Triple Doppler frequency spectrogram from a Triature Photonic Doppler Velocimeter

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Outline

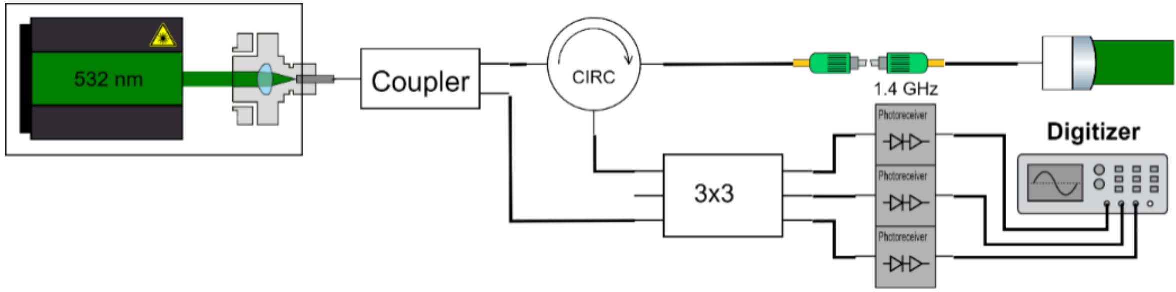
1. Working principle
2. Theoretical velocity profile
   A. 1550-nm Frequency-Shifted PDV
   B. 1550-nm Triature
   C. 532-nm Triature
3. 3ν signal processing with few real data

Triple frequency "3v" principle

⇒ Use of the 3 Triature PDV outputs to create a new signal, which is tripled in frequency by trigonometry

$$sin(3 \cdot \theta) = 4 \cdot sin(\theta) \cdot sin\left(\theta + \frac{2\pi}{3}\right) \cdot sin\left(\theta - + \frac{2\pi}{3}\right)$$

$$I_{3\boldsymbol{v}}(t) = K \cdot sin\left(\mathbf{3} \cdot 2\pi \cdot \int_0^t f_D(t) \cdot dt + \Delta\varphi\right)$$



$$I_1(t) = A_{ref}A_{sonde}(t)\sin\left[4\pi \cdot \frac{d(t)}{\lambda} + \Delta\varphi\right]$$

$$I_2(t) = A_{ref}A_{sonde}(t)\sin\left[4\pi \cdot \frac{d(t)}{\lambda} + \Delta\varphi + \frac{2\pi}{3}\right]$$

$$I_3(t) = A_{ref}A_{sonde}(t)\sin\left[4\pi \cdot \frac{d(t)}{\lambda} + \Delta\varphi - \frac{2\pi}{3}\right]$$

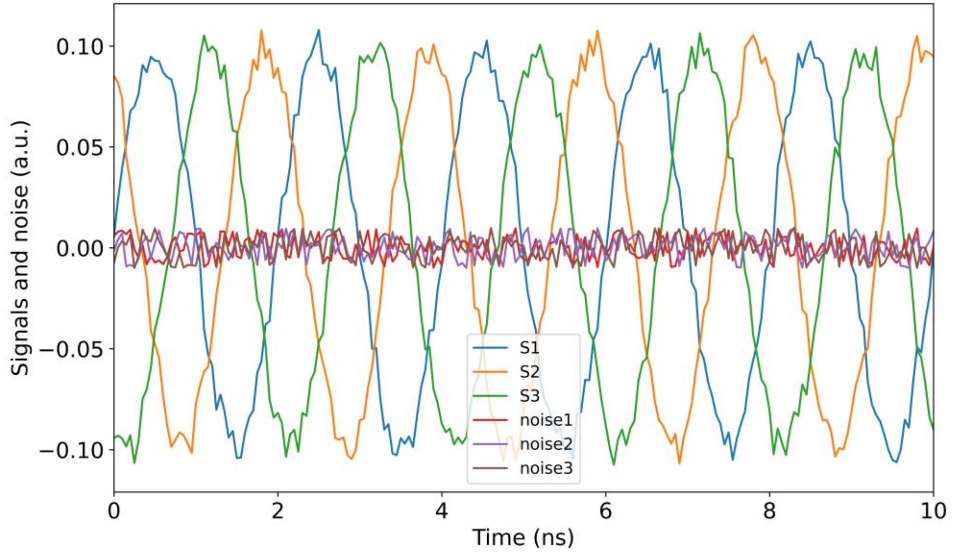
- Spectrogram signal processing
- Greater velocity resolution (3x)
- Greater time resolution (3x)
- More than one velocity profile possible*
- No derivative step (*i.e.* triature signal processing)
- No modification of the PDV system
- No increase in bandwidth (photoreceiver and digitizer**)

