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RECOVERING A SHORT TIMESCALE SIGNAL FROM A PAIR OF LONG-DELAY VISARS

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Abstract. We introduce the benefits of analyzing VISAR data in the Fourier domain, particularly for recovering the short time scale signal component. In particular, by combining data from two VISARS having different long delays, we effectively reproduce the short time resolution ability of a short delay while retaining the superior sensitivity to absolute velocity of a long delay. Two different delays are generally desired, not only to untangle integer fringe skips, but to circumvent the fact that a single VISAR cannot record signal components of frequencies periodic with its reciprocal delay. Combining two different delays solves this. We treat the VISARs as linear filters and process and combine the signals in the Fourier domain with a direct equation, without any iteration of time-retarded equations. The technique is demonstrated with a numerical simulation.
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INTRODUCTION

An important optical diagnostic in shock physics is a velocity interferometer ("VISAR") [1, 2, 3, 4], which measures the velocity history of a target by producing a fringe phase shift $\phi(t)$ vs time recording. Light reflected from a target is passed through an interferometer having a delay τ between its arms, whose output intensity is recorded, which can be converted into a $\phi(t)$ record.

The VISAR has historically operated in a "derivative" or "short-delay" mode where the detector is slow relative to the delay. In this case the target velocity is well approximated to be proportional to $\phi(t)$. However modern detectors such as streak cameras can be as fast or faster than a typical delay of $\sim$0.1 ns. Alternatively, keeping the detector response time the same, one desires to increase a VISAR delay to more sensitively and accurately measure the long time scale (or absolute) velocity changes. In these cases the VISAR behaves in a "difference" or "long-delay" mode. But this has traditionally made analysis of the short time scale behavior problematic, requiring iteratively solving retarded equations.

Fundamentally, the VISAR is a kind of displacement interferometer, where the fringe phase measures (in units of wavelength) the change during interval τ in the roundtrip distance between the apparatus and target. Let the target's position history be $X(t)$, and the illuminating and reflecting beams be normal to the target motion. Then ϕ (units of cycles) is essentially

$$\phi(t) = 2\frac{X(t) - X(t-\tau)}{\lambda} \tag{1}$$

(See Ref. [4] for a detailed treatment). Lets define an experimentally measured signal

$$S(t) \equiv \lambda\phi(t)/2 = X(t) - X(t-\tau) \tag{2}$$

An example $S(t)$ is shown in Fig. 3 (middle), for both long-delay and classical short-delay modes. When $\tau \to 0$, we see that the difference becomes derivative-like and

$$S(t) \approx \tau\frac{\partial X}{\partial t} = \tau v \tag{3}$$

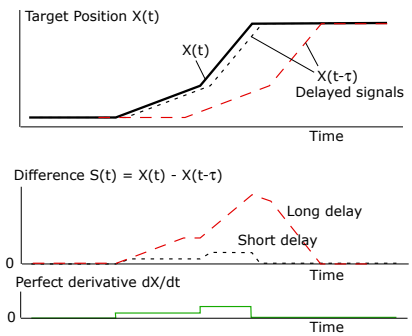

FIGURE 1. The velocity interferometer is a kind of displacement interferometer, where one arm sees a target delayed in time by τ relative to the other arm, and thus the fringes measure the change in target position over an interval τ. The short delay result (short dash) is similar to the perfect derivative dX/dt (bottom graph), which simplifies analysis. This paper deals with the long delay case (long dash), which had been problematic to analyze.

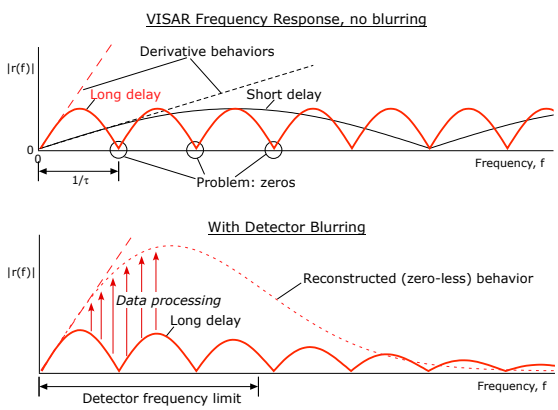

FIGURE 2. The VISAR frequency response has periodic zeros, spaced every $1/\tau$. This becomes important when the detector response is similar to or shorter than the delay. The lowest frequency behavior of a VISAR, where it is linear in frequency, approximates a derivative response (dashed lines). Everywhere besides the zeros, a long delay VISAR signal can be artificially boosted to behave similar to a derivative response. The issue of the zeros is solved by using two different delays.

