DOE/NV/25946--1671

Dynamic Surface Uncertainties Using Laser-based Interferometry

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Dunedin, New Zealand
Jan. 7-10, 2013

Joint work with
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This work was done by National Security Technologies, LLC, under Contract No. DE-AC52-06NA25946 with the U.S. Department of Energy and supported by the Site-Directed Research and Development Program.

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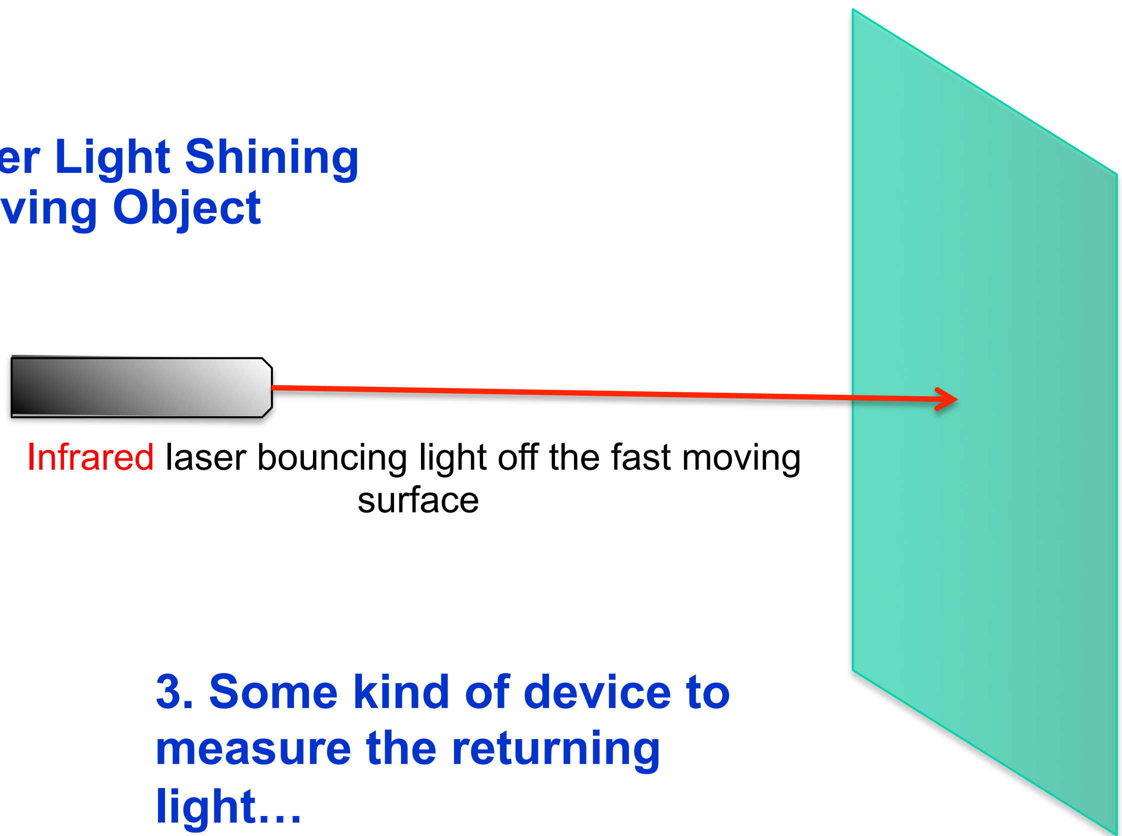
A modern interferometer

1. Laser Light Shining on Moving Object



Infrared laser bouncing light off the fast moving surface

2. Moving Surface

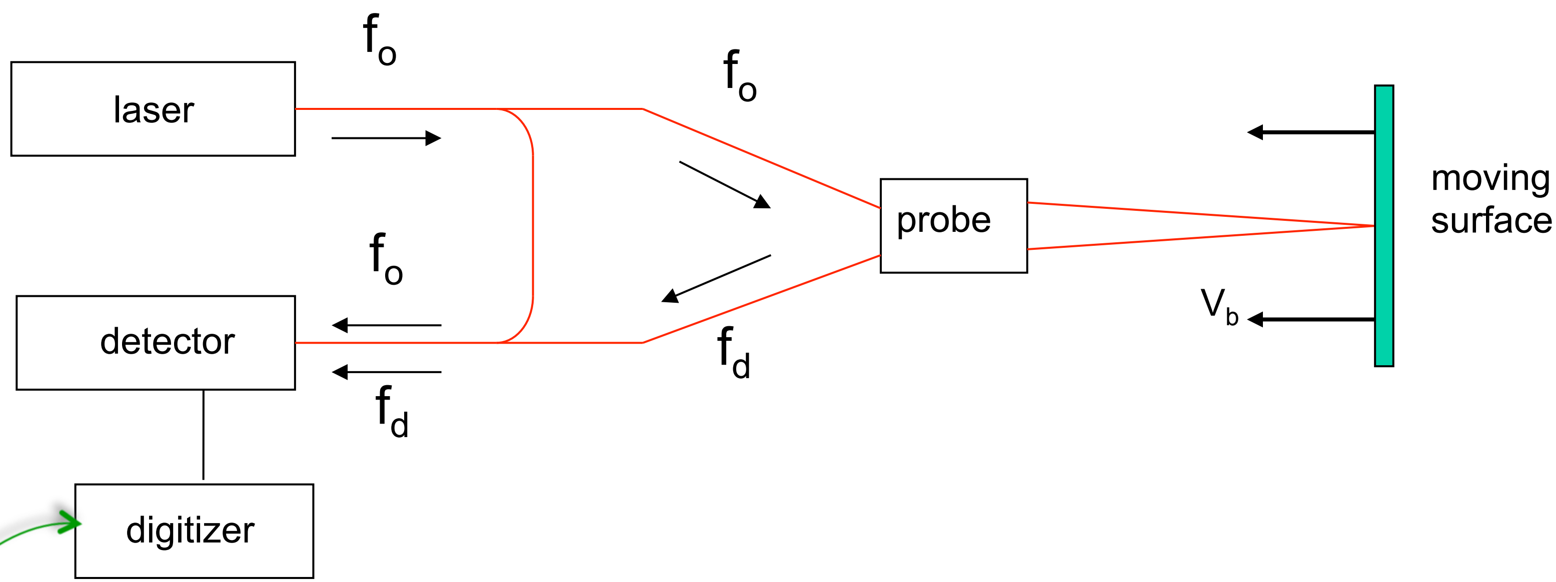
A “Fast” Moving Surface travelling at speed v_b

3. Some kind of device to measure the returning light…

1. PDV is a Simple, Portable Diagnostic Tool

Concept: Generate a beat signal using fiber transport

Photonic **D**oppler **V**elocimetry (PDV) works by fiber-optic mixing of undoppler-shifted light with doppler-shifted light and measuring the beat frequency