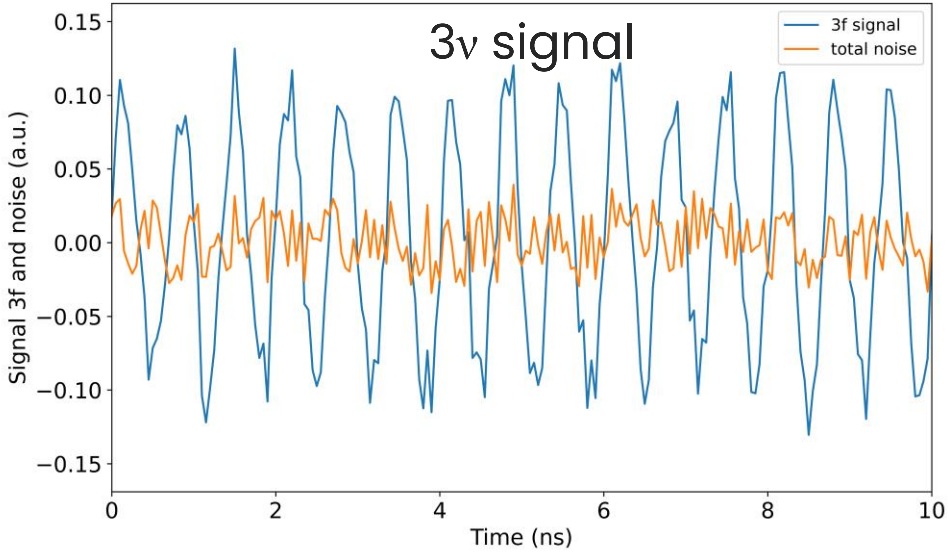
$$\lambda_{eff.@1550} = \frac{1550}{3} = \mathbf{516.7\ nm}$$

$$\lambda_{eff.@532} = \frac{532}{3} = \mathbf{177.3\ nm}$$

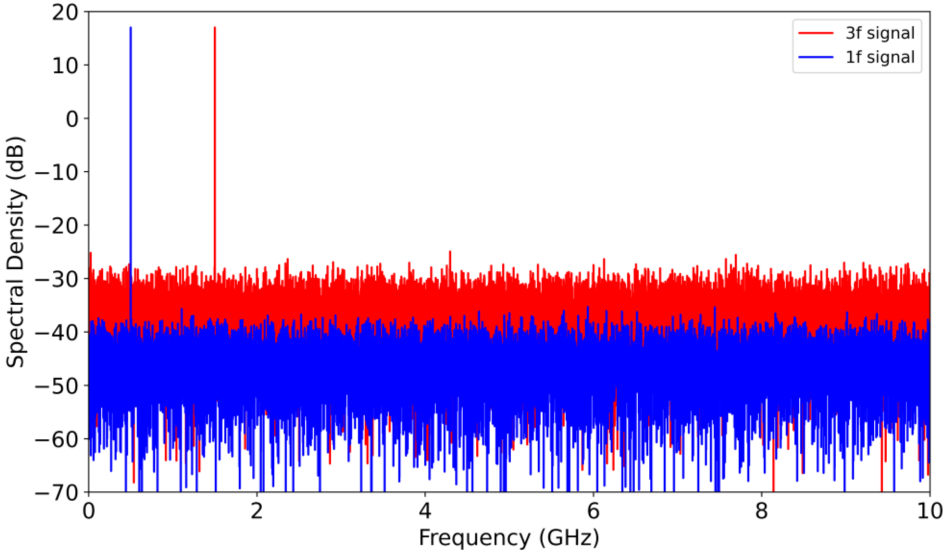
* warning: possible harmonics
** warning: the sampling rate should be tripled

