# Letters

## Bidirectional Doppler Signal Analysis Based on a Single RF Sampling Channel

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*Abstract*—**Recent introductions of low-cost high-performance devices have finally made feasible the implementation of "undersampling" techniques in different application areas. A significant example is represented by Doppler analysis, which typically involves the inspection of narrowband spectra around an RF carrier. This letter describes the implementation of an aliasing-free CW ultrasound Doppler system employing a "single" undersampling channel, in place of the two "quadrature" sampling channels already proposed by other authors. Implications in terms of clutter rejection are also discussed.**

### I. Introduction

BASE-BAND analysis of Doppler frequencies originated by moving targets (e.g., flying objects in radar environments or blood erythrocytes in ultrasound applications), typically involves demodulation of the received radio-frequency (RF) signal on two quadrature channels [1]. This approach presents a couple of intrinsic technical difficulties: to maintain a good linearity over a wide dynamic range, and to ensure an appropriate phase and amplitude matching between the two channels.

The possibility of eliminating much of the electronic circuits involved in quadrature demodulators, has attracted investigators in different application areas [2]–[5]. In [2] and [3], in particular, demodulation of narrowband ultrasound echographic signals is obtained by sampling the received RF signal at a rate lower than twice the highest absolute frequency (undersampling). In both cases, however, a "quadrature" technique is proposed, making reference to two channels, where the received signal is sampled with a reciprocal delay of one-fourth the period of the transmitted carrier [6].

### II. Single Channel Analysis

We have investigated the practical implications of using, in ultrasound Doppler analysis, a single channel of analog-to-digital (A/D) Conversion operating at RF. The first problem that we have faced is possible alias distortion due to overlapping of subsequent spectral repetitions generated by the undersampling process. When the equivalent complex band-pass signal [7] is not reconstructed, in fact, adjacent images of the original spectrum are likely to lie over each other.

However, this distortion can be avoided by properly choosing the sampling frequency $F_s$ with respect to the carrier frequency $F_o$. In particular, $F_s$ can be set at such a value that one of the images of the original narrowband Doppler spectrum results centered around the frequency $F_s/4$ [8]. In this case, if the bandwidth $B_d$ is narrower than $F_s/2$, any overlapping between adjacent spectral images is avoided (see Fig. 1), while flow direction discrimination is still allowed. Doppler frequencies $> F_o$ (corresponding to forward flow) are in fact translated between $F_s/4$ and $F_s/2$, while Doppler frequencies $< F_o$ (corresponding to reverse flow) are translated between $F_s/4$ and zero. The main limitation is that, for a given bandwidth $B_d$, the "minimum" sampling frequency $F_s$ has here to be $2 \cdot B_d$, while in quadrature sampling systems it is just equal to $B_d$.

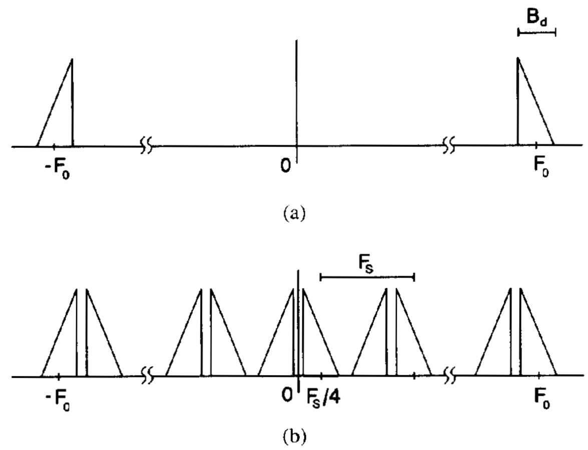


Fig. 1. (a) Spectrum of a Doppler signal modulating the carrier frequency $F_o$ over a bandwidth Bd. (b) Spectrum of the Doppler signal after undersampling at a frequency $F_s$ fixed according to (2).

By looking at pictures like that in Fig. 1(b), one can realize that the discussed conditions correspond to having a carrier frequency $F_o$ equal to an odd number of times the baseband center frequency $F_s/4$, i.e.:

$$F_o = (2K + 1)(F_s/4) \tag{1}$$

(where $K$ is an integer number), or, in equivalent terms:

$$F_s = 4F_o/(2K + 1) \tag{2}$$

Therefore, given the carrier frequency $F_o$, $K$ is chosen as the integer number which, when substituted in (2), yields the sampling frequency nearest to two times the expected Doppler bandwidth $B_d$.