Beat frequency = $f_b = f_d - f_o = 2(v/c)f_o$

Example: at 1550 nm laser and v = 1000 m/s:

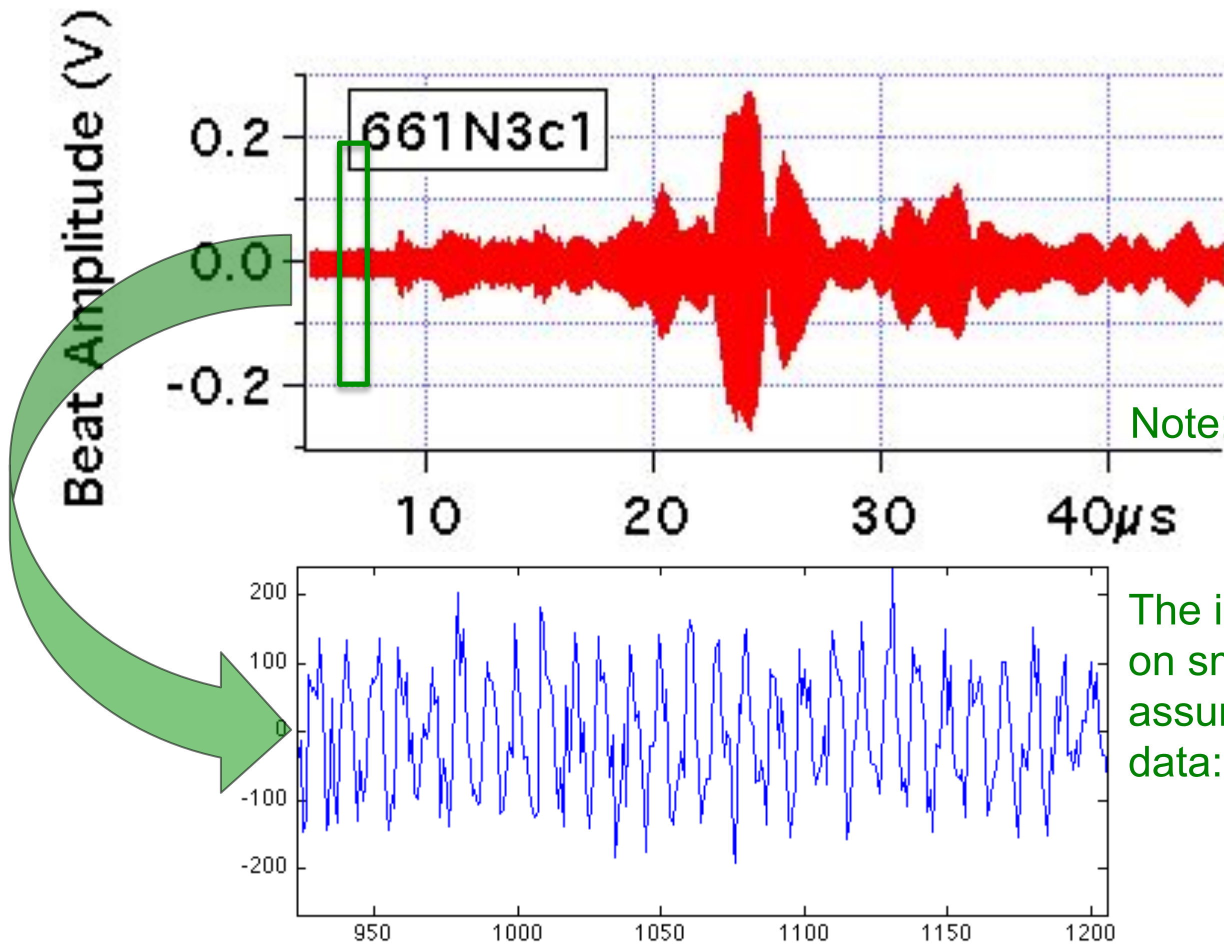
f_o = 193,414.49 GHz
f_d = 193,415.78 GHz

f_b = 1.29 GHz
(which corresponds to v_b = 1000 m/s)

$!

The recording system is expensive

PDV Data Analysis in Frequency Space – an FFT of the raw scope data yields frequency proportional to velocity



Quantity of interest is proportional to the *instantaneous* frequency of the signal:

$$\mathbf{v(t_k)} \approx \mathbf{c_0}\omega_\mathbf{k}\,\lambda_{\text{laser}}$$

Note: Amplitude isn't constant.

The idea: Estimate the frequency on smaller, overlapping chunks – assuming this local model for data:

$$A\sin(\varphi + \omega_k t) + \eta$$

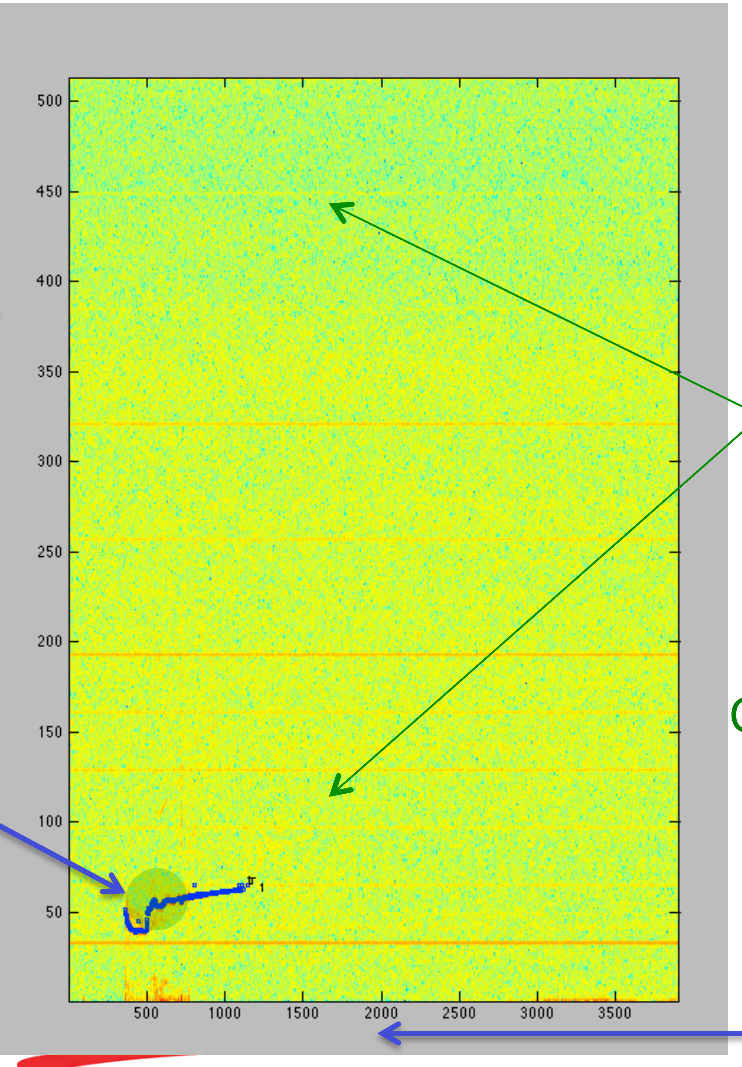
A few applications…

Because the diagnostic to works on a wide variety of time scales (1 m/s to 40 km/s) and is easier to operate than previous tools (e.g. VISAR, Fabry-Perot), it has a wide variety of applications