DIFFERENCE OR LONG-DELAY MODE

With detectors fast compared to τ we are in the "difference" or "long-delay" mode. Previous authors (see section 3.2 of Ref. [4]) have explored recovering

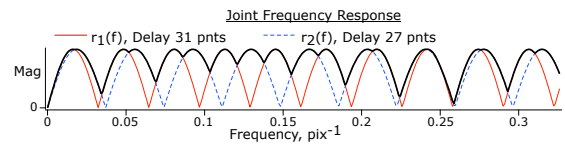

FIGURE 3. Frequency response $|r(f)|$ for a pair of VISARs having two slightly different delays (solid red & dashed blue), so that their zeros rarely overlap. A net response (thicker black) has fewer zeros.

$X(t)$ from $S(t)$ by iterative use of the retarded difference equation Eq. 2,

$$X(t) = S(t) + X(t-\tau) \tag{4}$$

There has been limited success with this. This author believes a more fruitful approach is in the Fourier domain rather than with time domain equations, because this makes more intuitive the deficiencies fundamental to the VISAR, and naturally suggests a strategy to correct for them. Theobald et al. have successfully used a frequency response approach[5] with a single VISAR to recover the short timescale response of shocked window refractive index.

FORBIDDEN SIGNAL COMPONENTS

For example, there are certain signal components that the VISAR cannot record, namely, those that are exactly periodic with τ. For example, if $X(t) = \sin(2\pi t/\tau)$ then Eq. 2 shows the measured signal $S(t) = 0$ everywhere. Since an arbitrary shape of $X(t)$ can be Fourier decomposed into a variety of frequencies, this means that components having frequencies near $1/\tau$, $2/\tau$, $3/\tau$, etc. will have near zero signal to noise ratio, which is bad. (See Fig. 2). This issue is not adequately discussed in traditional time domain methods of analyzing the retarded equation Eq. 4, but becomes immediately obvious when plotted in the Fourier domain.

VISAR AS A FILTER

Our solution is to model the VISAR as a linear filter producing signal $S(t)$, and that the difference equation represents an impulse response $R(t) = \delta(t) - \delta(t-\tau)$ consisting of a positive

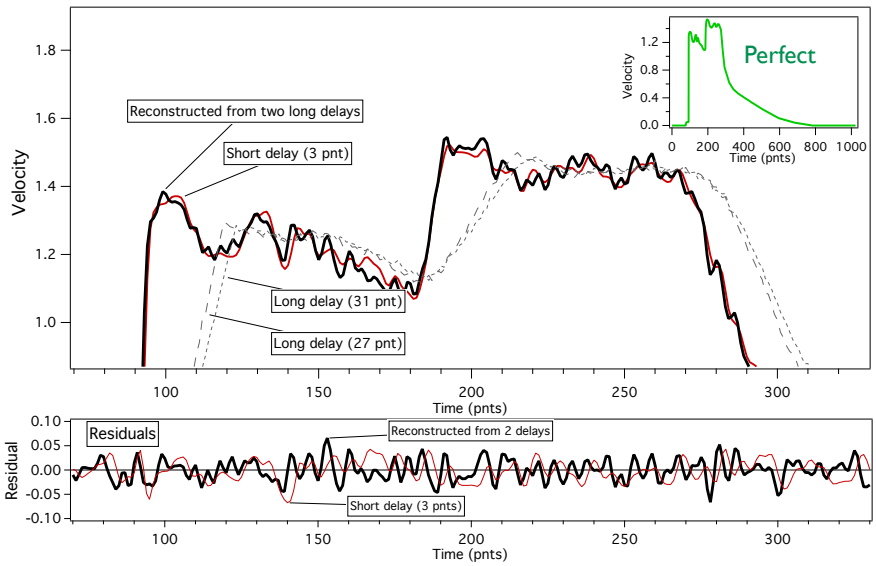

FIGURE 4. (Top graph) Reconstructed VISAR signal (thick black) from two long delay VISARs is similar to signal of a conventional short delay of 3 points (thin red), using simulated data with random noise. The two long delays have delays of 31 points (short dashed gray) and 27 points (long dashed gray). The residuals from the perfect signal (inset) are plotted in bottom graph.

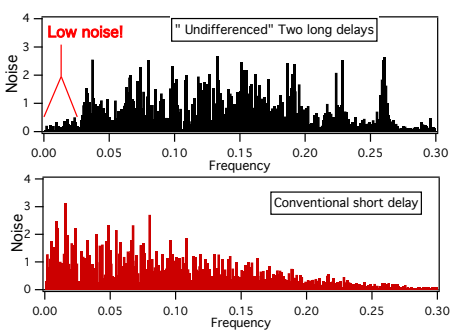

FIGURE 5. The FFT of residuals shows noise spectra, comparing this technique to conventional (3 pnt delay). Our technique produces much lower noise for absolute velocities (period>40 points), yet comparable noise averaged over mid to high frequencies. Choice of delays affects this.

and a delayed negative spike. So the data signal $S(t) = X(t) \otimes R(t)$ is the target position $X(t)$ convolved with the instrument impulse response.