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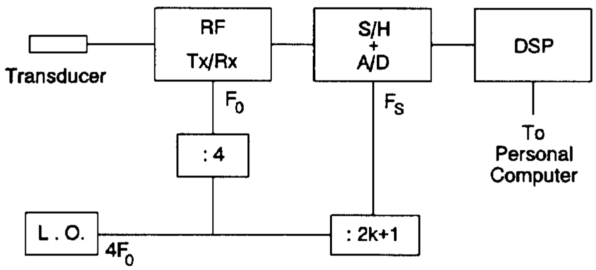


Fig. 2. Block diagram of the experimental Doppler system.

## III. Clutter Rejection

The second problem to be considered is the elimination of high-level low-frequency components originated by fixed and/or slowly moving targets ("clutter"). In conventional systems the quadrature components of the demodulated Doppler signal are high-pass (HP) filtered prior to be A/D converted with, typically, 8-bit resolution. Since this analog filtering is omitted here, A/D conversion must be performed over a wider dynamic range and, especially in continuous wave (CW) systems, at least 10-12 bits become necessary.

HP filtering can be suitably performed in the digital domain in all cases where the system is equipped with a software-reconfigurable digital signal processor (DSP). In particular, when the Doppler signal is analysed through a fast Fourier transform (FFT) algorithm, the undesired components can be directly suppressed in the frequency domain, by setting to zero the corresponding spectral samples.

However, this frequency domain filtering fails if the effect of clutter is not limited to a few frequency bins. Since an FFT is always performed on signal segments of finite length (i.e., on a limited number of points), each frequency component is spread over a large number of bins according to the sinc function response. Possible strong echoes related to fixed or slowly moving targets can therefore generate spectral "sidelobes" capable of masking weaker, but more significant, Doppler components. To avoid this undesirable effect, the use of a weighting window, such as the popular Hamming function, can here play a fundamental role. As known [9], these windows involve lower sidelobes than a rectangular window, since they combine within a single main lobe most of the spectral energy associated with a given continuous wave input signal. The above mentioned masking of weaker Doppler components by a high level clutter can thus be avoided.

## IV. Experiments

We have experimentally verified the above considerations by implementing a Doppler ultrasound system organized as in Fig. 2. The transducer is here excited in a Continuous Wave mode at $F_o = 4$ MHz. The received signal, after proper RF amplification, is sampled at approximately 15 100 Hz. This sampling frequency, obtained by dividing a 16 MHz Master Clock by a factor $2K+1 = 1057$, was chosen in order to allow Doppler shifts up to almost $\pm 4$ kHz to be properly analyzed.

For sampling, the AD9100 Sample/Hold (by Analog Devices, Norwood, MA) was chosen for its extremely low aperture jitter (1 ps rms), while the less stringent timing requirements for the A/D converter (one 12 bit conversion must be completed in several tens of $\mu$s) has led to the choice of the popular AD7870. Real-time FFT is performed by means of a TMS320C25 (by Texas Ins.) DSP, which is also used to impose a programmable window on the input signal, as well as a programmable "mask" on the spectral output (i.e., by zeroing undesired components around $F_s/4$).

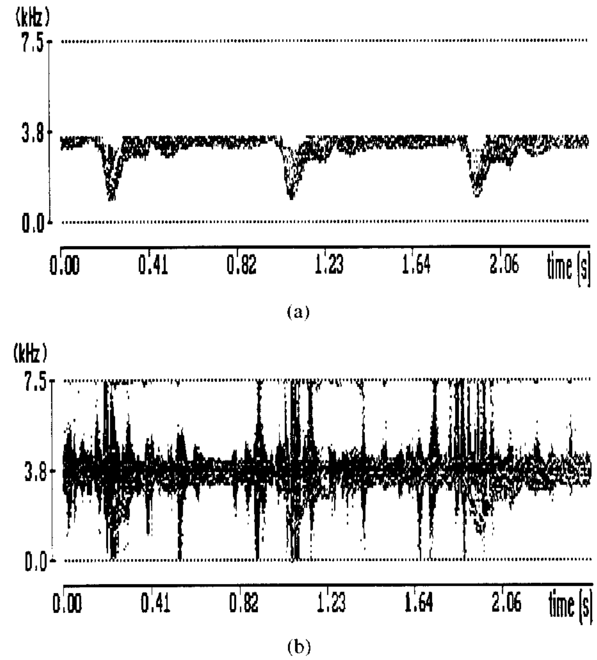


Fig. 3. Spectrograms obtained from inspection of a human carotid artery. In (a), a Hamming window was imposed on the Doppler data, while in (b) a rectangular window was used.