- Shock physics experiments – investigations into Equations-Of-State (EOS) that relate pressure, temperatures, energy, and volume.
- Diagnostic for HE experiments/dynamics
  - CTH (projectile) model verification
  - Expanding ring experiments (accelerometry)
  - High-speed shock-wave propagation models

Example Spectrograms (based on overlapping Fourier transforms of the recorded data)

Vertical axis is frequency which is proportional to velocity



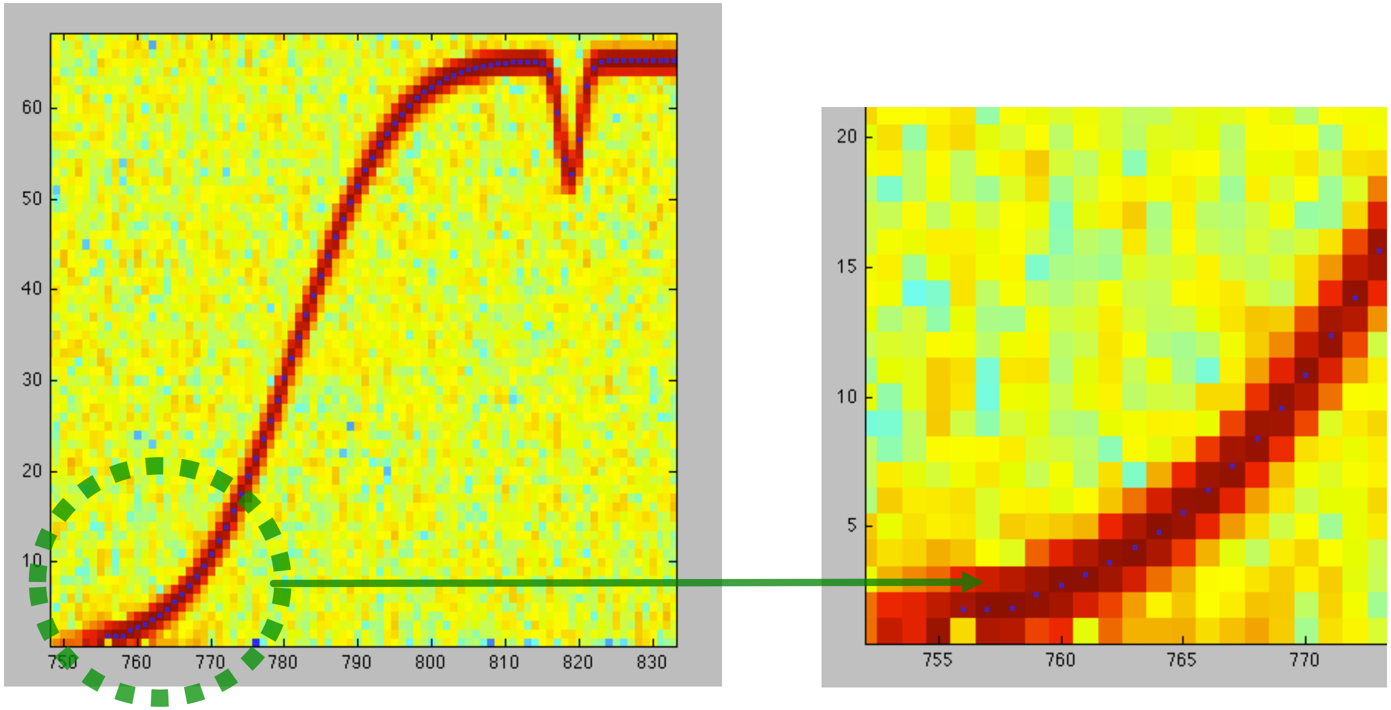
A great deal of the capacity of the recording system isn't used.

Next slide focuses on Smaller scale dynamics

Color indicates "power" or energy at that frequency

Horizontal axis is time

Classical Approach to Frequency Estimation: Short-term Fourier Transform (STFT)



Recall : $v(t_k) \approx c_0 \lambda \omega_k$

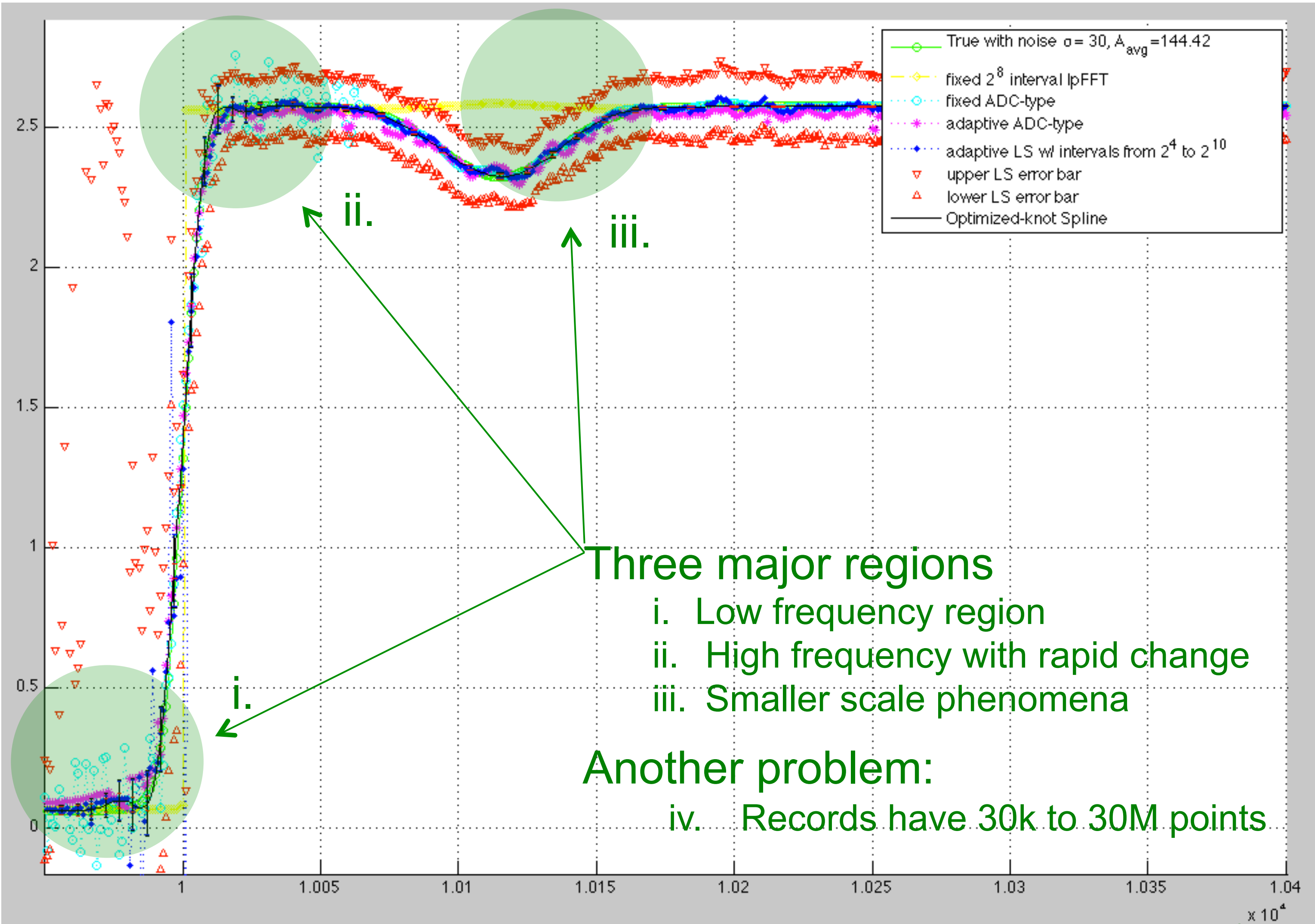
- For each vertical column, find pixel with maximum intensity.

