Approaches to line VISAR analysis

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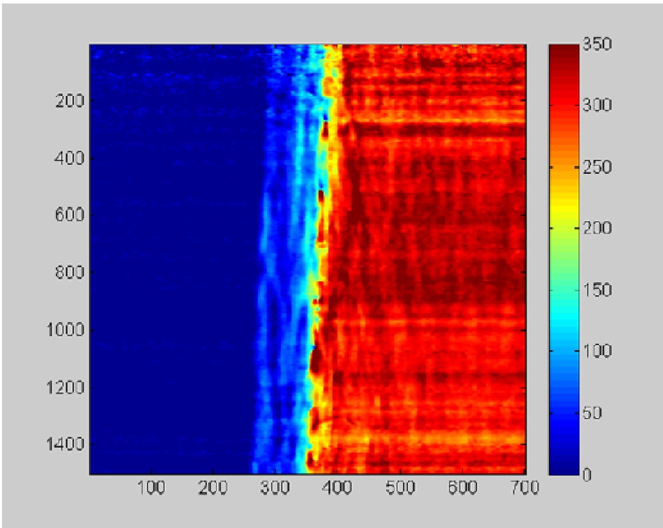
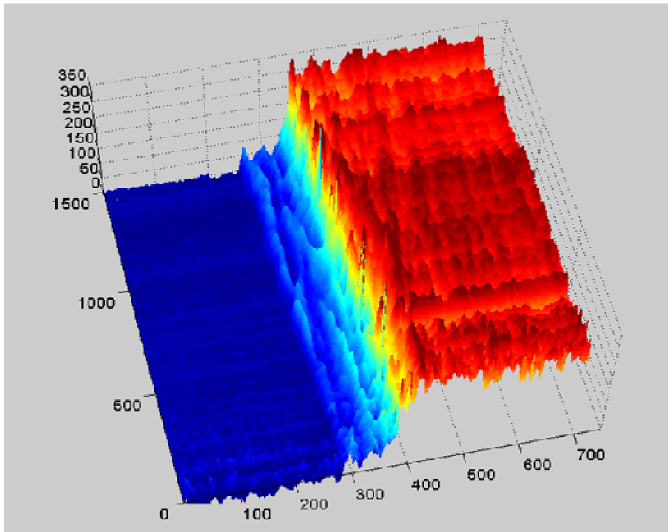
Spatial Velocity map m/s

Position ~1.5 mm



Time ~1.5 µs

Velocity m/s



Time ~1.5 µs

The motivation

- To improve our material modelling by studying material behaviour at grain scale and high strain rates.

Our requirement

- Demonstrate our capability to field spatially resolved velocimetry at a resolution of 50 μm or better.

Line imaging VISAR

Has been reported by many…….

W. Hemsing (1979), D.Bloomquist (1982), K.Baumung (1996),
W. Trott(2000), T.Vogler (2004), M.Furnish, J.Asay, T.Ao **SNL**

P.Celliers (2004), D.Bradley **LLNL**

Progress at AWE (2013)

"We are now capturing single image line VISAR data from gas gun impact experiments and are developing our analysis methodology."

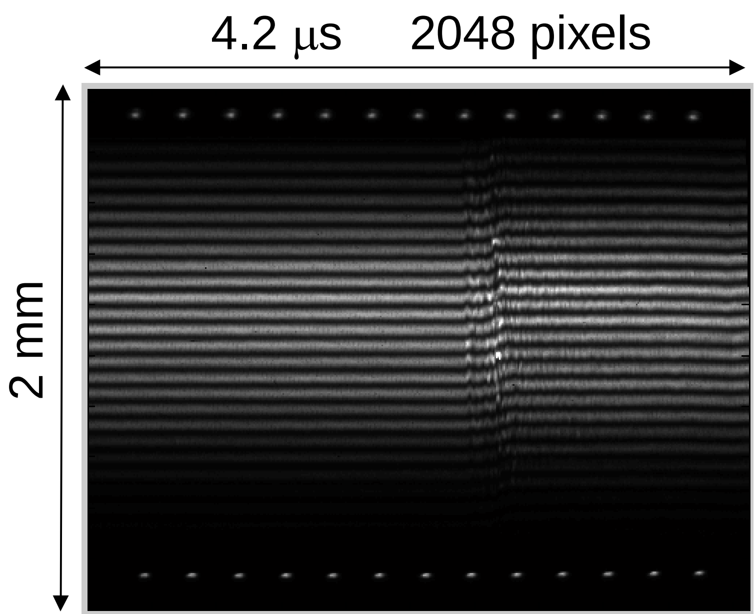
‘Whistle stop’ tour of Line VISAR

VISAR is an optical differentiator.

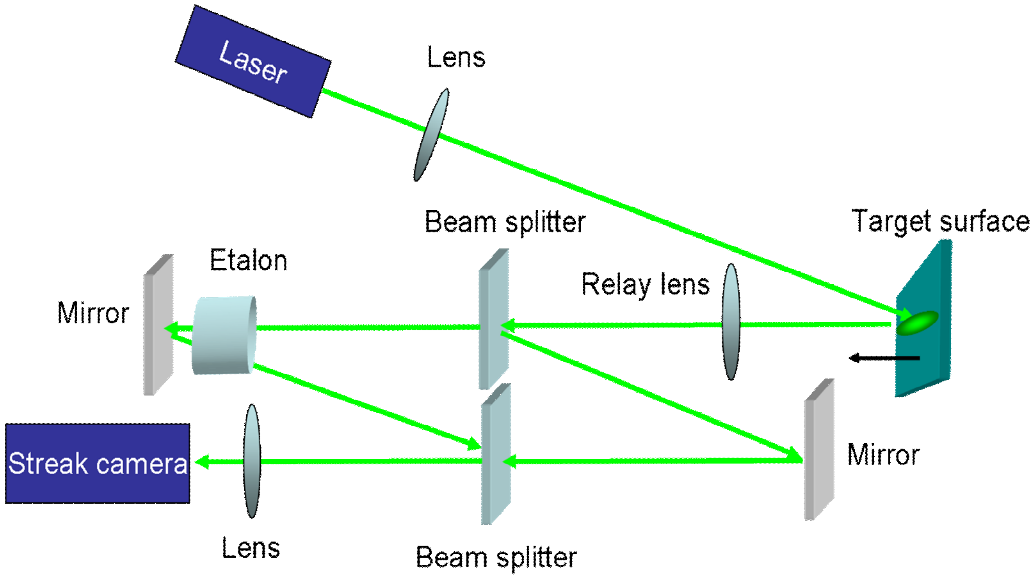
The light returned from the target is divided by amplitude. Then after delaying one beam with an etalon and recombining the two beams a fringe pattern is created by optical interference.

The pattern beats in time at a frequency equal to the difference in frequency between the two beams. The velocity information is contained within the phase of the fringe data.

Timing markers at 300 ns

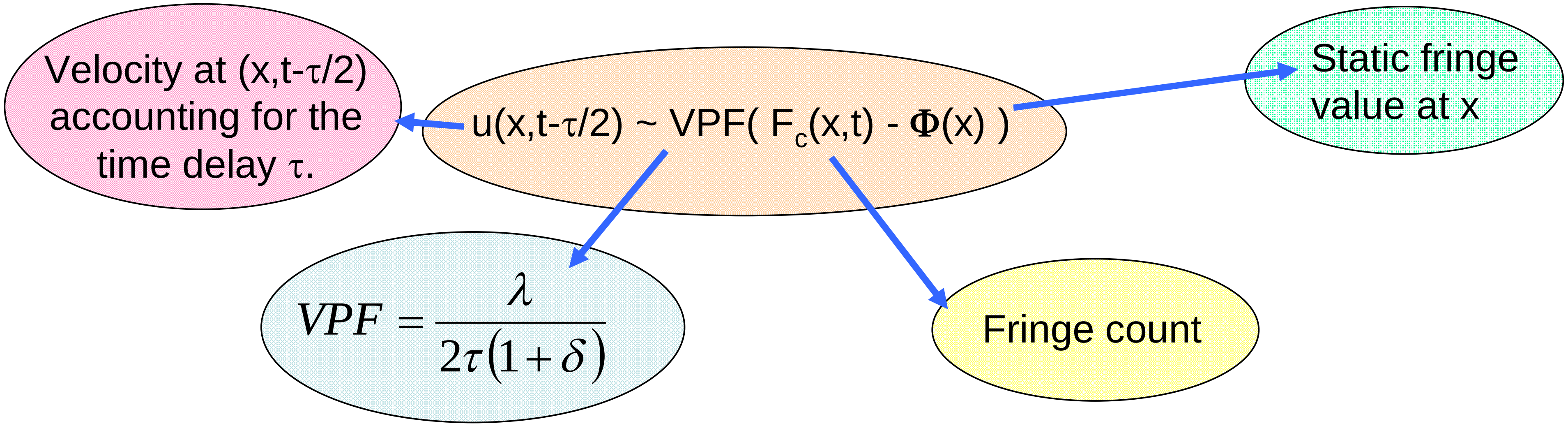


Line VISAR Optical configuration.



General form of the Line VISAR approximation.

This is an approximation that is valid only if the fringe phase may be considered constant for the etalon period τ.



VPF : A constant known as the **Velocity Per Fringe.**

$F_c(x,t)$: The fringe value at (x,t) plus the total integer number of fringes cycled through.

τ: Etalon time delay, **λ:** wavelength

Φ(x) : The static fringe state. Set by the initial static fringe comb.

(1+δ) : Dispersion correction for the etalon.

What are the issues with measuring the phase of the fringes ?

- The fringes are the **sum of two optical waves.**

The method needs to accommodate for **varying magnitude** and **offset** due to the spatially varying **beam intensity**.

Line VISAR is an **amplitude sensitive** diagnostic.

Amplitude noise can be created by…..

The streak camera as **fixed pattern** and **random thermal noise**.

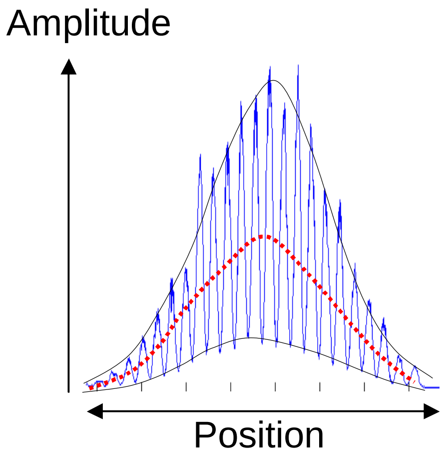
By coherent interference '**Speckle pattern**'. -> Dirty optics or spatial variations on the target surface -> '**Surface roughness**'.

Localised **reflectivity changes** on the surface of the target.

Cameras can also create **distortion** in the image.

Poorly aligned optical components and **back reflections** can also create **phase distortions**.

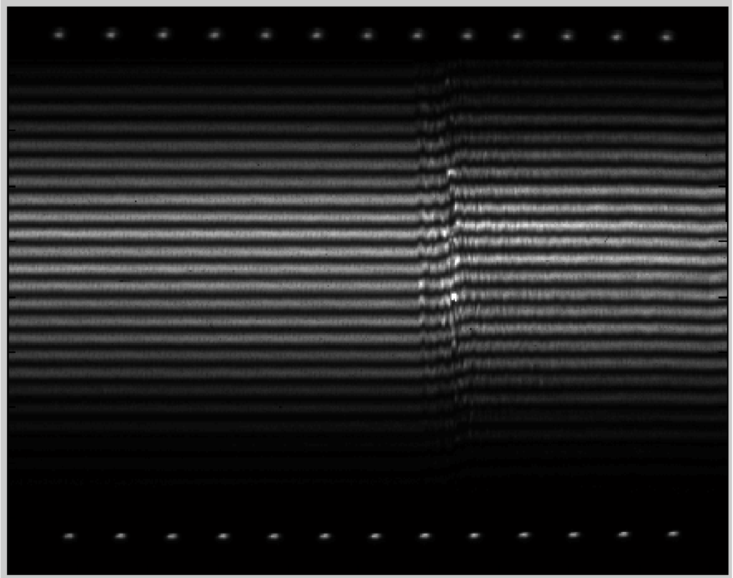
Real fringe data



Line VISAR fringes are '**Open fringes**' f(x,t), they are not circularly connected as apposed to 'Closed fringes' that one may find in for example a plate distortion measurement f(x,y).

The approaches considered here are directed towards analysis methods that preserve **spatial** and **temporal** resolution for **open** fringe data.

