 s, Rc = 34.8516 m}

{For this case, f(-∞)=120.6972 Hz and f(+∞)=116.6525 Hz, so fmean=118.6749 Hz}