$$\omega_k \approx \underset{i=k \ldots k+2^p-1}{\arg\max} \left| FFT(data_{i=k}^{k-1+2^p}) \right|$$

- Interpolated FFT uses nearby intensities to give fractional pixel values.

Is there a better way to do estimate the instantaneous frequency of our recorded signal?

Other Methods to Estimate Frequency (i.e., Velocity)



Three major regions

i. Low frequency region
ii. High frequency with rapid change
iii. Smaller scale phenomena

Another problem:

iv. Records have 30k to 30M points

50 data points/tick mark

Other Methods: Least-Squares Estimation

$$\text{Fit } y(t) = A(t)\sin(\Phi(t)) + \eta$$

Recall that $v(t) = c_0\lambda\omega(t)$

with

$$\Phi(t) = \varphi_0 + \varphi_1(t - t_c) + \varphi_2(t - t_c)^2,$$
$$A(t) = A_0 + A_1(t - t_c).$$

- Spectrogram gives initial estimate for x_1. The spectrogram can also provide estimates for x_0 ,x_2 , and A_0.
- Use linear least squares to yield an initial estimate for the *remaining parameters.*
- Use those starting values to begin the nonlinear least squares routine.

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Another way to analyze PDV: Transforming the data into statistics

A 2^p long "window" of data can be thought of more simply as a discrete Sine function on an interval $[-T_k/2, T_k/2]$ centered at zero:

Hilbert Transform

Complex white noise

$$A\sin(\Theta+\omega t)+\eta \rightarrow Ae^{i(\theta+\omega t)}+\zeta$$

$$Ae^{i(\theta+\omega t)}+\zeta \rightarrow \theta+\omega t+\varepsilon/A$$

These are approximations that we hope hold for small chunks of data

Algebra and a few approximations

Imaginary part of noise (may no longer be Gaussian)

Issues w/ real data:

1. Amplitude not really constant
2. Noise levels very high
3. Argument of sine function isn't really linear

We have so far ..

i. **FFT-based methods**
ii. **LS polynomial fitting**
iii. **Spline**

Having not even answered our initial question, let's do something more complicated …

let's ask for estimates in the uncertainty in our methods.

Uncertainty Estimates: Random & Fitting Errors

Difficult to estimate

$$E_{total} \cong \sqrt{c_1^2 \sigma^2_{noise} + c_2^2 \ddot{v}(t)^2 + c_3^2 \ddot{A}(t)^2}$$

Random error due to oscilloscope noise and time jitter

Fitting errors (Bias), 2nd derivative estimated with divided difference of velocity

Note that here,

$$c_1 \cong \frac{C_1 \Delta t^{-3/2} N^{-3/2}}{A_0}, \text{ and } c_2 \cong C_2 \Delta t^2 N^2 .$$

Analogous issues using spline-based approaches

Main Questions:

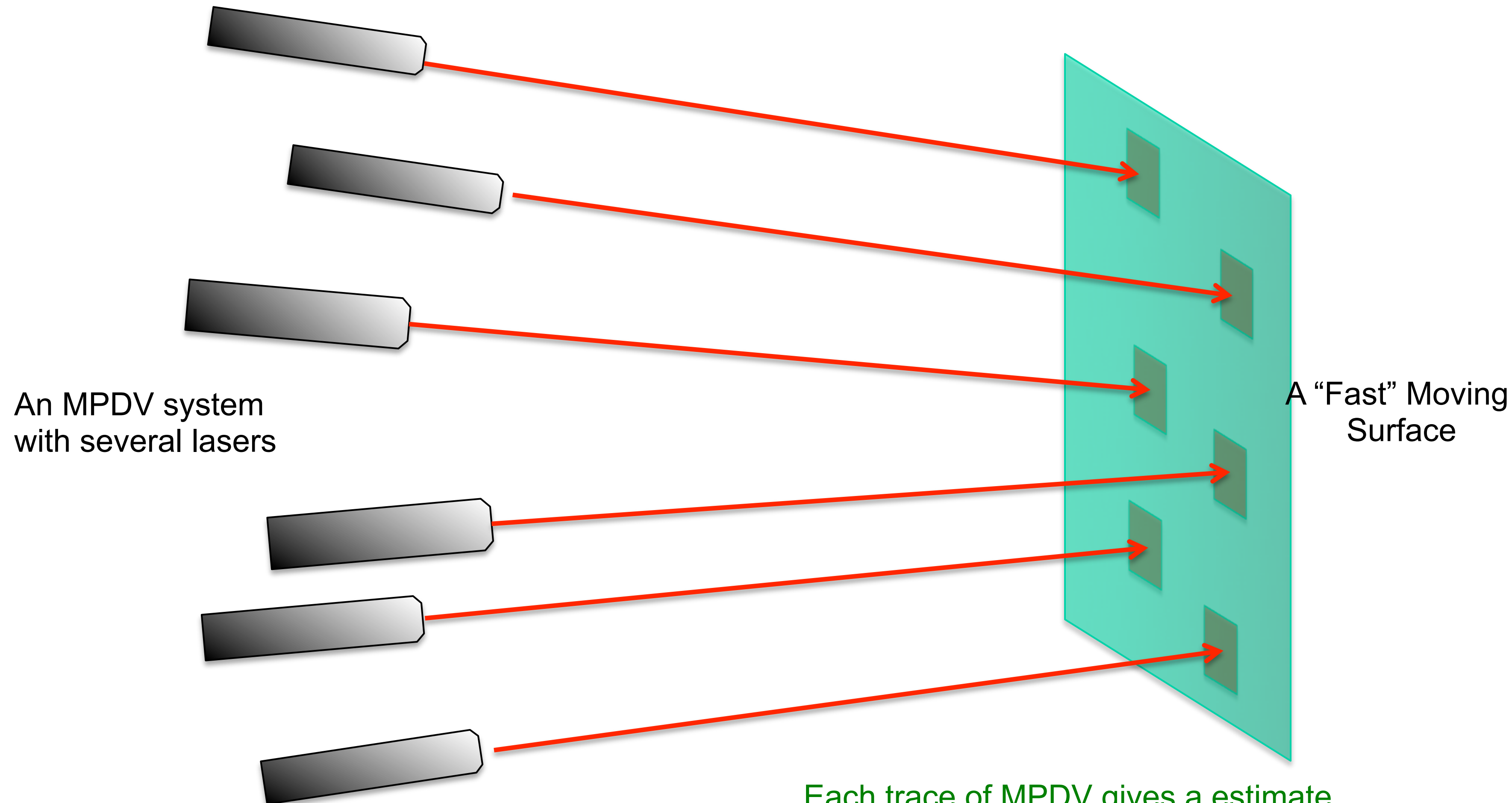
- **How to estimate the phase (or frequency) of a single point of PDV?**
  - **With reliable (and useful) error bars, error estimates**
  - **On data sets that can vary in length from 30k to 30M points**
  - **Usable at very low signal:noise levels**
  - **Usable on signals that can have very large changes in derivative**