Further as we only have one camera the approaches are biased towards **single image analysis**. We will be implementing '**Quadrature**' or '**Phase shifting**' next year with two cameras.



Single image fringe analysis methods

There are two types of method for fringe analysis.

- **'Local methods'** Implementing a localised neighbourhood or regional algorithm.

For example, '**The Quadrature approximation method**'.

Applied to line VISAR by W.Trott, M.Knudson, L.Chhabildas, J.Asay. AIP Conf. Proc. 505, 993 (2000).

Alternatively '**Fringe Tracking** (FT)' Not commonly reported for line VISAR.

- **'Global methods'** which generally apply Fourier integrals across the complete field.

For example the "**The Fourier transform method** (FTM)".

Applied to line VISAR by P.M.Celliers LLNL. Review of Scientific Instruments Vol 75 **11** (2004).

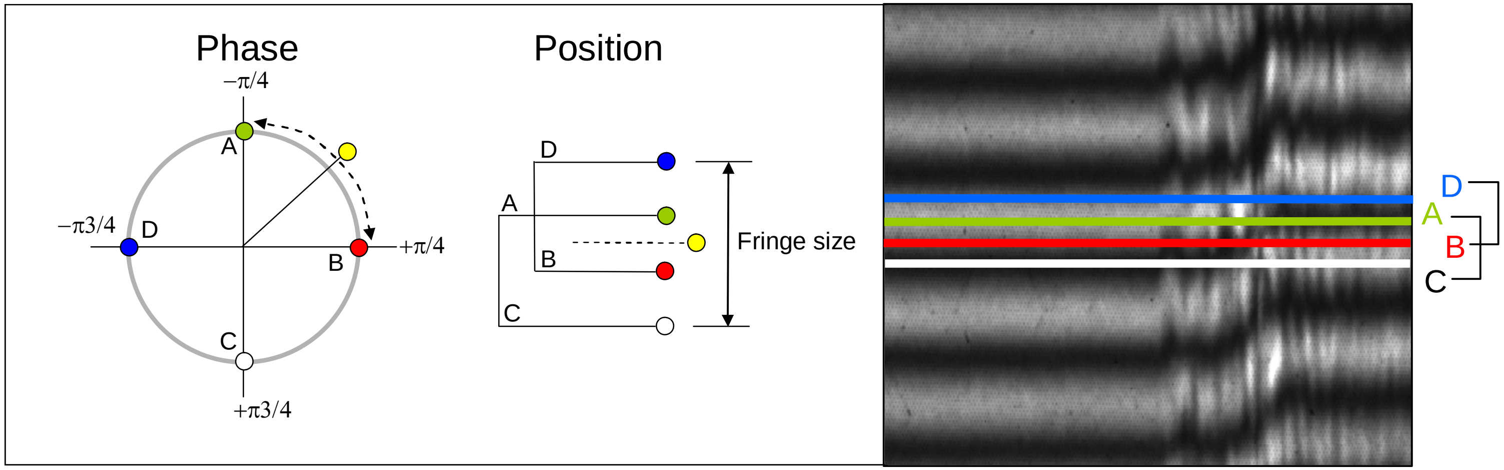
Reference to M.Takeda J.Opt.Soc.Am./Vol.72,No.1/January 1982

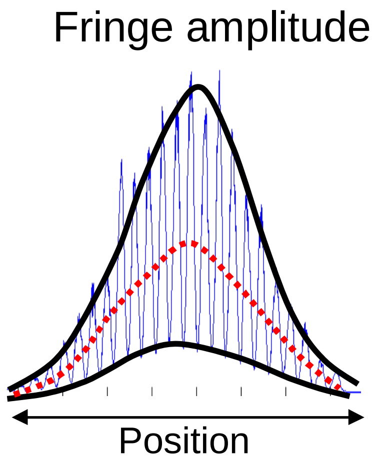
Alternatively '**Wavelet analysis**' "**1D Continuous Wavelet Transform** (CWT)".

Similar to the Fourier method but with the benefits of a localised analysis provided by discrete wavelets.

'Quadrature approximation method'

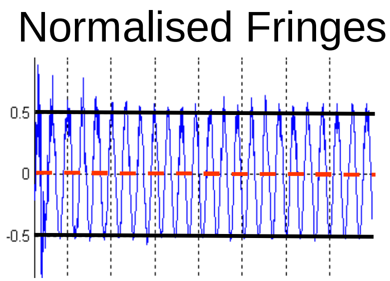
Reported by W.Trott, M.Knudson, L.Chhabildas, J.Asay. AIP Conf. Proc. **505**, 993 (2000).



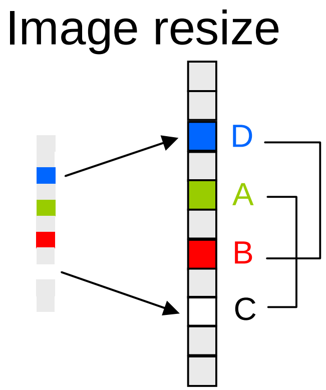


To achieve this analysis it is necessary to.

- Normalise the amplitude of the fringes.
- Resize the data to suit discrete analysis.



The resized fringe ¼ wave length must be an integer number of camera pixels.

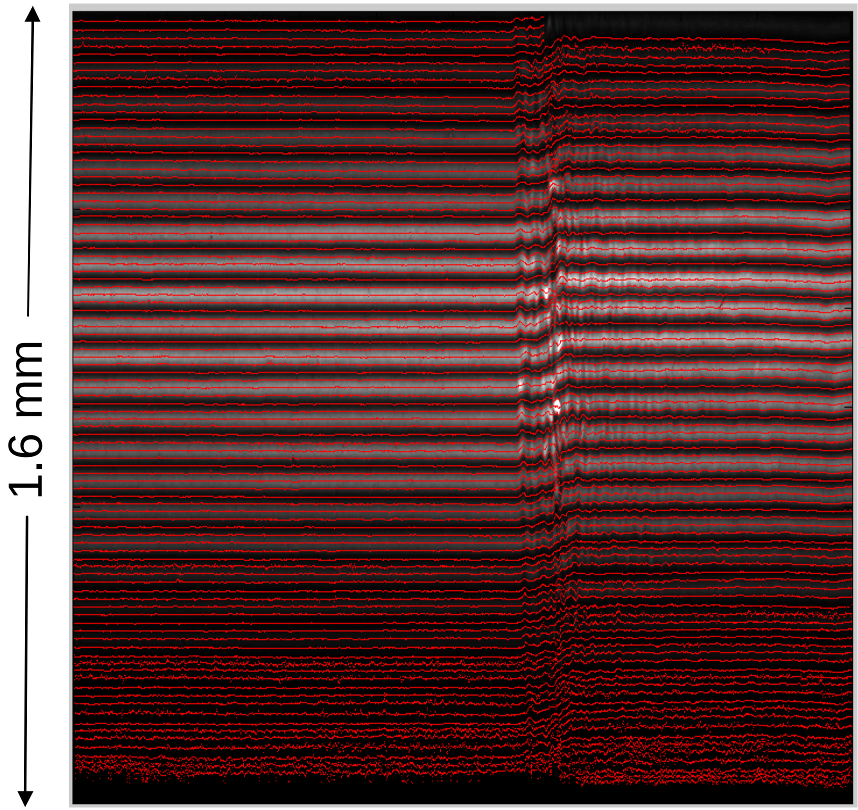


$$\theta = \mathrm{atan}((n_a A - n_c C)/(n_b B - n_d D))$$

n_k normalising coefficients

Fringe tracking

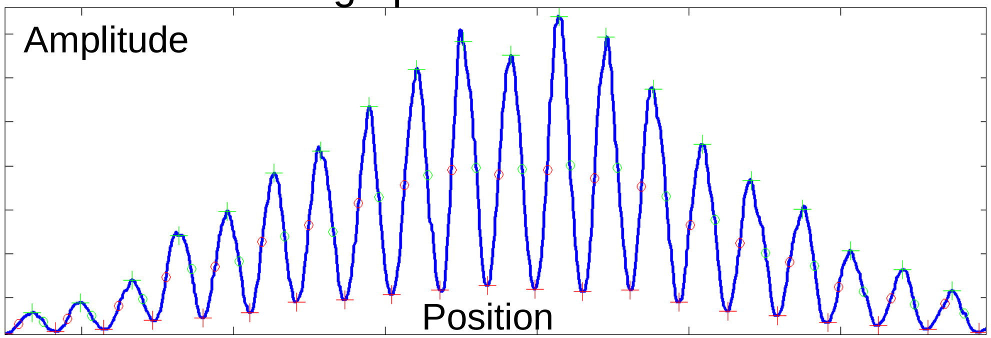
Fringe tracked solutions



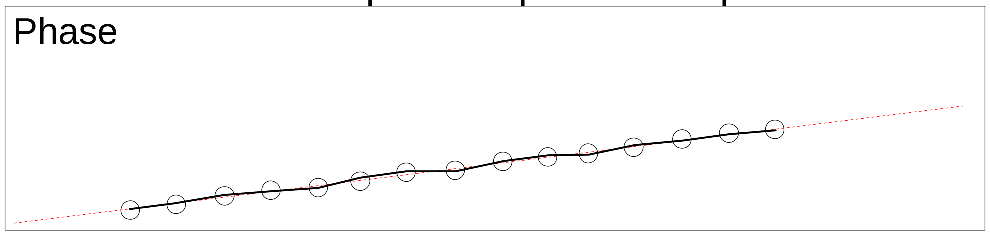
Effectively one measurement every ¼ fringe. [In this example 16 μm.]

- Each fringe is tracked and assigned a relative phase value at a position x.
- Peaks, troughs and points of inflection are tracked.
- The phase between fringes is estimated by linear interpolation.

Fringe profile with solutions



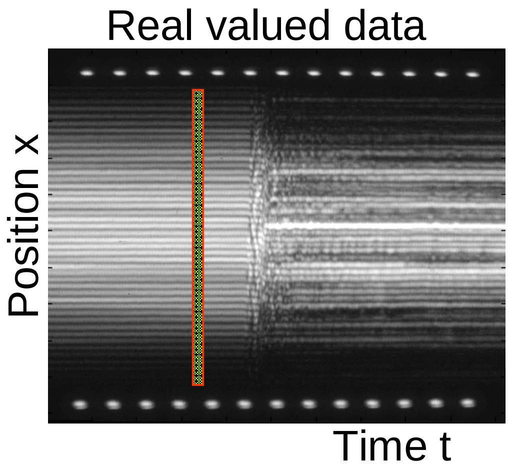
Interpolated phase ramp



Position

Fourier transform method ‘FTM’

M Takeda J. Opt. Soc. Am/Vol. 72, No1/January 1982



Takeda describes the fringe pattern as

$$\mathbf{g(x,y)=a(x,y)+b(x,y)\cos[2\pi f_o x+\phi(x,y)]}$$

Taking Fourier transforms of the real valued fringe data

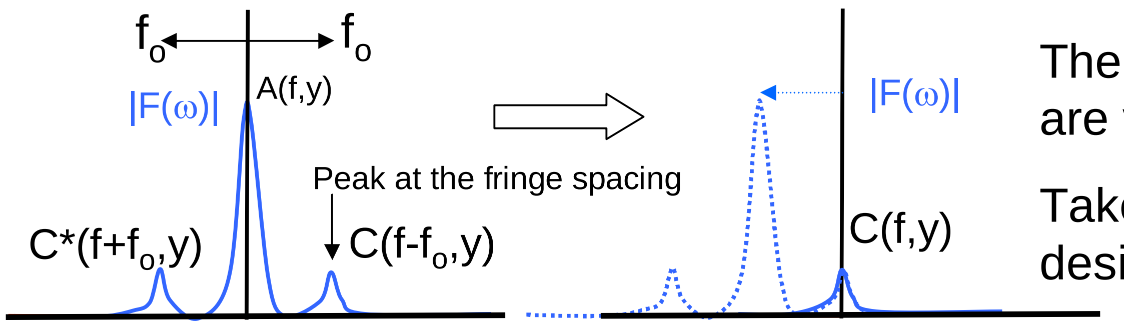
three peaks in the Spectra are obtained.

$$\mathbf{G(f,y)=A(f,y)+C(f-f_o,y)+C^*(f+f_o,y)}$$

Then after filtering and translation by f_o the phase is separated by taking logs of the inverse Fourier transform.

$$\mathbf{Log[(c(x,y)]=\log[(1/2)b(x,y) + i\phi(x,y)]}$$

Fourier Transform G(f,y) Filtered Transform



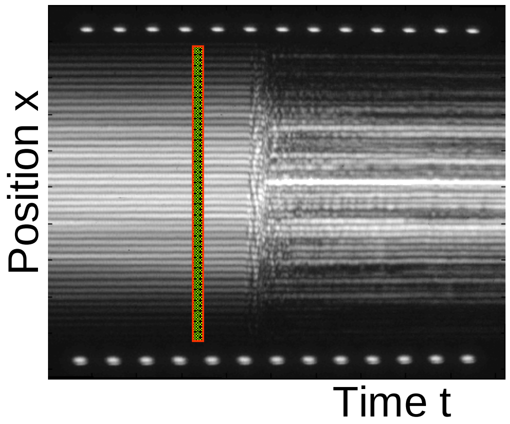
The assumption is that a, b and ϕ are very low frequency terms.