Basic exemple on virtual noisy signals



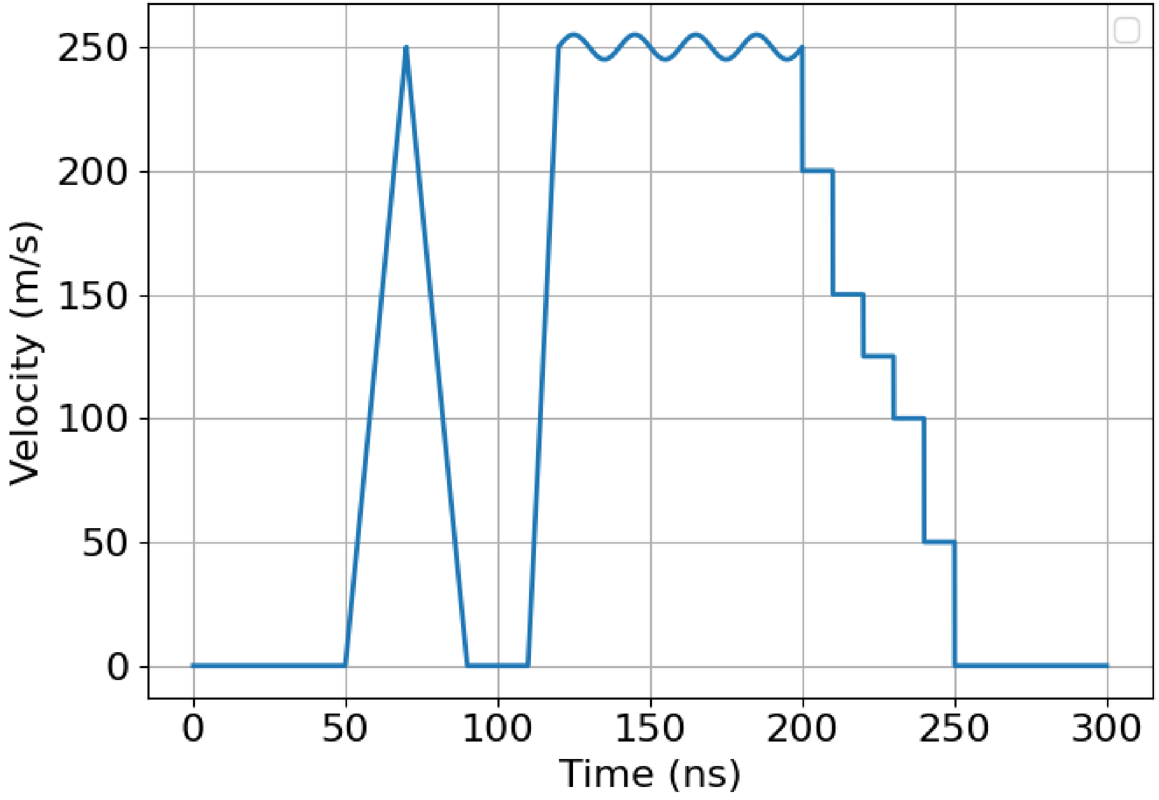


NoiseX3



Here with 10% noise, the noise floor increases by ~10 dB.

Theoretical velocity profile



Characteristics :