It is conceptually useful to model detector blurring as a convolution of fringe phase with an impulse response $D(t)$, having frequency response $d(f)$, so that $S(t) = X(t) \otimes R(t) \otimes D(t)$, even though in reality it is a convolution of the complex fringe as in $W(t) = \gamma(t) e^{i2\pi\phi(t)} \otimes D(t)$. We find this (small signal) approximation works well everywhere except at any discontinuous jumps in velocity.

In Fourier space convolutions become multiplications. Let the lower case designate the Fourier transform, so $s(f) = FFT\ S(t)$ etc. Then the unblurred instrument response is $r(f) = 1 - e^{-i2\pi\tau f}$, and with detector blurring

$$r(f) = (1 - e^{-i2\pi\tau f})\, d(f), \tag{5}$$

and the VISAR output in frequency space is

$$s(f) = x(f) r(f). \tag{6}$$

Figure 2 shows $r(f)$ for the unblurred (top) and blurred (bottom) cases. The periodic zeros (interval $1/\tau$) in the magnitude of $r(f)$ are the prominent feature. They manifest the inability of a single VISAR to measure a signal that is exactly periodic with the delay τ. Note that a slow detector would have a very narrow frequency response that would make this issue moot, because $r(f)$ would only be significant for the lowest f before the first zero. The lowest f is where the derivative behavior occurs (where $r(f)$ is linear with f).

Inverse Solution

It is tempting to directly solve for the target motion via a division

$$x(f) = s(f)/r(f) \tag{7}$$

but the zeros in $r(f)$ obtained from a single VISAR thwarts this by creating infinities, since measurement noise inside $s(f)$ prevents the numerator from decreasing simultaneous with the denominator $r(f)$.

Combining Two Signals

Our solution is to get rid of the zeros by using a second VISAR measuring the same target but having a slightly different τ, and hence having different zero positions. (Conveniently, it is standard practice to use two VISARs, to resolve integer fringe skips.) The goal is to make it rare that two zeros are at the exact same frequency f, for the range of f most important for the science. Thus we prefer an irrational number for the two delay values. There is a variety of choice, and we explore here a ratio 31/27= 1.148.

Then we effectively combine the larger of each signal at each f to form a composite signal $x_{12}(f)$

$$x_{12}(f) = \frac{w_1(f)s_1(f)/r_1(f) + w_2(f)s_2(f)/r_2(f)}{w_1(f) + w_2(f) + \varepsilon} g(f) \tag{8}$$

where w_1 and w_2 are weights which should go to zero as $r(f)$ goes to zero, so that the noisier component is discriminated against. We use $w(f) = |r(f)|^2$ in the simulation, but power law exponents from 1 to 4 give about the same rms average noise to a few percent. The epsilon is a very small number (10^{-6}) to prevent the denominator from ever becoming zero (which ruins the inverse Fourier transform) and may be omitted.

To avoid high frequency noise where there is little science signal we then an apply a Gaussian blurring $g(f)$, which is an arbitrary apodization. We effectively use $g(f) = d^2(f)$ in the simulation (we actually omit $d(f)$ from $r(f)$ in Eq. 5). Then we inverse Fourier transform it to produce $X_{12}(t)$.

The result is then differentiated to convert it from a displacement to a velocity. VISAR phase data is often step-like, and to avoid ringing artifacts in the FFTs the data can be temporarily symmetrized by reflection about the time axis so that the boundaries match.

Noise Frequency Distribution

The results for simulated data on two VISARS of delay 27 and 31 points, a detector Gaussian blur of 3 points, added random noise, and an apodization Gaussian blur of 3 points are shown in Fig. 4, compared to a classical VISAR having a short delay of 3 points with the same added noise (of both detectors averaged to make it fair). The Fourier spectrum of the residuals (Fig. 5) shows that the absolute velocity determination (f <0.025, or features having periods greater than 40 points) is better than 4 times less noisy than the short delay VISAR. (Choice of delays affects this.) The rms mid to high frequency (f=0.025 to 0.3) average noise is only 40% larger than the conventional short delay ($\sim$10% of long delay), but obviously has different coloration.

In other words, by our technique one can get the long timescale performance of a long delay without sacrificing the short time scale performance of a short delay. The delay choice can be adjusted to optimize the noise coloration for the expected kind of science signal.

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