Takeda did not describe how to design the filter.

Fourier transform method ‘FTM’

“As a Hilbert transform implemented with Fourier transforms.”

Real valued data



The **complex analytic signal** $z(x)$ is the original signal $f(x)$ plus $f(x)$ **convolved** with $1/(\pi x)$. The imaginary part is the **Hilbert transform** of $f(x)$.

$$H\left(f\left(x,t\right)\right)=\frac{1}{\pi}P\int_{-\infty}^{+\infty}\frac{f\left(\tau\right)}{x-\tau}d\tau$$

P : Cauchy principal value

$$z\left(x,t\right)=f\left(x,t\right)+iH\left(f\left(x,t\right)\right)$$

Numerically it is efficient and convenient to turn the convolution into a Fourier transform of the fringe data.

$$f\left(x,t\right)\otimes\frac{1}{\pi x}=F^{-1}\left\{F\left(f\left(x,t\right)\right)F\left(\frac{1}{\pi x}\right)\right\}$$

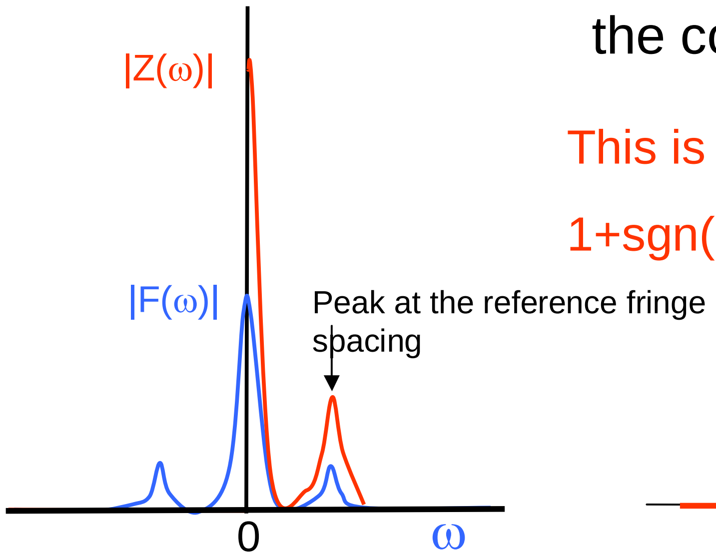
$$-i\,\mathrm{sgn}(\omega)$$

Fourier transform method ‘FTM’

“ We calculate $Z(\omega)$ in terms of Fourier transforms of the real fringe data, apply the quadrature filter $1+\mathrm{sgn}(\omega)$ and then invert the transform to create the complex analytic signal $z(x)$ ”

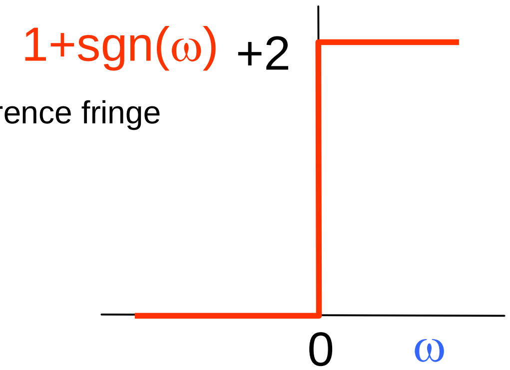
$$Z(\omega) = F(f(x))(1+\mathrm{sgn}(\omega))$$

$$Z(\omega)\ \begin{cases} 2F(\omega), & \omega>0 \\ F(\omega), & \omega=0 \\ 0, & \omega<0 \end{cases}$$

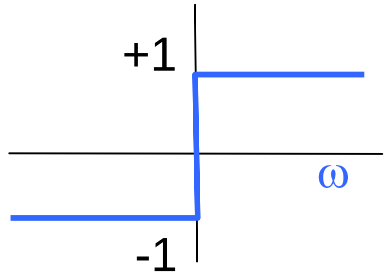


“The **phase** at any point x is the **argument** of the complex function $z(x,t)$.”

This is known as a Quadrature filter.



sgn(ω) : Signum function



$$\begin{cases} 1, \text{ for } \omega > 0 \\ 0, \text{ for } \omega = 0 \\ -1, \text{ for } \omega < 0 \end{cases}$$

Fourier transform method 'FTM'

We now have the **phase** at any point **x** as the **argument** of the complex function.

But unlike Takeda we need to subtract the phase of the reference fringes.

Remember that….. $u(x,t-\tau/2) \sim VPF(F_c(x,t) - \Phi(x))$

There are no assumptions about the background or amplitude terms. So we need to either filter these out in the frequency domain or normalise in the amplitude domain.

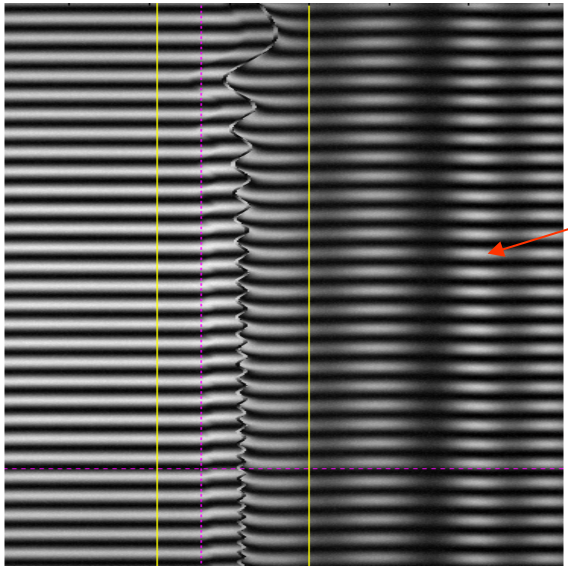
I suggest that …………………..

"By using the measured full field reference fringes we deal appropriately with the small but important phase variations in the fringe pattern. That is assuming these are stable."

"The key to high resolution line VISAR analysis is in how we design the filter."

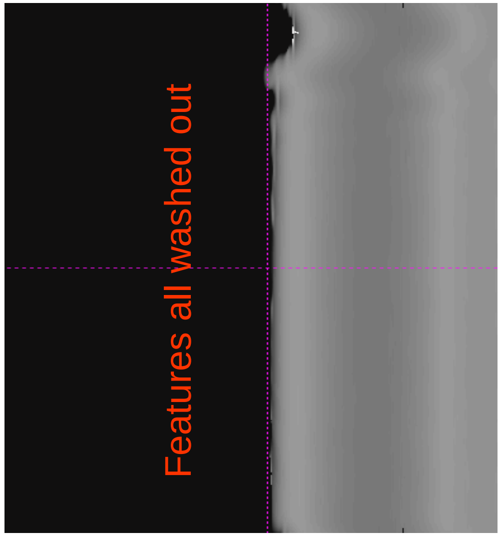
Band pass filtering reduces spatial resolution

"Be very careful when applying band pass filters to line VISAR data."

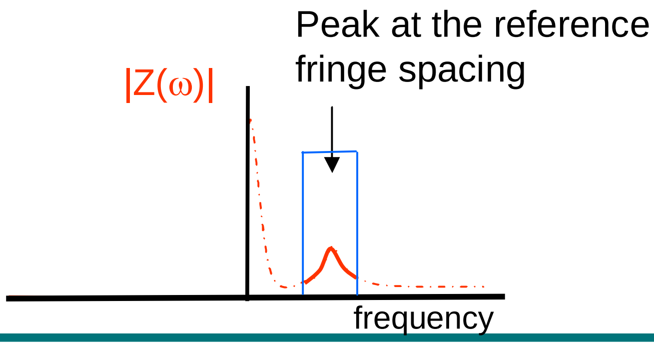


Low frequency amplitude modulation across the whole field.

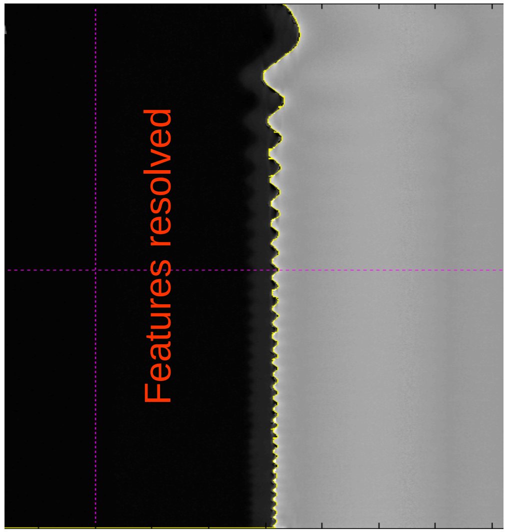
Narrow band filter



If we apply a narrow band filter we limit our spatial resolution.



Broad band filter



Continuous Wavelet transform 'CWT' 1D

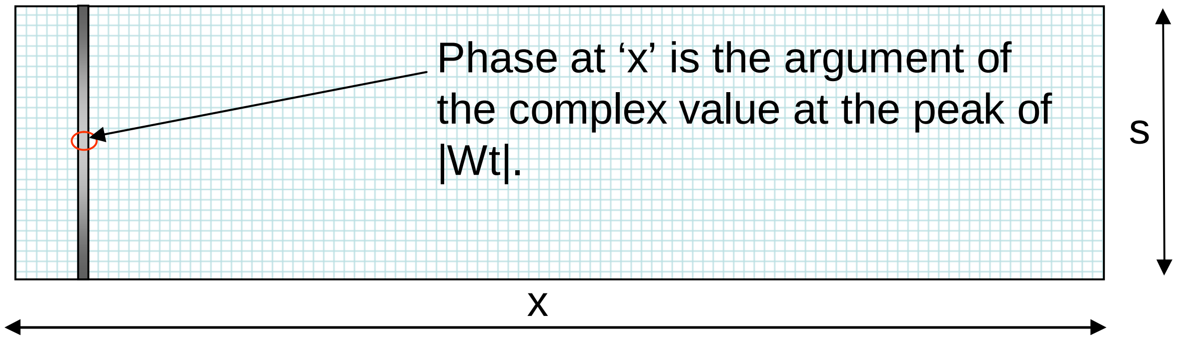
Wavelet analysis is similar to Fourier analysis however it has the advantage of spatial localisation.

$$Wt(x,s) = f(x,t) \otimes \psi^{*}(x,s)$$

This is a process of dilations and translations of a mother wavelet function ψ.

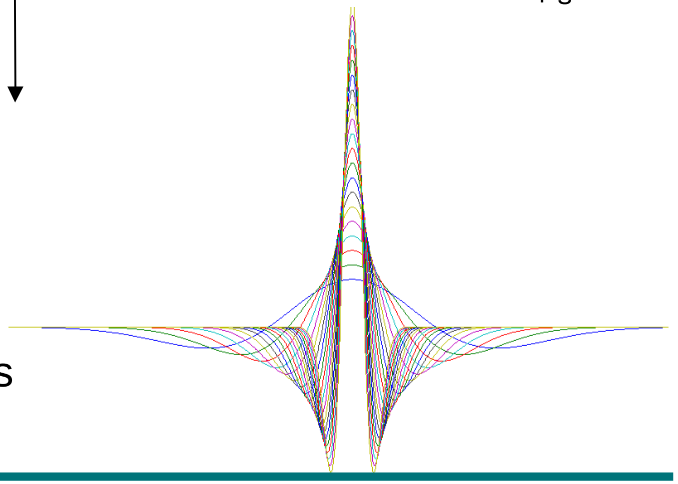
The dilation parameter 's' controls the wavelet scaling.

Matrix of coefficients Wt



$$\psi_s(x) = \frac{1}{\sqrt{s}}\psi\left(\frac{x}{s}\right)$$

Scaled wavelets ψ_s



Every discrete fringe column produces a 2D (x,s) matrix of coefficients. -> This is a very slow method.