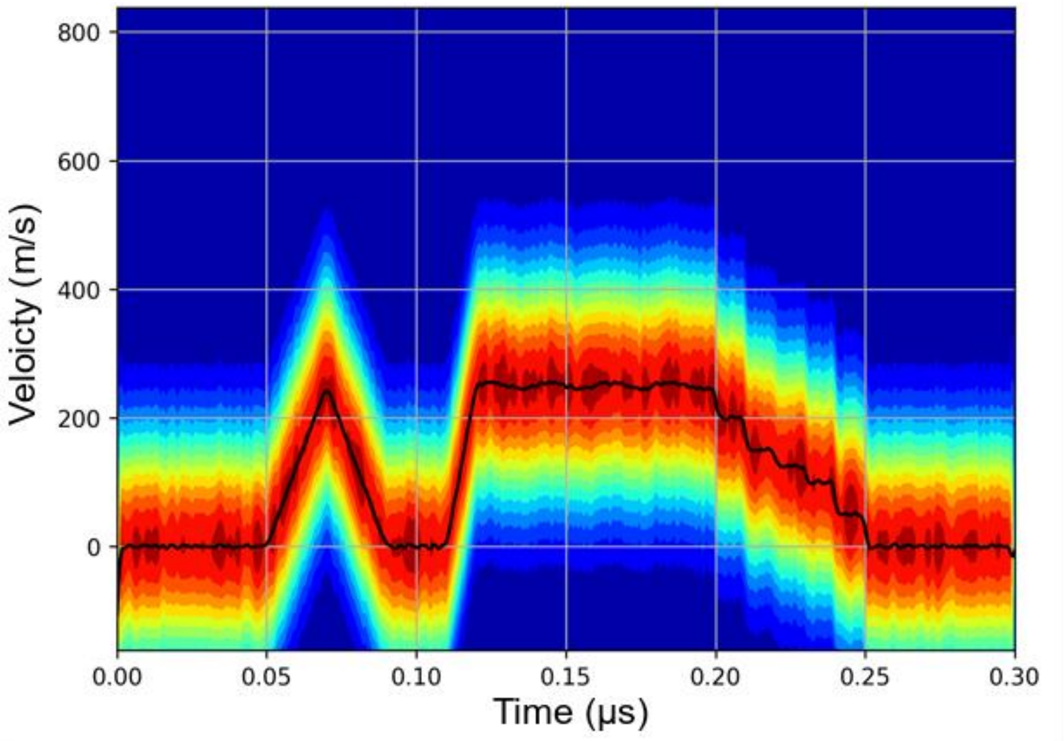
- Peaks in 20 ns ↑ & 20 ns ↓
- A sharp front in 10 ns
- Modulations ±5 m/s around 250 m/s
- Many steps down in 20 ps (50 Gs/s)

Simulated systems :

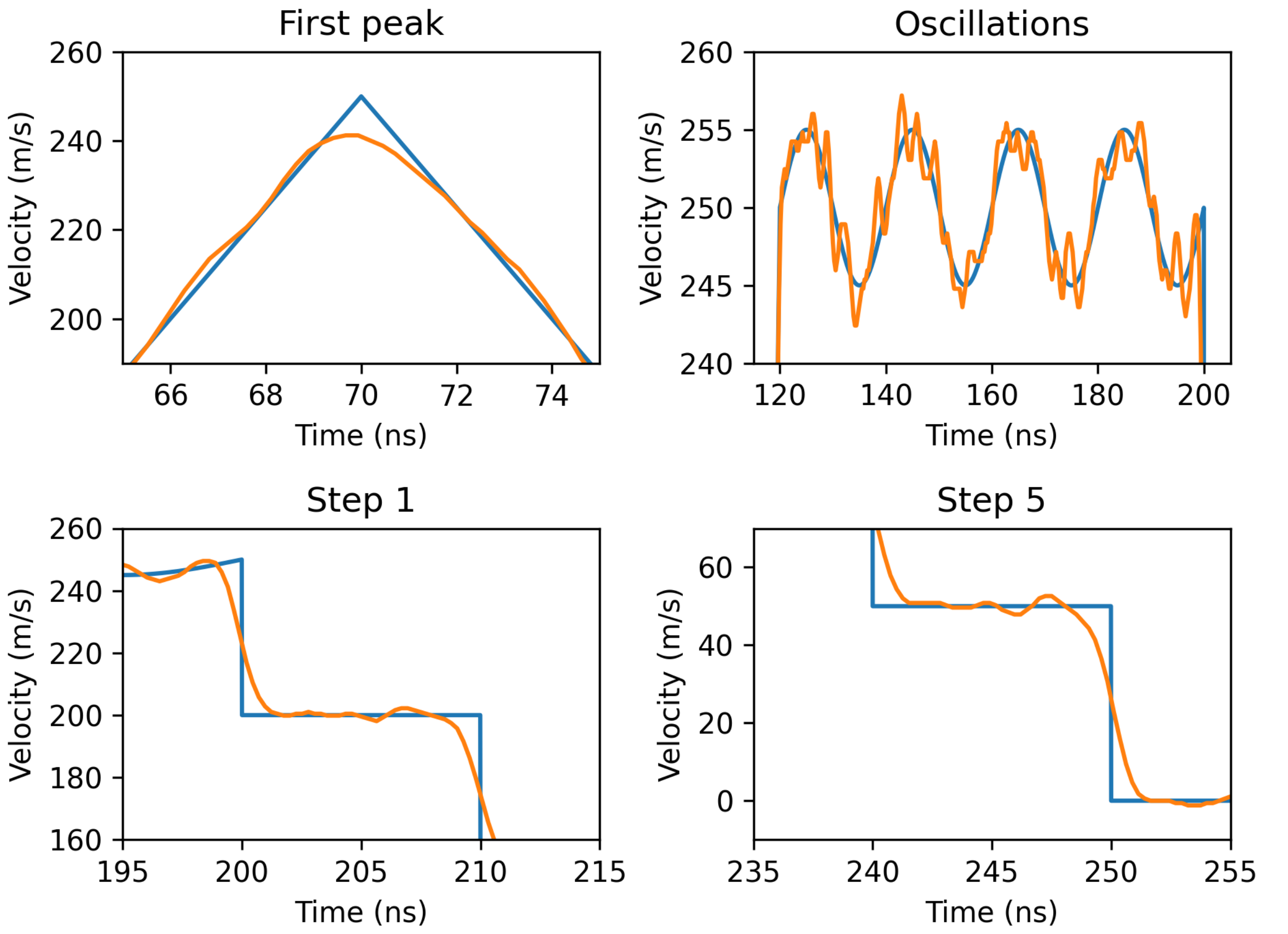
- 1550-nm PDV with a 1000 m/s shift (1.29 GHz)
- 1550-nm Triature PDV
- 532-nm Triature PDV