Things we've looked at so far …But aren't really happy with yet.

- STFT and IpFFT approaches
- Smoothing splines and a home-brewed technique or two
- LS parameter fitting and Peano-Kernel approximations for errors
- Local Polynomial Approximations

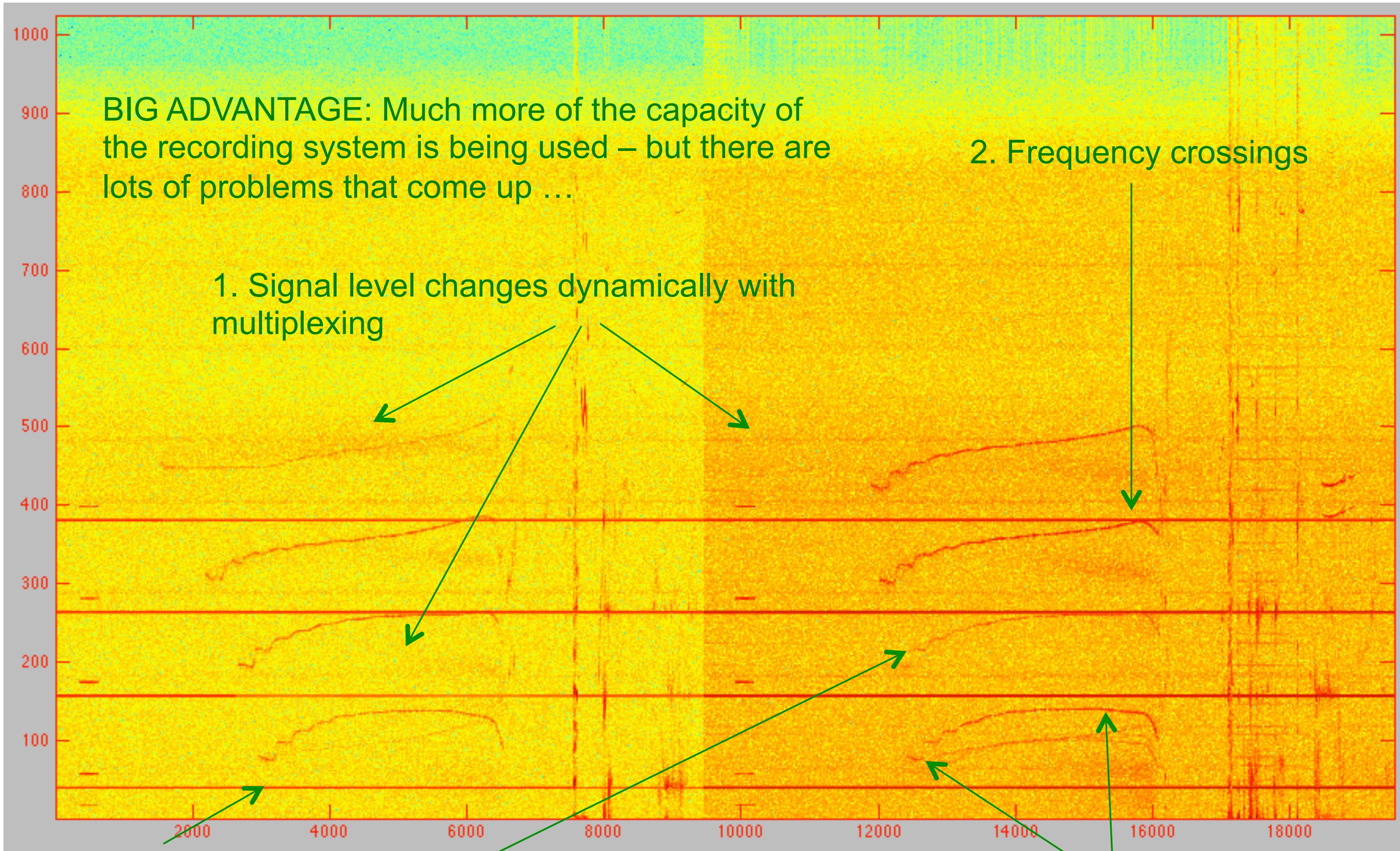
Having not even answered our initial questions, let's do something more complicated …

If one PDV system is good, then several should be even better: MPDV – multipoint (multiplexed) PDV systems.