So far we have only looked at the 'Mexican hat' wavelet. This wavelet is the 2nd differential of a Gaussian function.

Fast approximation to ‘CWT’ 1D

- We can convolve the complex analytic signal with the sum of the real valued ‘Mexican hat’ wavelets numerically efficiently using Fourier transforms.

This can be considered as.

A complex quadrature filter with all of the frequency properties of the wavelet group.

“This may not be the true implementation of wavelet analysis but it is extremely quick and can be a very good approximation.”

“ Useful when making user interfaces where an immediate solution is expected by the user.”

Complex analytic signal filtered by the scaled wavelet group

Fourier transform of the fringe data at t

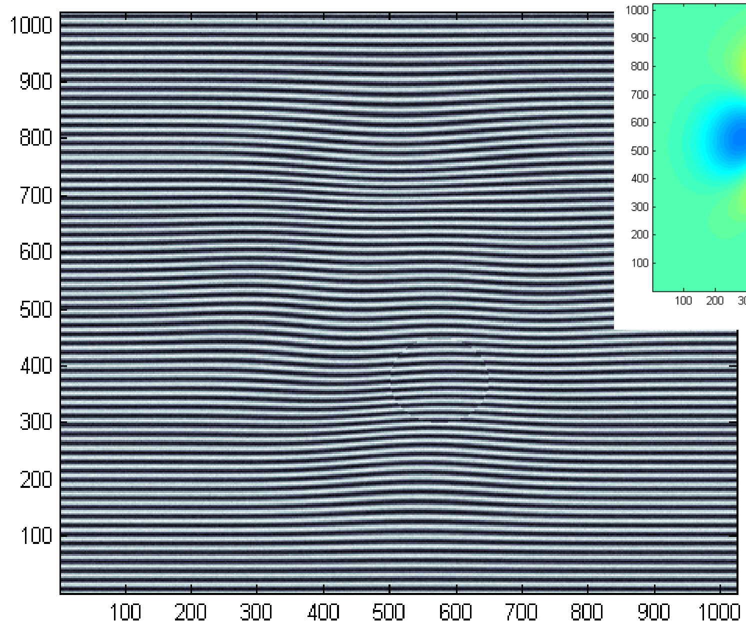
Fourier transforms of the n scaled wavelets. Summed at each frequency ω.

$$z_{\psi}(x,t) = F^{-1}\left\{ \left(1+\operatorname{sgn}(w)\right) F\left(f(x,t)\right) \sum_{n} F\left(\psi(x,s_n),w\right) \right\}$$

Matlab Peaks function with additional disc object

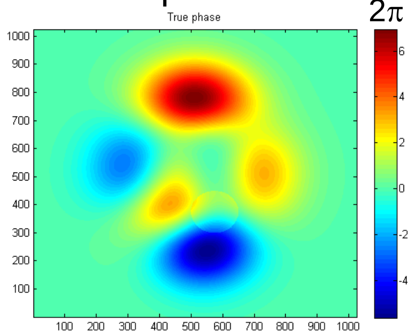
Gaussian 5% standard deviation amplitude noise

Synthetic fringes

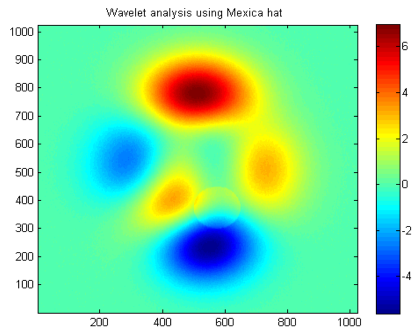


True phase

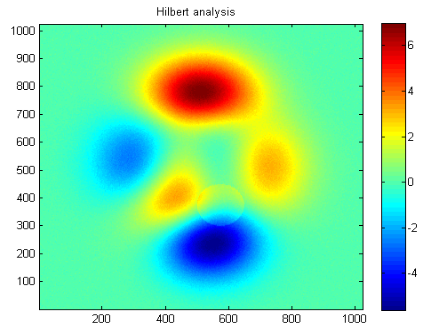
2π



Phase measured using 1D Wavelets (Mexican Hat)

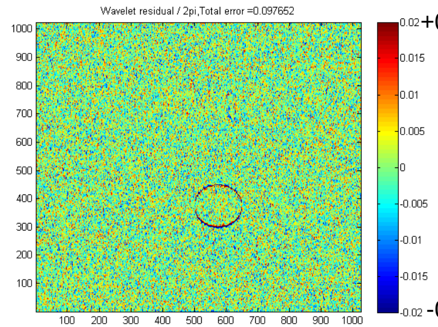


Phase measured using Fourier method



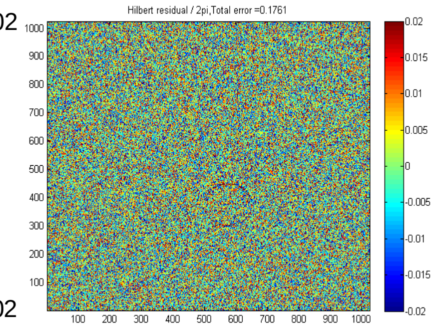
Ratio of total residuals (Wavelet / FTM) ~1/2

Wavelet Residual / 2π



Std of residual 0.006

FTM Residual / 2π



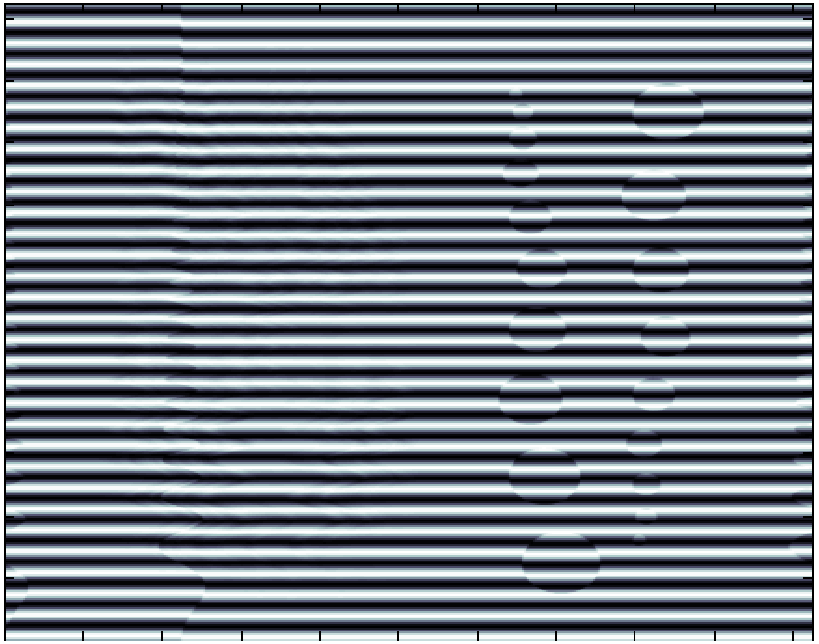
Std of residual 0.011

To get the best results we need to optimise the range of the scaling values generating the wavelet group to suit the data.

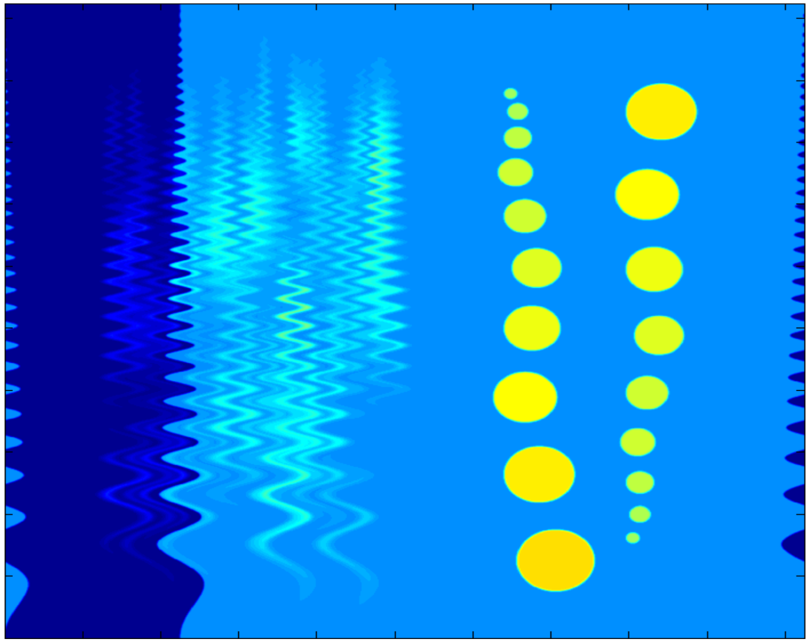
A more realistic but simple synthetic data problem

- Flat beam profile and no amplitude offset. “We can ignore normalisation issues.”
- No noise. “Spatial resolution is related to fringe density and noise.”
- Step similar to a shock wave in an impact experiment.
- Small disturbances similar to elastic waves and finally discrete discs.
- Same fringe density as our data example.

30 fringes over 2048 pixels



True phase solution



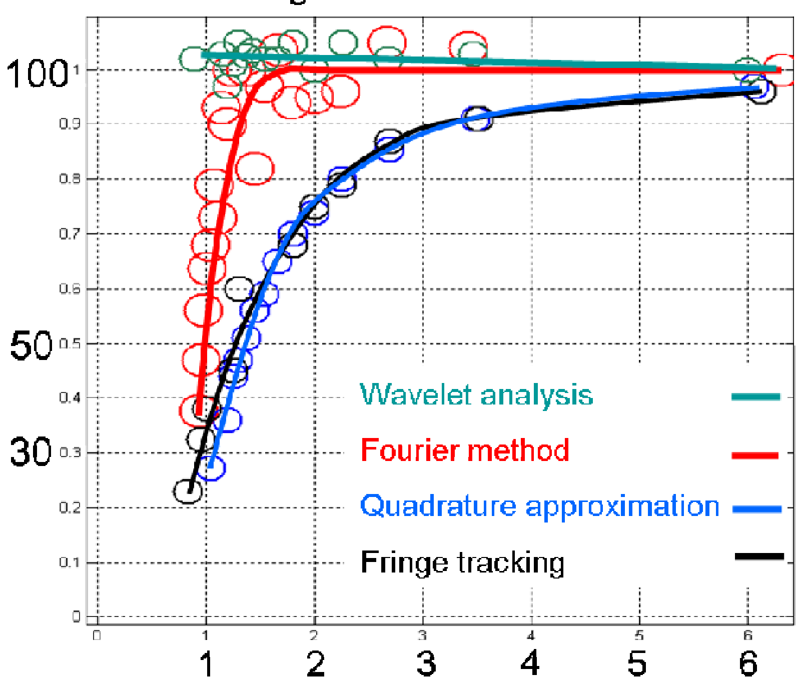
Synthetic data problem #1 (No noise)

Simple synthetic fringe data allows us to compare analysis methods.

1D Wavelet analysis proves to be the superior method.