1550 nm FS-PDV (Reference)

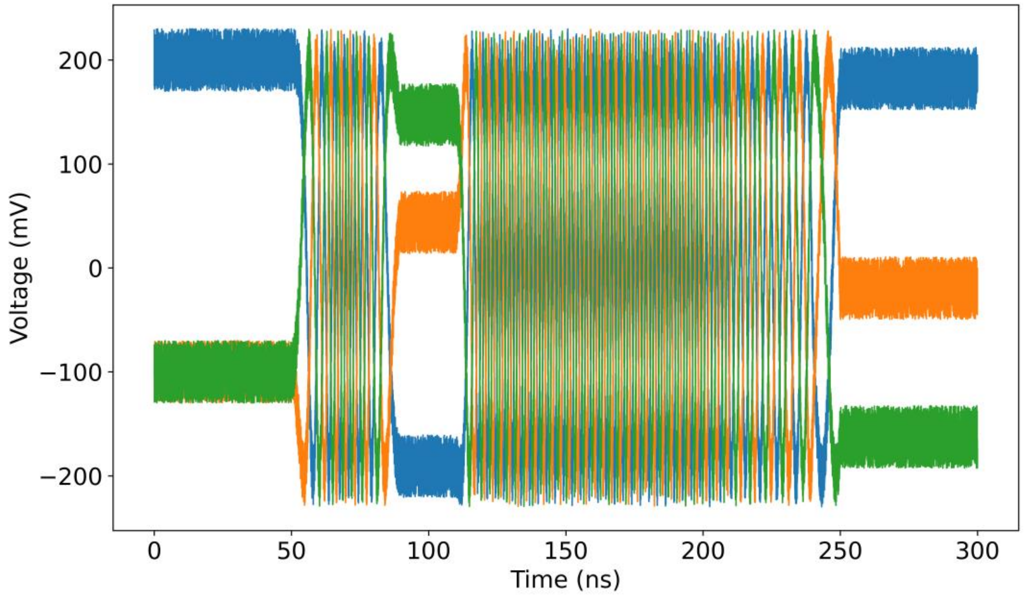
f_{Shift} = 1.29 GHz => 1000 m/s



σ = 2.78 m/s



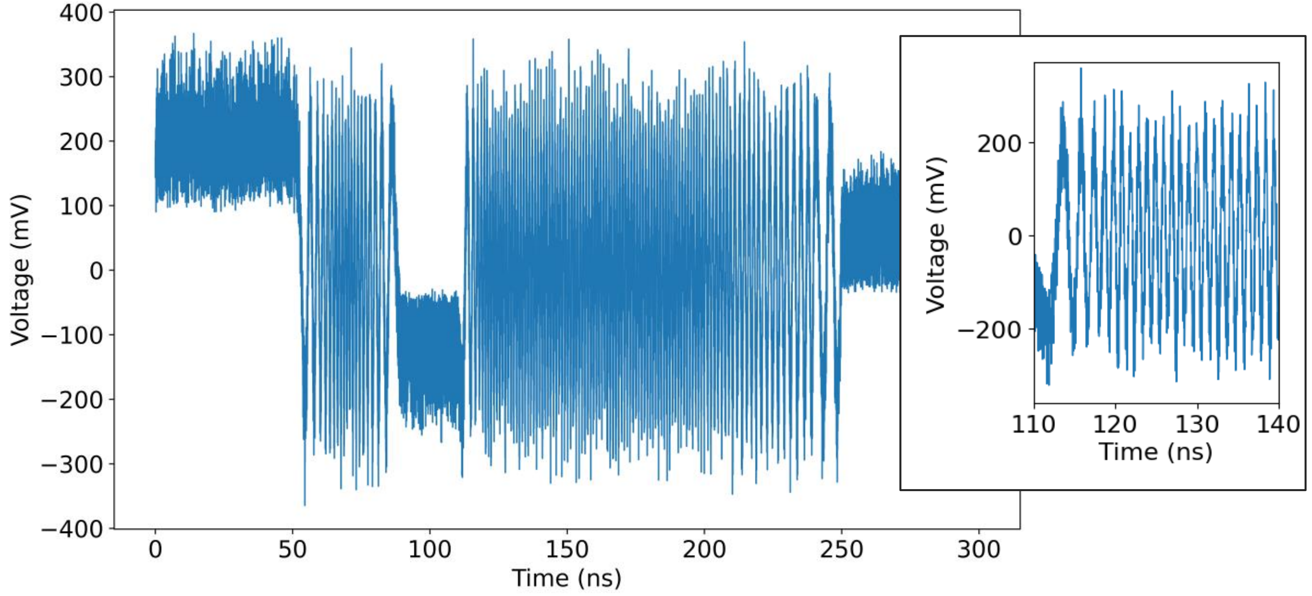