The DSP is interfaced to a Personal Computer for displaying output spectral data. Since the system is aimed at analyzing Doppler signals generated by blood flow, the display has been organized according to the "spectrogram" format used in most instruments for medical use. Examples are given in Fig. 3, where the grey levels in each vertical frequency-line correspond to different spectral amplitudes. Fig. 3(a) shows the spectrogram obtained according to the discussed method when blood flow in a human carotid artery was investigated. Hamming weighting of FFT input data was included and three FFT output samples around $F_s/4$ have been set to zero. Since the beam-to-vessel angle was here larger than 90°, a reverse flow has been detected. By using angles lower than 90°, forward flows were obtained, with Doppler frequencies detected in the $[F_s/4 - F_s/2]$ range. It can be observed that this spectrogram, except for zero-Doppler frequency being shifted to $F_s/4 \approx 3.8$ KHz, is equivalent to those which are obtained with conventional systems.

Fig. 3(b) shows the spectrogram which is obtained if the same input data are not Hamming weighted: it is apparent how much the significant signal is masked by the sidelobes of spectral components induced by the vessel walls moving at the heartbeat rate. Even when a unidirectional flow is investigated, these sidelobes spread over both positive and negative frequency ranges.

## V. Conclusion

The correct operation of the method discussed here is demonstrated by the equivalence between results like that in Fig. 3(a) and spectrograms obtained with conventional approaches. By fixing the sampling frequency according to (2), a single A/D conversion channel can be substituted to quadrature demodulators, HPF's and A/D converters. Frequency domain filtering, in particular, can be suitably performed by the same DSP used for Doppler frequency analysis, provided a proper weighting window is imposed to the input signal.

When compared to conventional systems, the major possible limitations can be found in dynamic range and noise performance. Simple low-pass filters following the quadrature demodulators must in fact be replaced by a highly tuned and accurate band-pass filter. The absence of time-domain high-pass filtering then imposes severe requirements to the A/D converter resolution.

The problems of noise performance and clutter rejection discussed above, are similar to those faced in 2-D flow mapping systems [10], where Doppler signals related to different range cells are not independently filtered before sampling. Actually, the method discussed and implemented here on a CW system, can also be used for pulsed wave analysis, provided that the pulse repetition frequency (PRF) fulfills the relationship given in (2) for $F_s$ rate. In this case, the integer $K$ should also be chosen at such a value to yield a PRF capable of avoiding possible range-ambiguities, as in conventional systems.

## References


[1] D. H. Evans, W. N. McDicken, R. Skidmore, J. P. Woodcock, *Doppler Ultrasound - Physics, Instrumentation and Clinical Application.* Chichester: Wiley, 1989, pp. 84–98.

[2] J. E. Powers, D. J. Phillips, M. A. Brandestini, and R. A. Siegelman, "Ultrasound phased array delay lines based on quadrature sampling techniques," *IEEE Trans. Sonics Ultrason.*, vol. SU-27, pp. 287-294, 1980.

[3] F. Forsberg and M. O. Jorgensen, "Sampling technique for an ultrasound Doppler system," *Medical and Biological Eng. and Computing*, pp. 207-210, Mar. 1989.

[4] R. Groshong and S. Ruscak, "Undersampling techniques simplify digital radio," *Electronic Design*, pp. 67-78, May 1991.

[5] J. Jensen, Oral Communication, 7th New England Doppler Conf., Interlaken, May 1993.

[6] S. H. Chang, S. B. Park, and G. H. Cho, "Phase-error-free quadrature sampling technique in the ultrasonic b-scan imaging system and its application to the synthetic focusing system," *IEEE Trans. Ultrason., Ferroelec. Freq. Contr.*, vol. 40, pp. 216-223, 1993.

[7] A. V. Oppenheim and R. W. Schafer, *Discrete-time Signal Processing.* New York: Prentice-Hall, 1989, pp. 686-688.

[8] L. Bessi, "Tecniche Digitali per Elaborazione Dati nei Flussimetri Doppler ad Ultrasuoni," Laurea Thesis, University of Florence, June 1991.

[9] F. J. Harris, "On the use of windows for harmonic analysis with the discrete Fourier transform," *Proc. IEEE*, vol. 66, pp. 51-83, 1978.

[10] I. A. Hein and W. D. O'Brien, Jr., "Current time-domain methods for assessing tissue motion by analysis from reflected ultrasound echoes - a review," *IEEE Trans. Ultrason. Ferroelec. Freq. Contr.*, vol. 40, pp. 84–102, 1993.