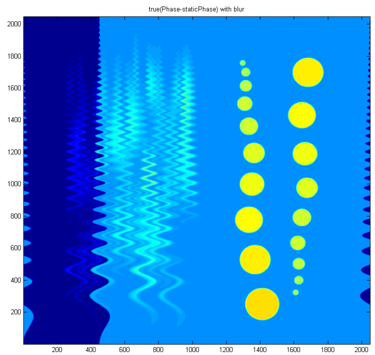
Measured phase MTF

Signal Modulation %

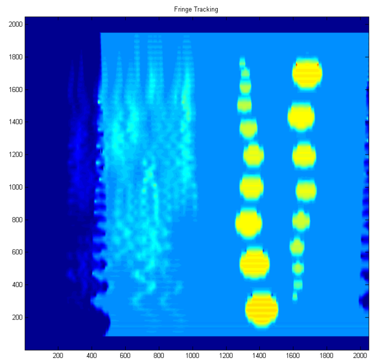


Carrier fringes / test cycle

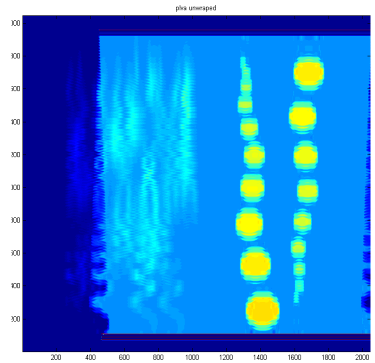
True phase Solution



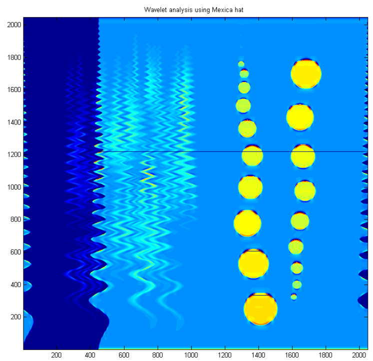
Fringe Tracking



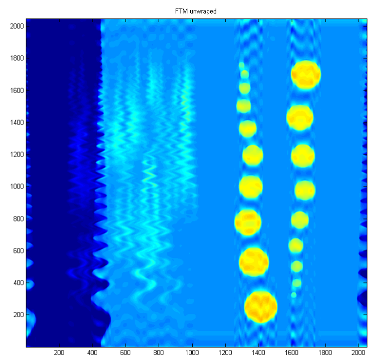
Quadrature approximation



Wavelet 'Mexican hat'

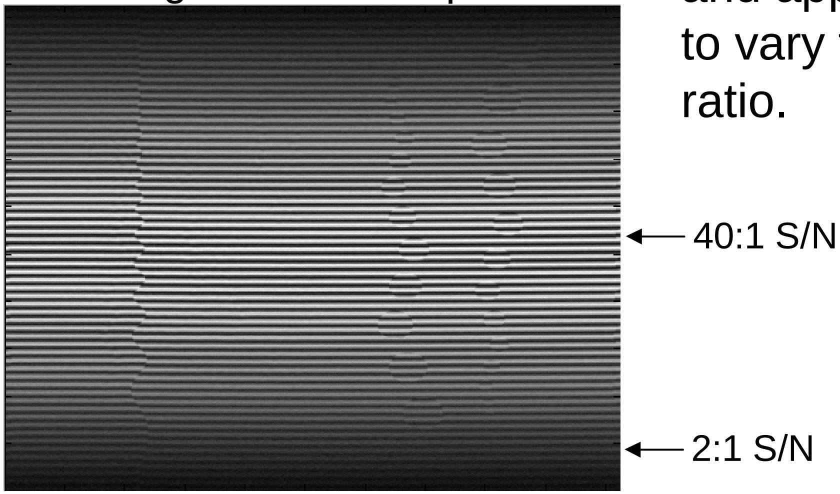


Fourier method

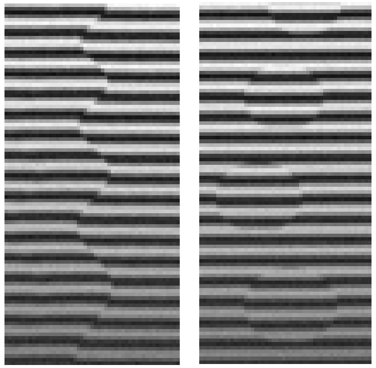


Synthetic data problem #2 (with noise)

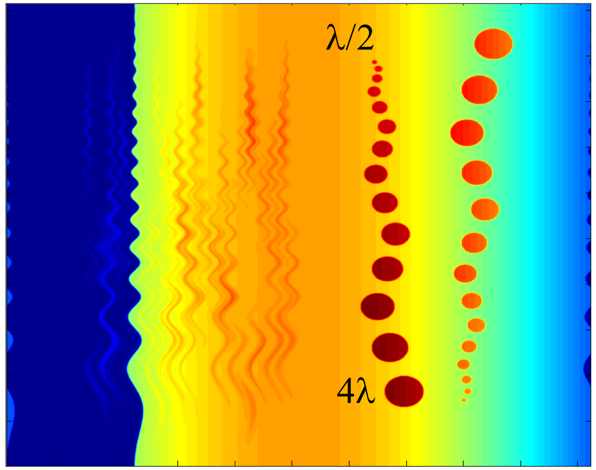
60 fringes over 2048 pixels



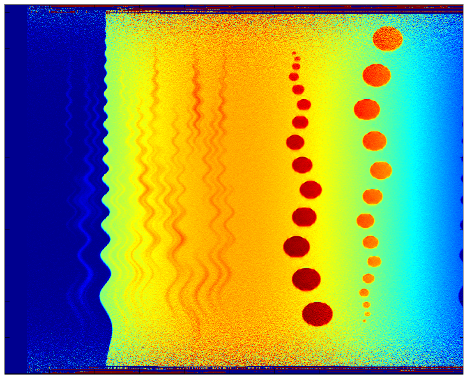
Double the fringe density and applying a beam profile to vary the signal to noise ratio.



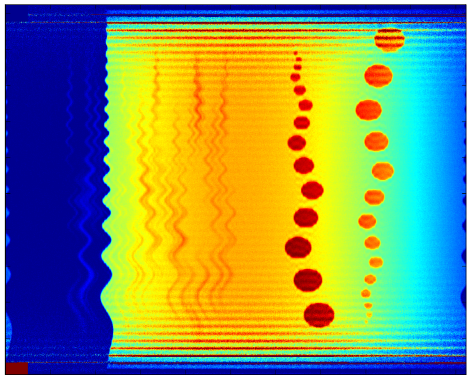
True phase solution



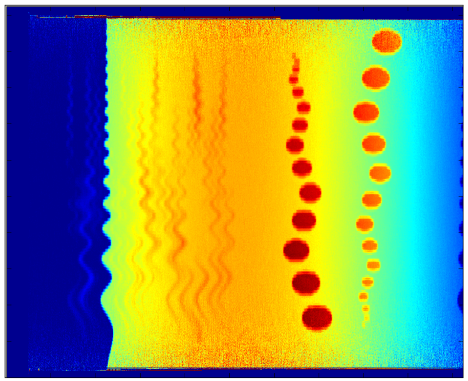
1D Wavelet 'Mexican hat'



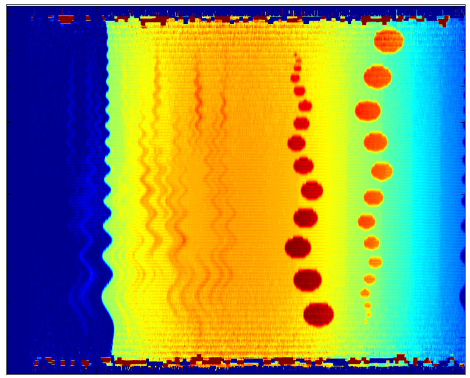
Fourier method



Quadrature approximation



Fringe tracking



Single camera test problem #2 (with noise)

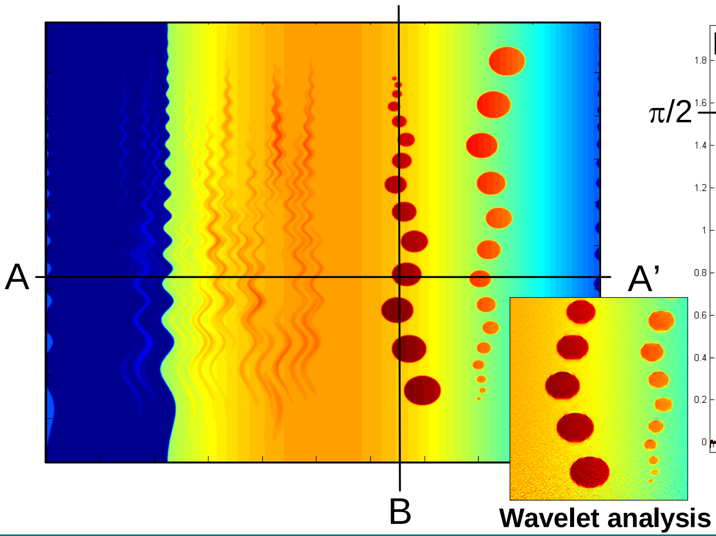
- Single image line VISAR can be effective if the fringe density is high.
- At least >**2** fringes per feature are required for both the ‘Quadrature approximation’ and ‘Fringe tracking’ methods.
- The Fourier Transform method can be unstable at discrete edges. Requires >**3/2** fringes.
- 1D Wavelet analysis can operate at <**1** fringe spacing.

True phase

Fourier method FT

Quadrature approximation

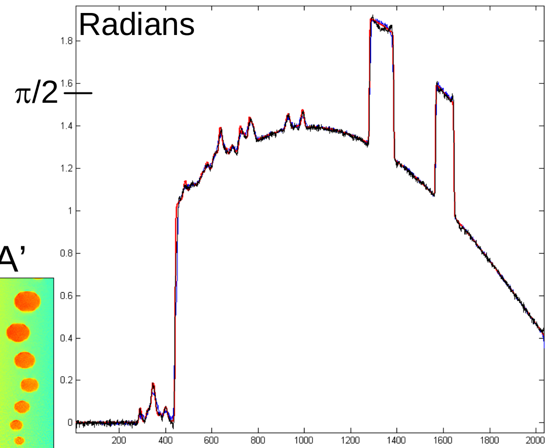
True phase solution



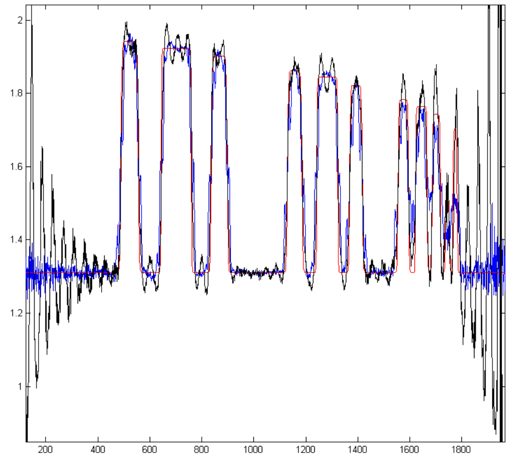
Wavelet analysis

Analysis of test problem #2

Phase profile A-A’



Phase profile B-B’

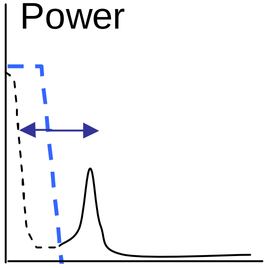


A small improvement to the FTM method

The phase can have large errors if we do not remove the low frequency part of the power spectrum.

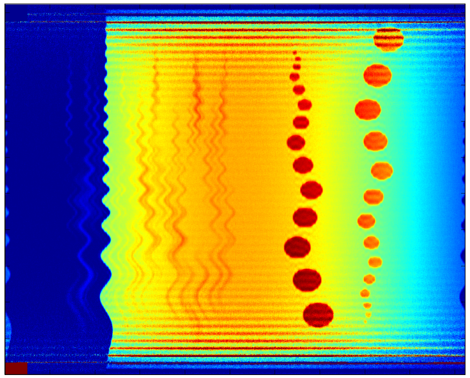
Normalisation can be achieved in frequency space with a high pass filter. Although it is often difficult to design a filter that corrects all parts of the image.

High pass filter

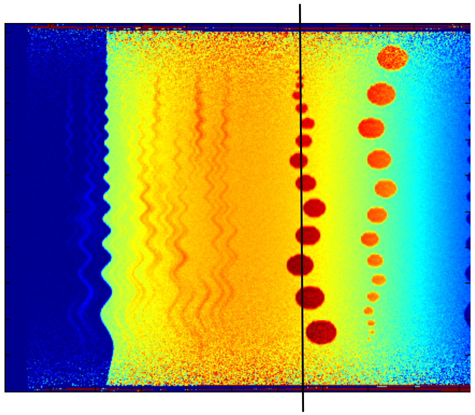


"I find that the Fourier method can be improved if the data is normalised in amplitude space before processing."

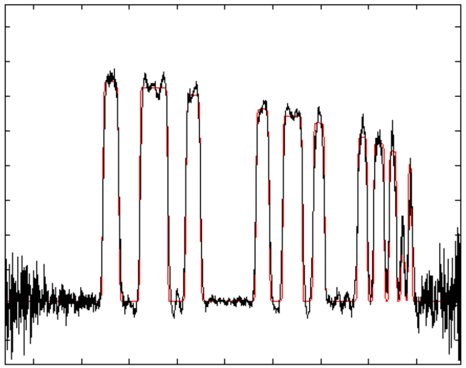
Fourier method with a simple DC filter.



Fourier method applied to amplitude normalised fringes.



Phase analysis is still very noisy and sensitive to step changes.



Two camera synthetic test problem #3 with noise

Two cameras in quadrature $\pi/2$ out of phase. 60 fringes on each camera.

Same level of random amplitude noise added to each camera.