1550 nm Triature signals



Sampling : 50 Gs/s

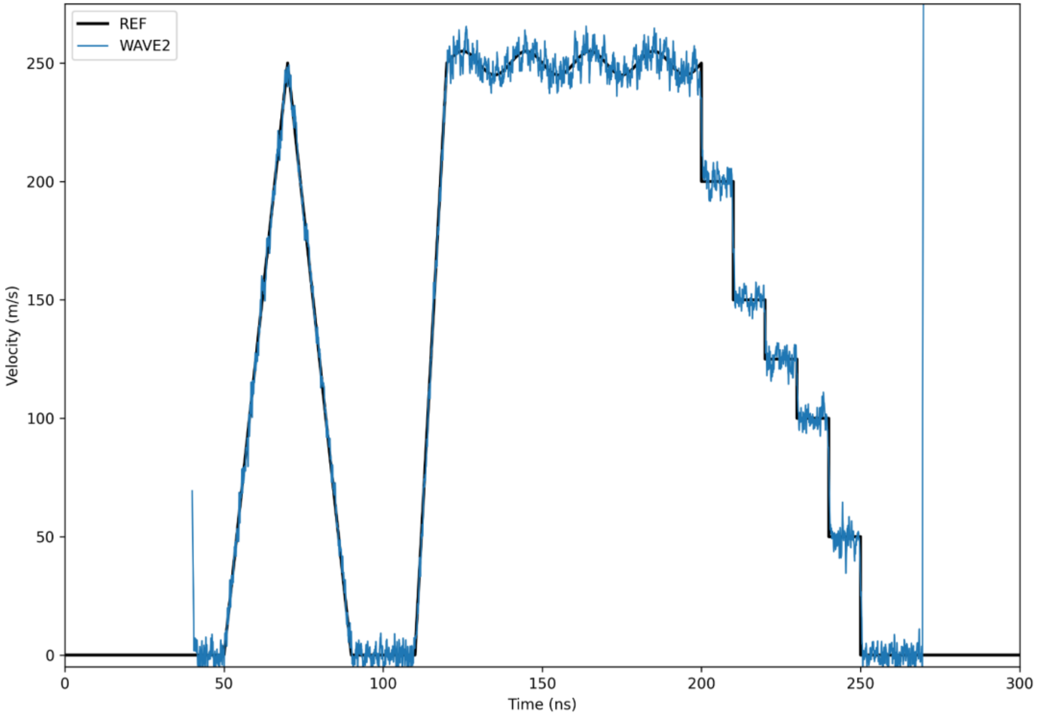
$\lambda_{eff.@1550} = 516.7\ nm$