Each trace of MPDV gives a estimate of position +/- some an error (sometime unknown)

MPDV challenges w/ extraction & error analysis



5. Extended Baseline problem

4. High background noise and signal drop out

3. Adaptive window length important to cover these very different regions

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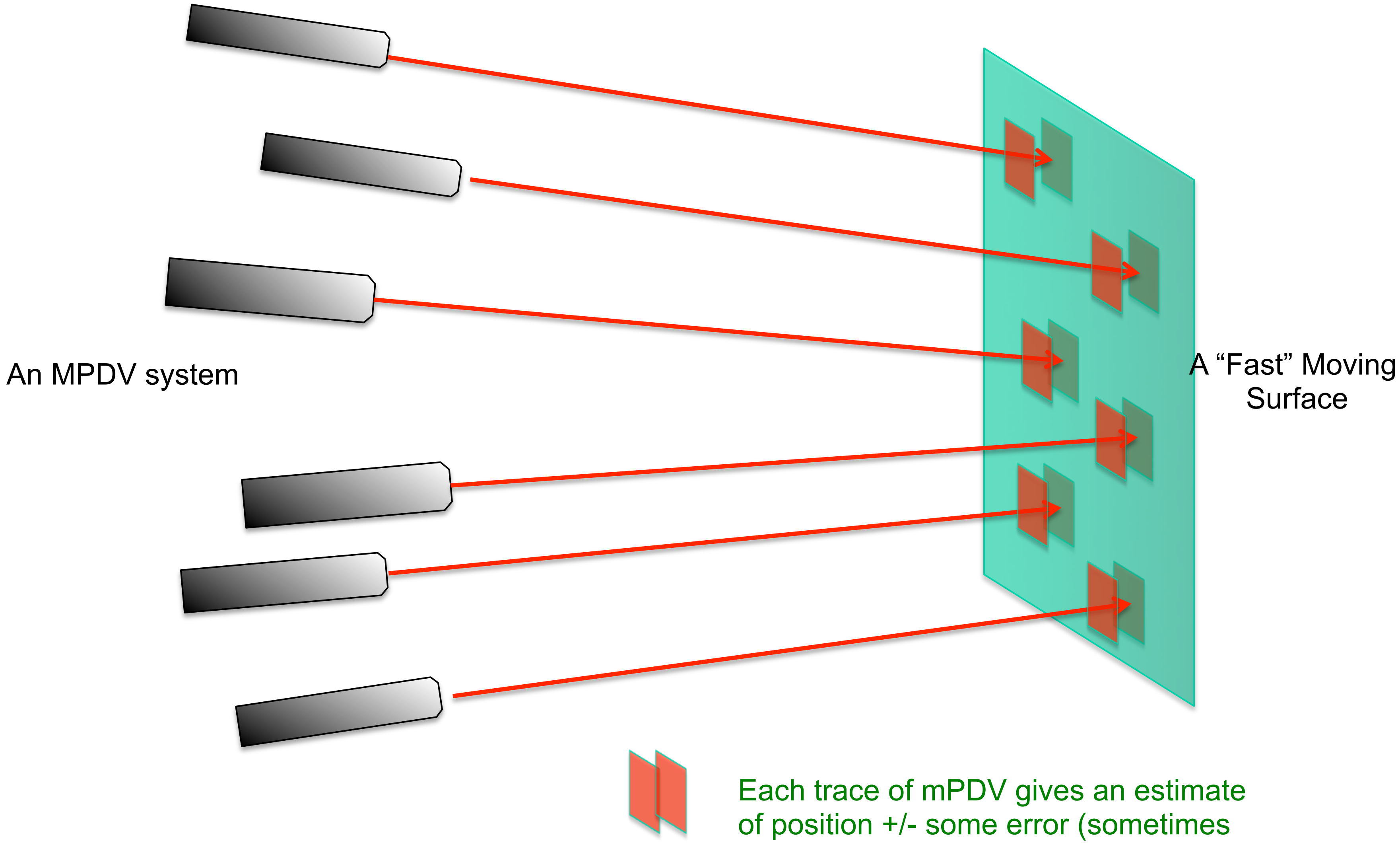
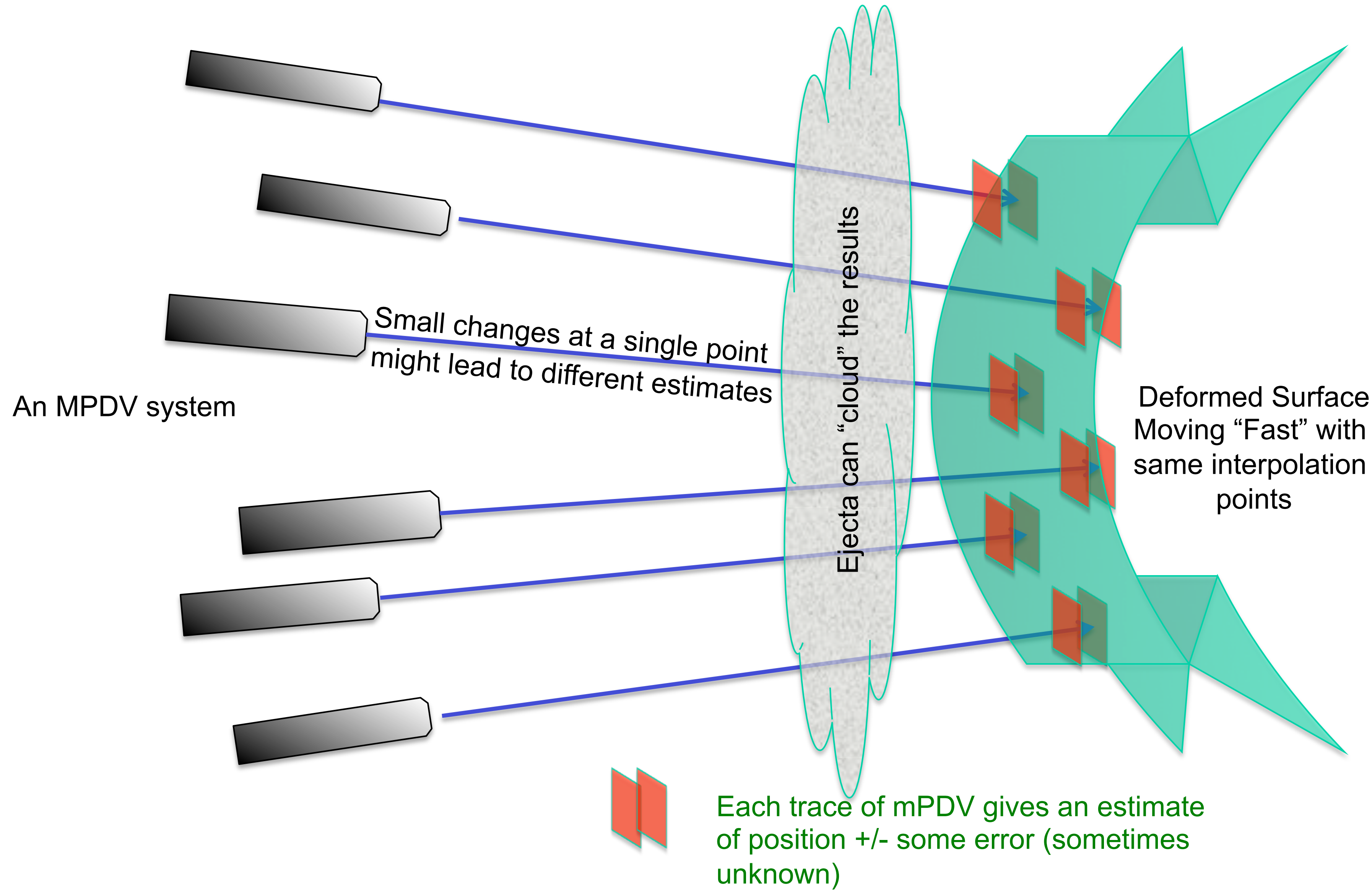
Question: How accurate are these visualizations?