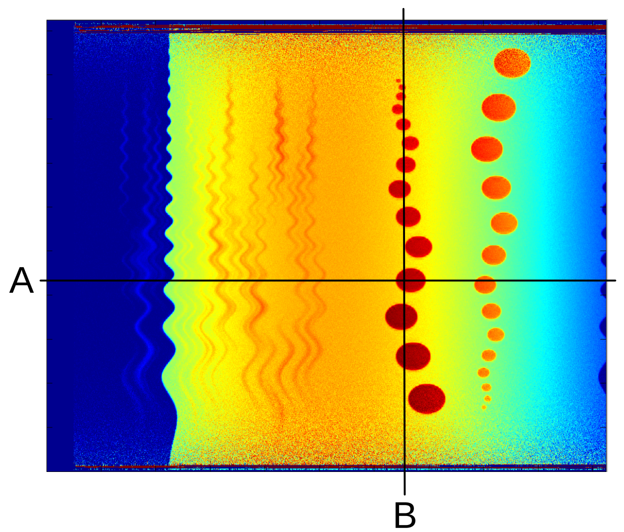
Beam power split into the two images equally.

Solution found simply by dynamic phase – static phase.

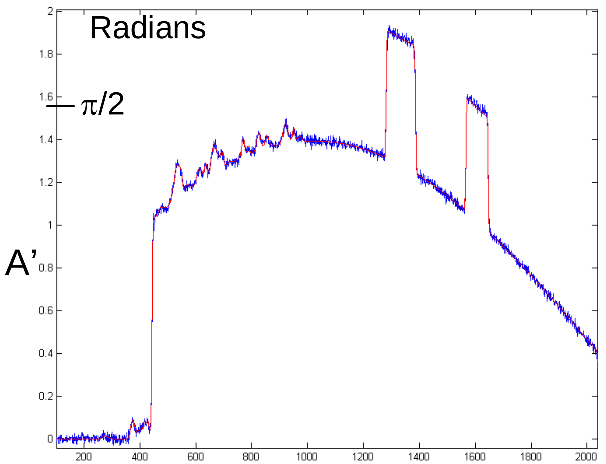
phase $\phi(x,t)$ = atan(((image1-b_1)/k_1) / ((image2-b_2) / k_2))

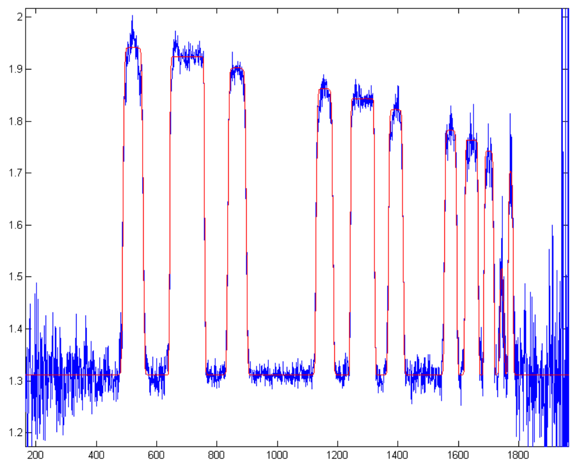
k_n Fringe amplitude estimate.
b_n Back ground estimate
} Normalisation parameters

Phase solution

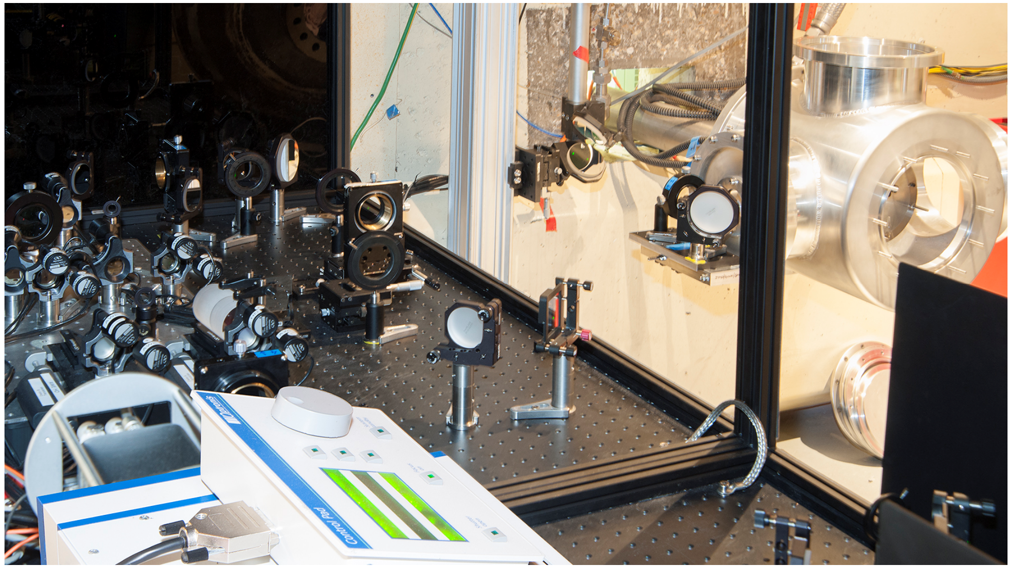


Phase analysis of the test problem





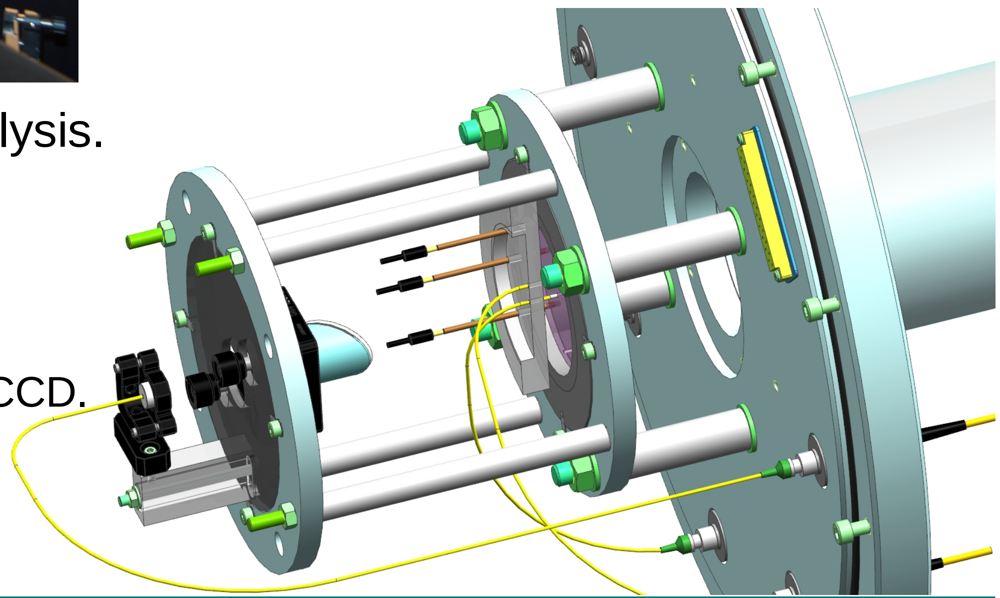
Gas gun at AWE



- Single stage Helium gas gun.
- 3 m long barrel, 70 mm bore.
- Velocity range 150 – 900 m/s.
- Laser 10 W 532 nm Verdi.

- PDV probes to compare our velocity analysis.
- Target contained within vacuum.
- Single streak camera.

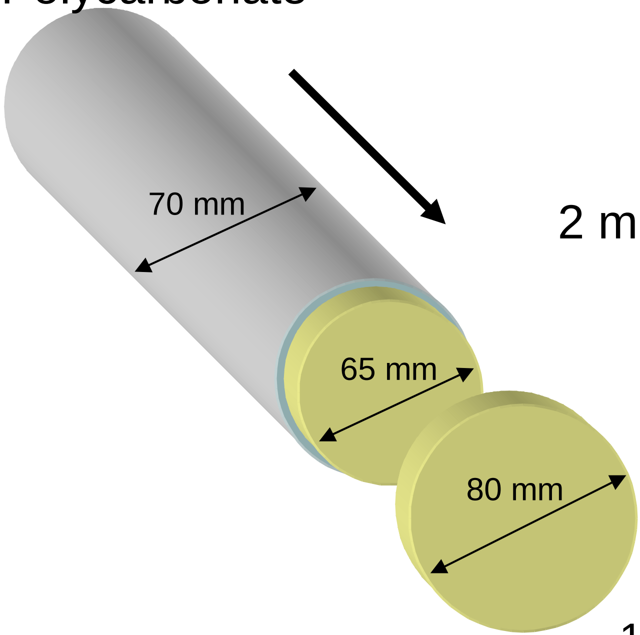
  Optronis SC-51 with a Spectral Inst S1 1000 CCD.
- Two camera quadrature next year.



Fe/Fe Symmetric impact experiment

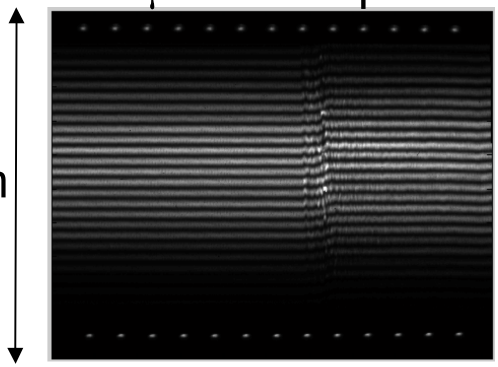
Shot name FeLV 2a.
Fe / Fe, Iron (Armco) 4 mm / 4 mm.
VPF 581 m/s 63 μm fringes.
Diamond machined surface to reduce speckle pattern noise.
Impact velocity 356 m/s.
Pressure ~6.5 GPa.

Sabot
Polycarbonate

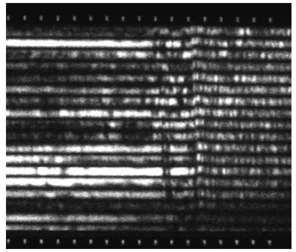


4.2 μs 2048 pixels

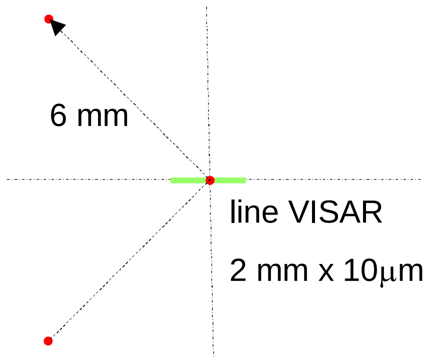
2 mm



Speckle pattern noise example



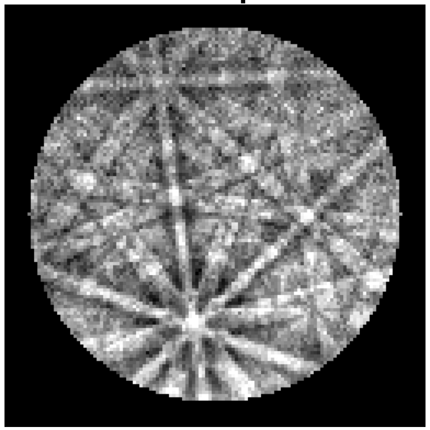
3 surface PDV measurements
spot size 200 μm



1D zone out to a radius of ~31 mm

Grain orientations and size distributions are homogenous

Diffraction pattern

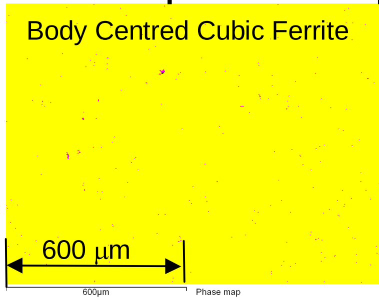


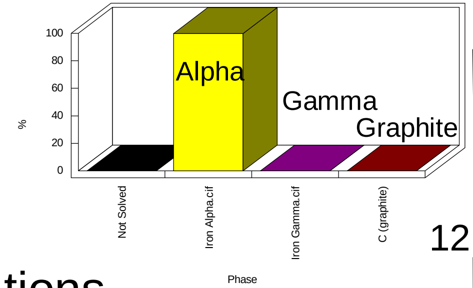
Electron Back Scatter Diffraction EBSD

For Iron (Armco) sample.

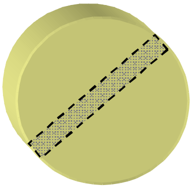
Dr Nigel Park, Graham Newton AWE

Material phase map

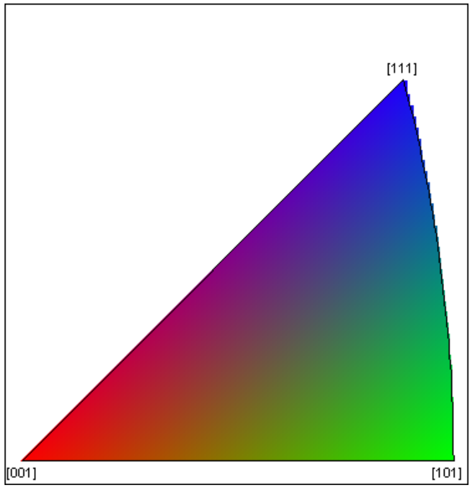




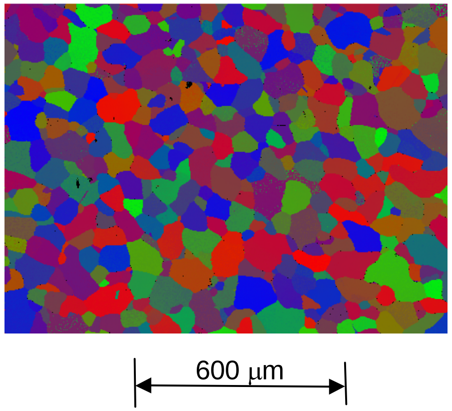
Phase map shows predominately Alpha phase with <<1% Gamma.



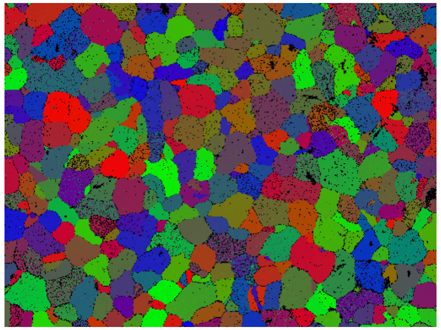
Grain orientations

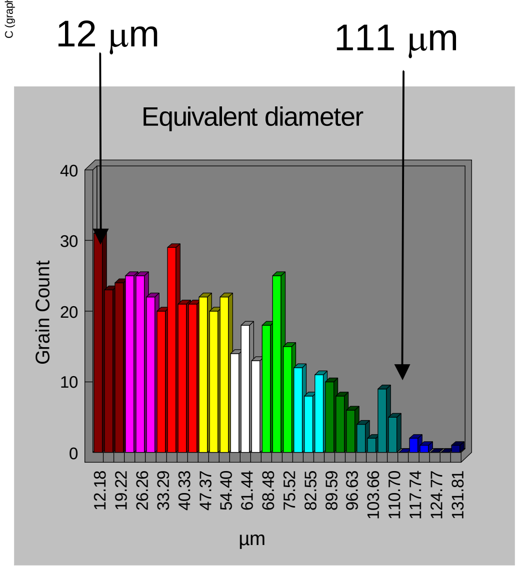


Section through target



Free surface

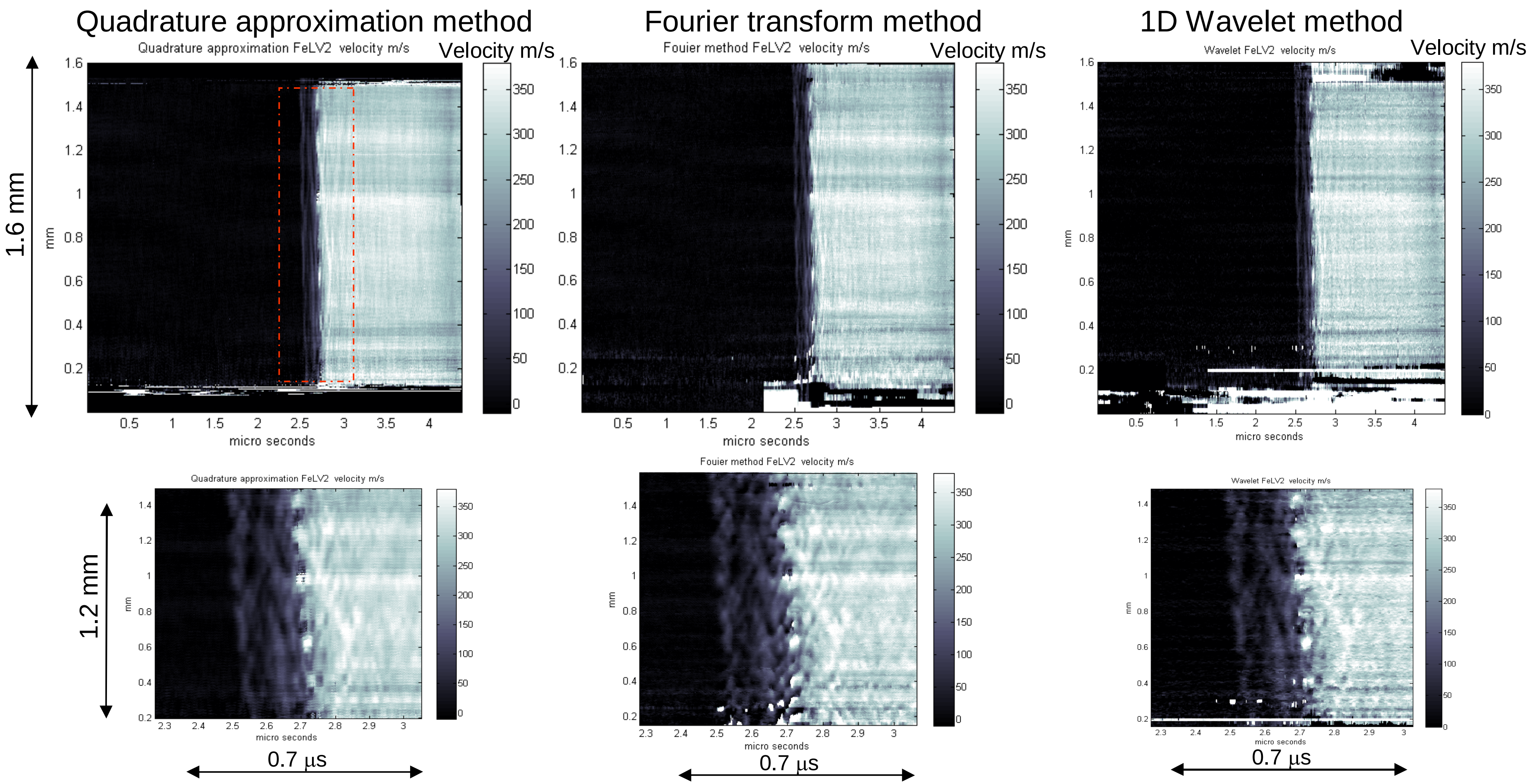




Symmetric impact data Fe / Fe, Iron (Armco)

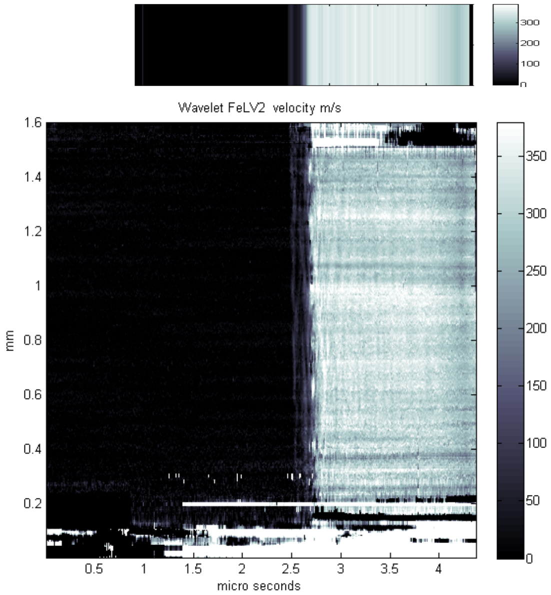
Impact at 356 m/s

VPF 581 m/s, 63 μm fringes.

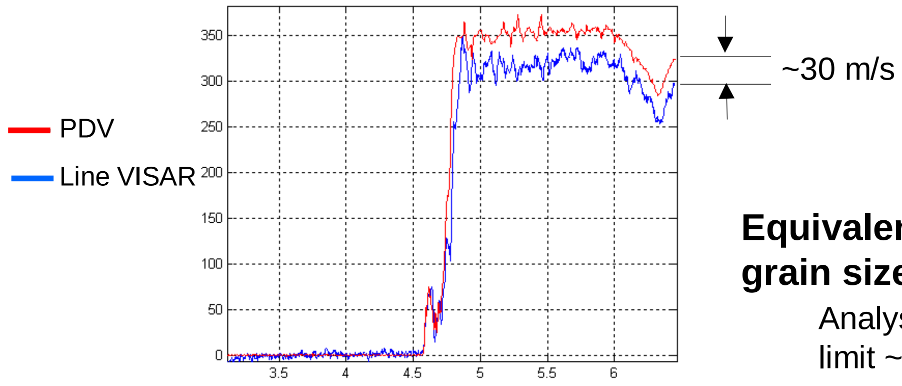


Comparison with PDV data

PDV data shown as an image

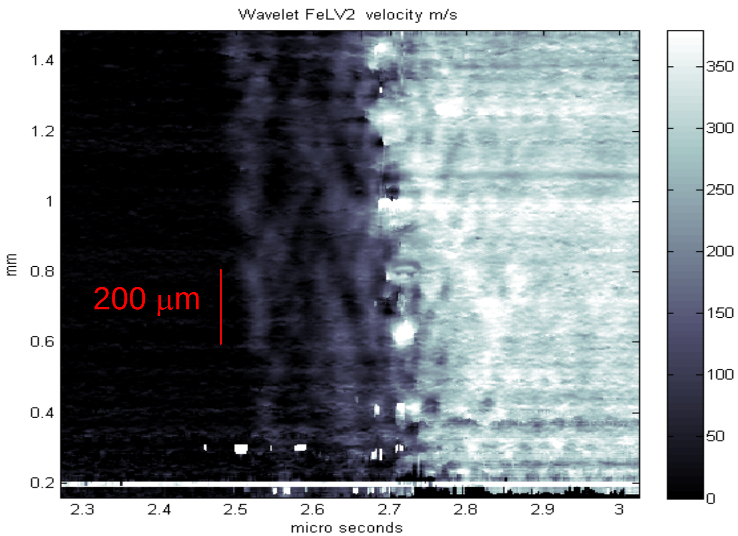


Line VISAR averaged over 100 μm to match the effective spot size of the PDV.



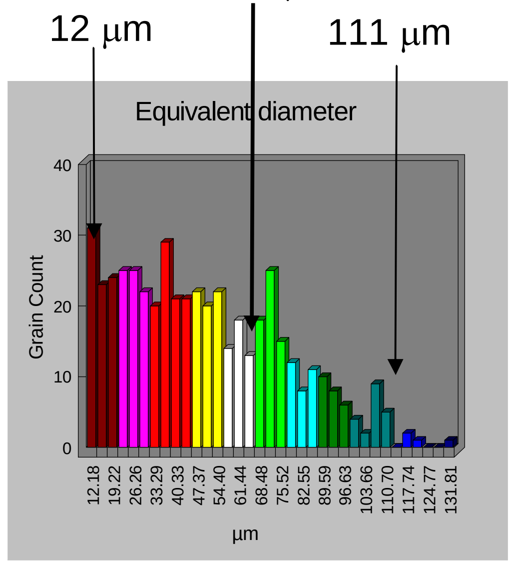
“Too soon to say that we have a correlation with grain size or that we can resolve grain size features.”

“We are now working towards producing 20 μm fringes.”



Equivalent diameter grain size distribution

Analysis resolution limit ~63 μm



Fringe instability is causing significant velocity errors

This streaky pattern is produce by fringe instability and is dynamic during the event.

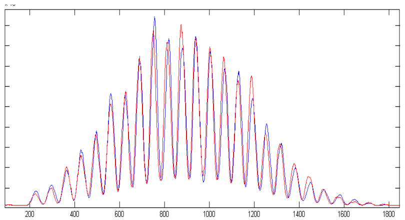
Not representative of the velocity of the target surface. Not generated by the analysis.

We believe that it may be caused by back reflections coupling to the laser.

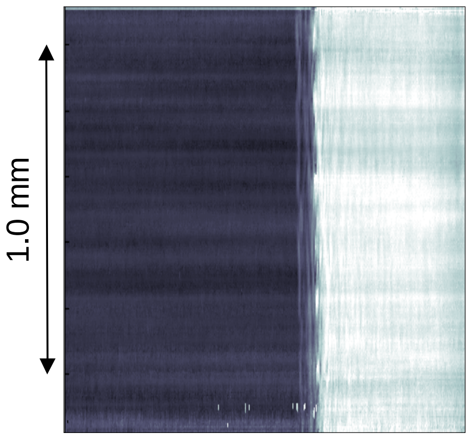
We are going to implement a Faraday rotator to isolate the laser.