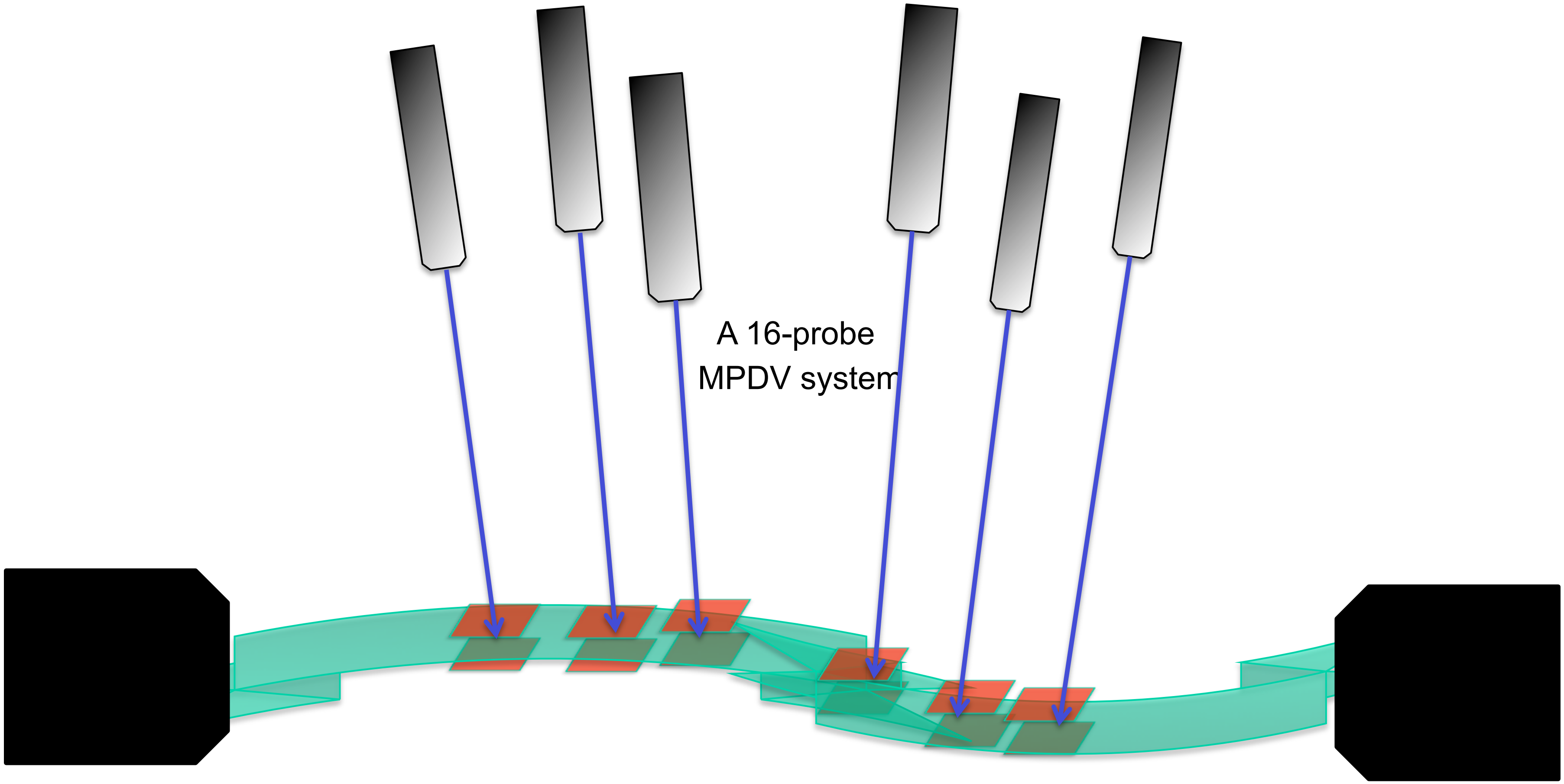
Each trace of mPDV gives an estimate of position +/- some error (sometimes unknown)

Question: How accurate are these visualizations?