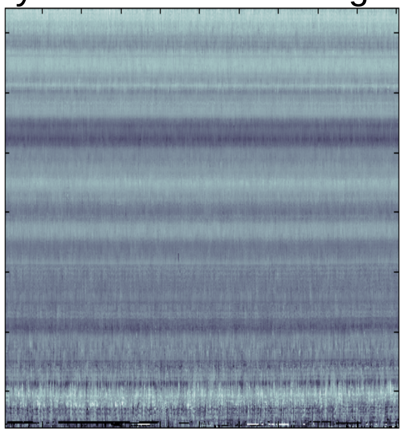
These small non-uniform phase changes are significant ~ ±5% VPF or ± 30 m/s velocity error.

Fringe profile from two static fringe images shows instability.

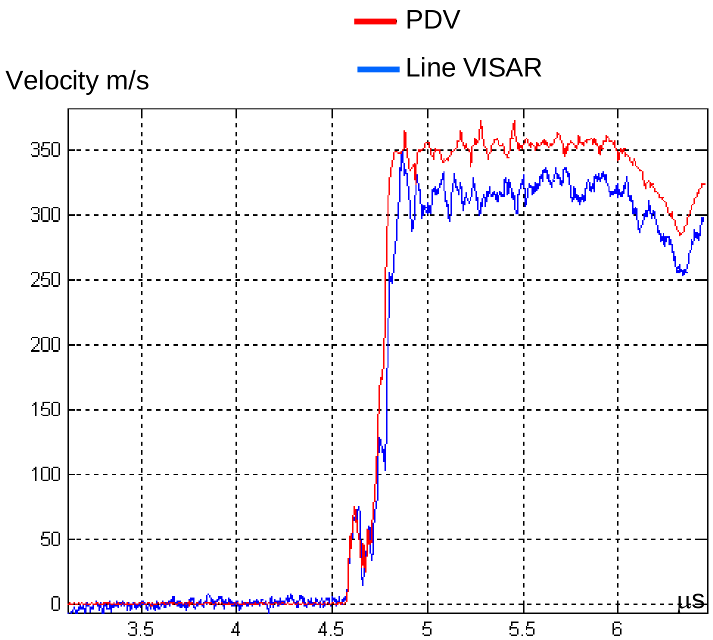


Analysis of two static fringe images



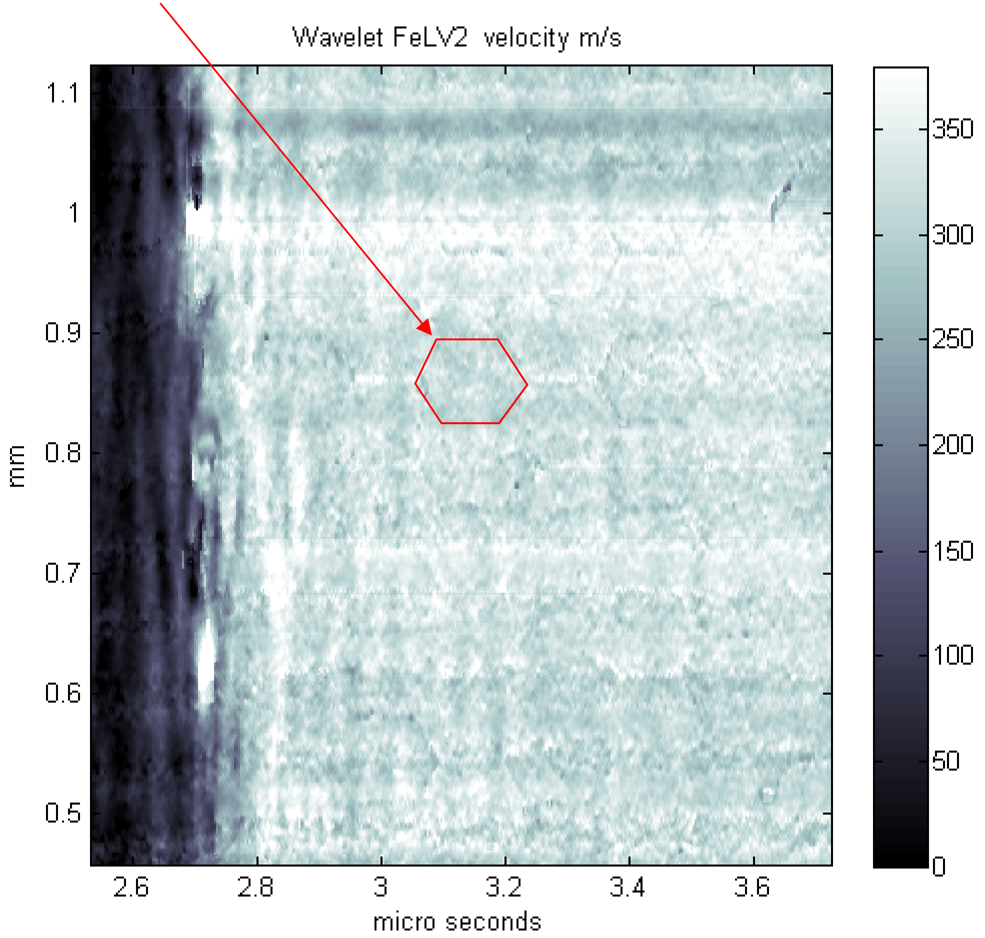


Line VISAR averaged over 100 μm to match the effective spot size of the PDV.



Fixed pattern noise

Fix pattern noise due to the tapered fibre intensifier inside the camera.

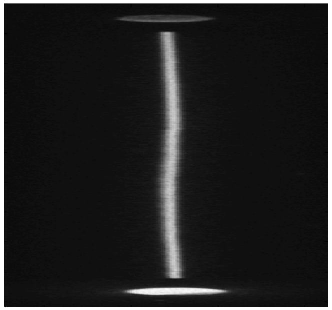


Now that we have a high resolution analysis it becomes necessary to consider removing fixed pattern noise.

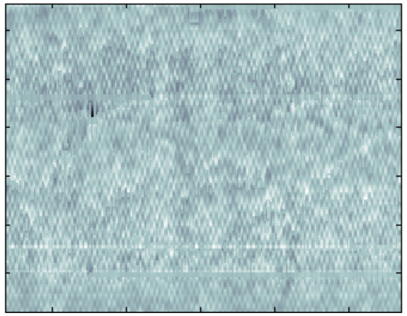
We are also characterising our streak camera for image distortion.

Slit distortion

~ +-5 pixels



Fix pattern noise due to the tapered fibre intensifier.



High resolution line VISAR requires precise alignment of the optics a high fringe density and a high resolution analysis method.

Shot 'FeLV 2a' had **63 μm** fringes and the focusing could have been improved.

Not quite good enough to meet our requirements of 50 μm.

After much work on the optical bench we are now able to produce ~**14** μm fringes.

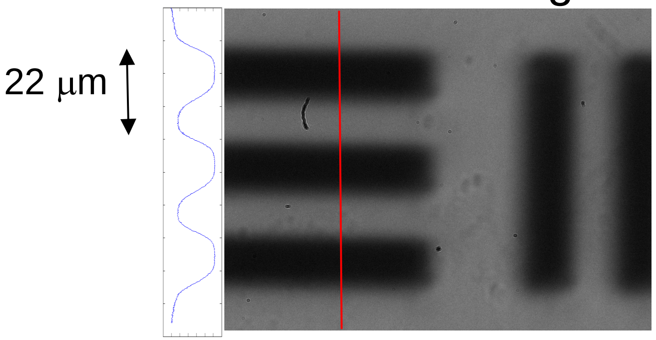
Image of a standard resolution target.

USAF 1951 Group 5 E4   45.25 lp/mm
~**11μm** features in the object plane.

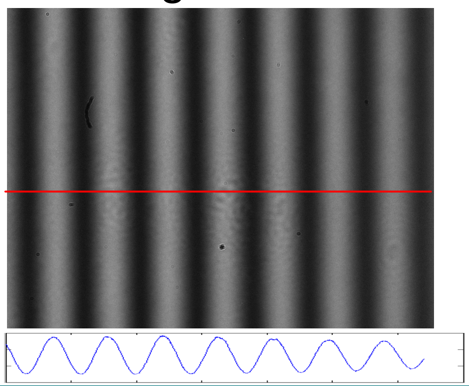
Incoherent diode illumination.

Image of 14 μm fringes at the focal plane entering the streak camera.

Resolution target



Fringe data



Conclusions

High resolution line VISAR (<50 μm) requires.

- **Precise alignment of the optics on the bench.**

  Avoid back reflections and optimise focusing, invest time here!

  Suggest a Faraday rotator at the source.

  Ideally mechanically isolate the target from vibration sources.

  Very important to measure the VPF correctly.

- **High standard of target surface preparation to reduce speckle pattern.**

  Polishing or diamond machining.

- **A high density of fringes.**

  At least 3/2 fringes per feature for the Fourier transform method.

  ‘Quadrature approximation’ and ‘Fringe tracking’ methods require >2 fringes.

Conclusions

- **Single camera line VISAR is a viable option for our 50 μm resolution goal.**
  We believe that we can demonstrate ~14-22 μm resolution this year.

- **Analysis method must maintain the resolution of the optical system.**
  Narrow band pass filtering should be avoided in line VISAR analysis.

- **We recommend the 1D CWT analysis as an approach for line VISAR.**
  The Fourier analysis method can be unstable although may be improved by the application of a well designed complex quadrature filter.

  - > An approximation to Wavelet analysis can be implemented extremely quickly.

  - The 'Mexican hat' function works fine well. Need to study other wavelets

Future work

- **Address fixed pattern noise.**

Thoroughly characterise the camera that we have been using.

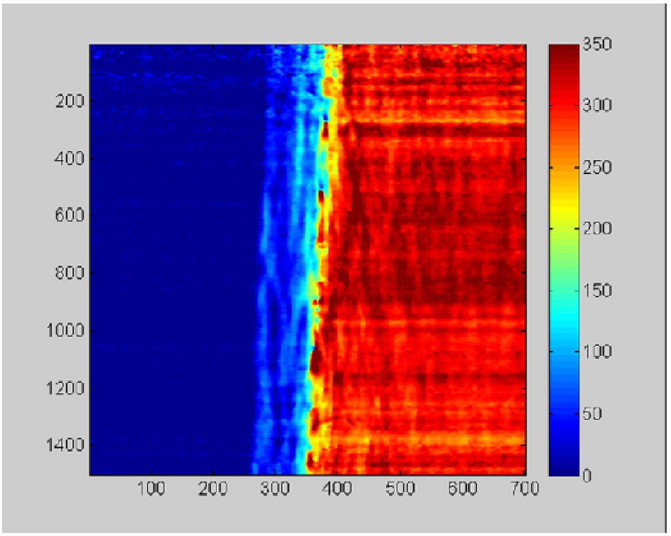
- **Mechanically isolate the target from the gun.**

Possible but is a considerable ‘engineering and safety case’ project.

Introduce Faraday rotator to isolate the laser.

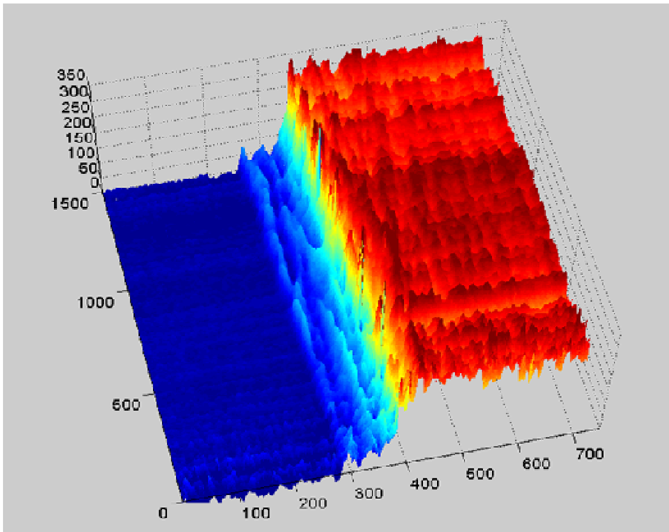
Spatial Velocity map m/s

Position ~1.5 mm



Time ~1.5 μs

Velocity m/s



Time ~1.5 μs