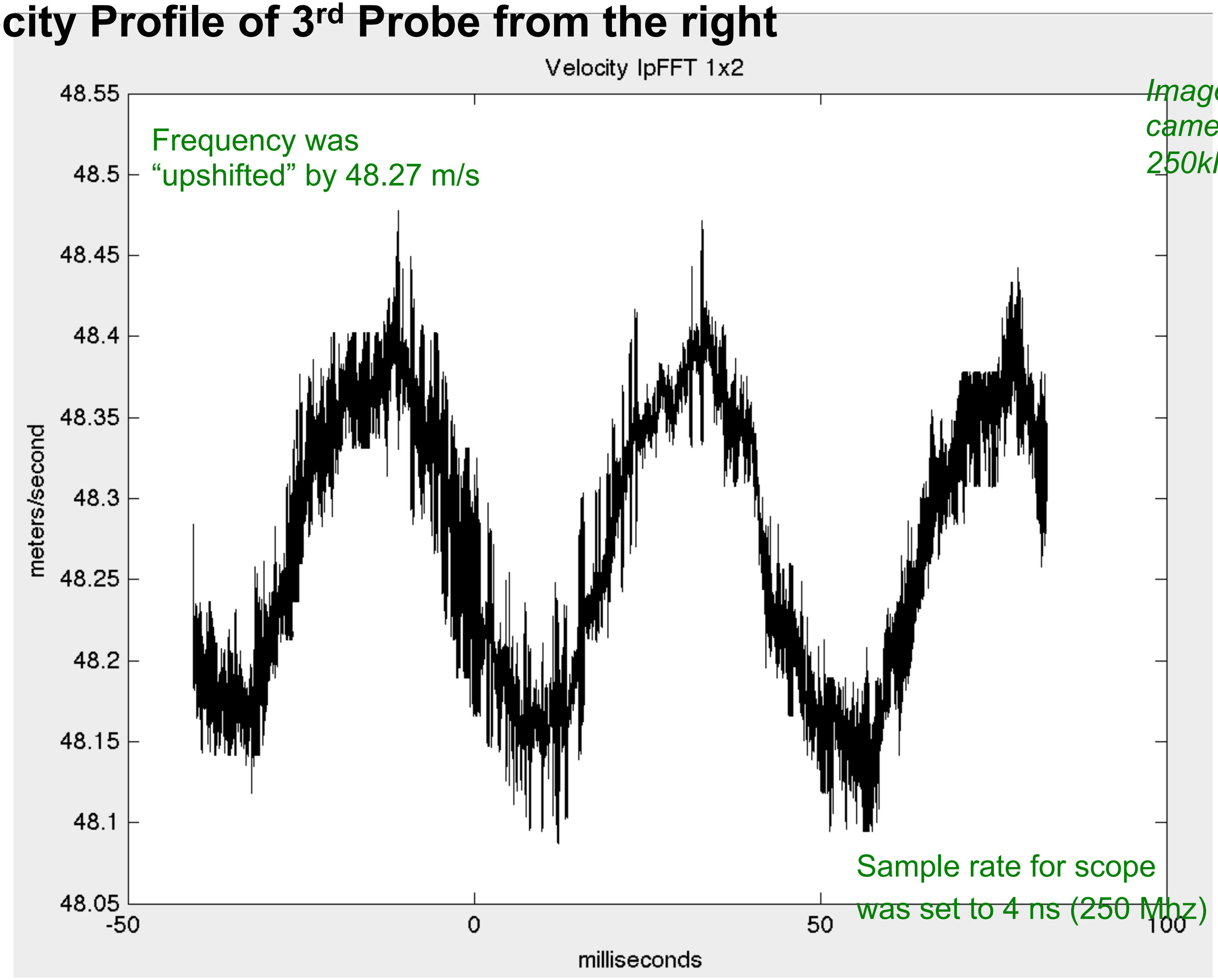
… It’s very hard to bench mark these kind of systems at the velocities that are of interest to researchers …

Proposed Experimental Setup



Vibrating band under tension filmed with high-speed camera.

Velocity Profile of 3rd Probe from the right



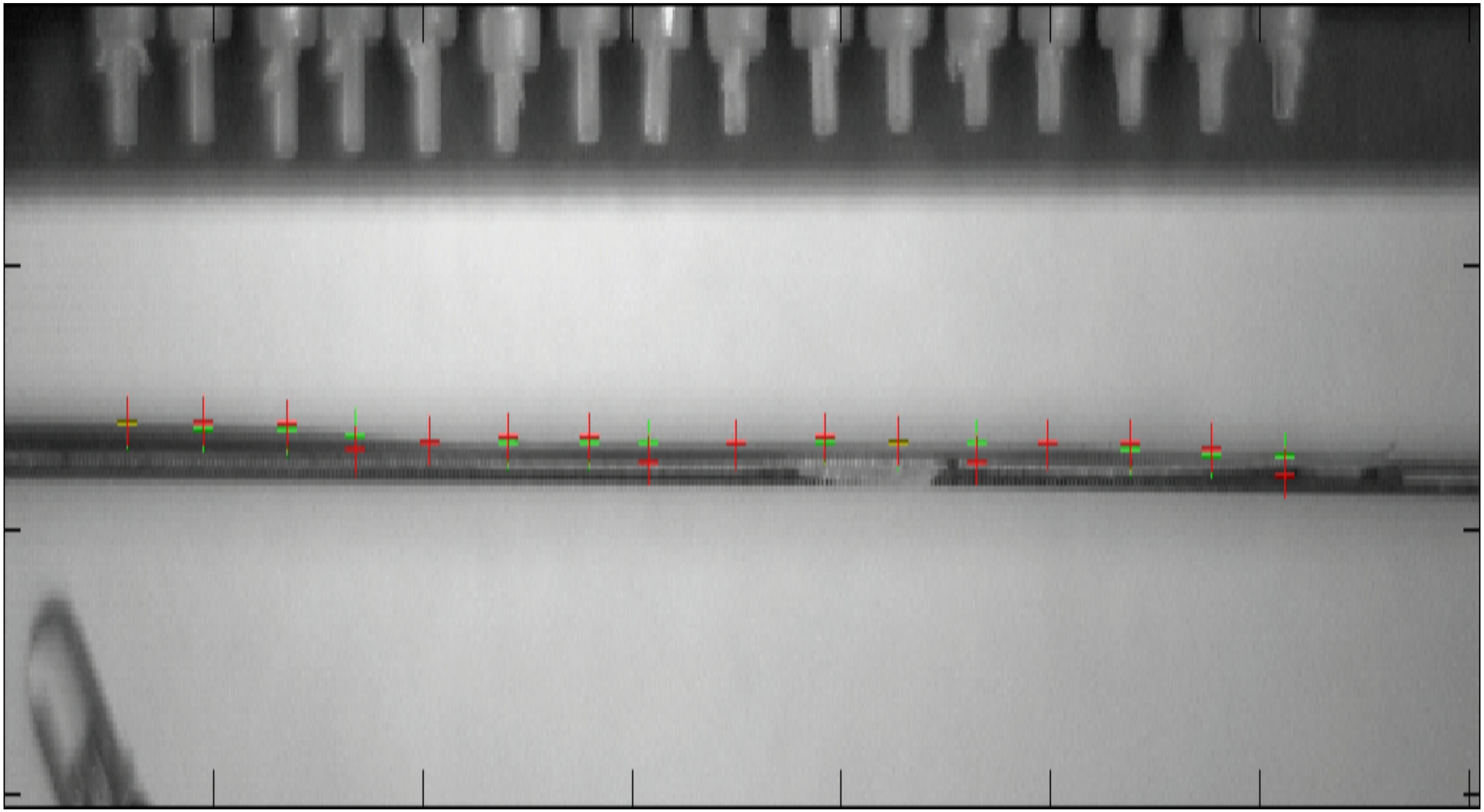
Frequency was "upshifted" by 48.27 m/s

Image rate for camera 250kHz

Sample rate for scope was set to 4 ns (250 Mhz)

Vibrating band movie:

Green is camera, red is PDV-FFT estimate



Main Questions:

- How to estimate the phase (resp. frequency, acceleration) of a single point of PDV?
  - With reliable (and useful) error-bars, error-estimates
  - On data sets that can vary in length from 30k to 30M points.
  - Useable at very low signal:noise levels
  - Use on signals that can have very large changes in derivative.

- **How to estimate the surface profile using mPDV system and provide reliable (and useful) error-bar estimates?**
  - **This questions has all of the constraints & questions of single-point PDV data analysis (above), but whereas it is**
  - **Oversampled in time (sample rate is 50 GS/sec), but sparse in spatial dimension (16 to 124 points of PDV for example)**