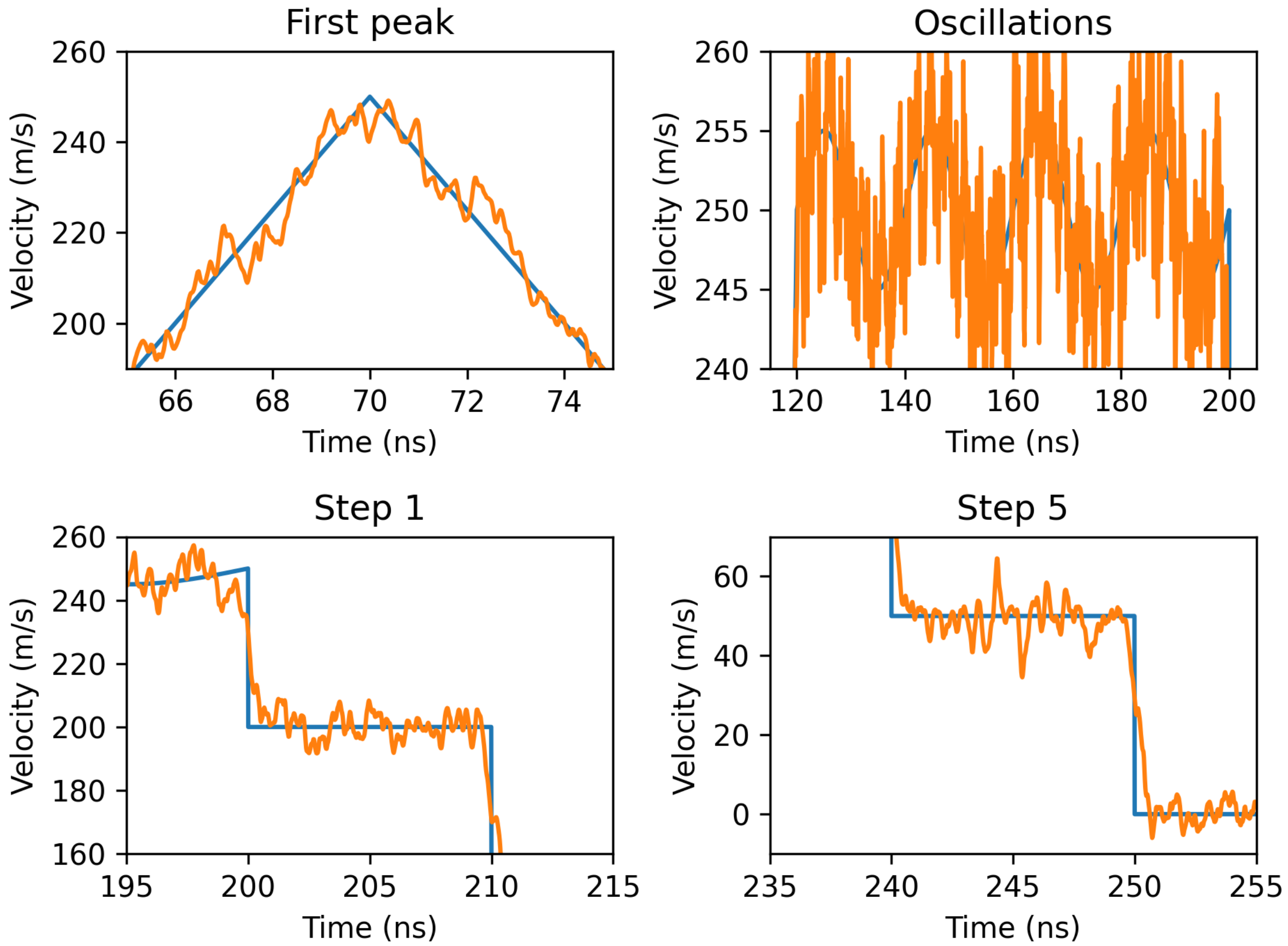
3ν signal



The noise level has increased but the fringes are clearly visible

1550 nm Triature Phase Analysis



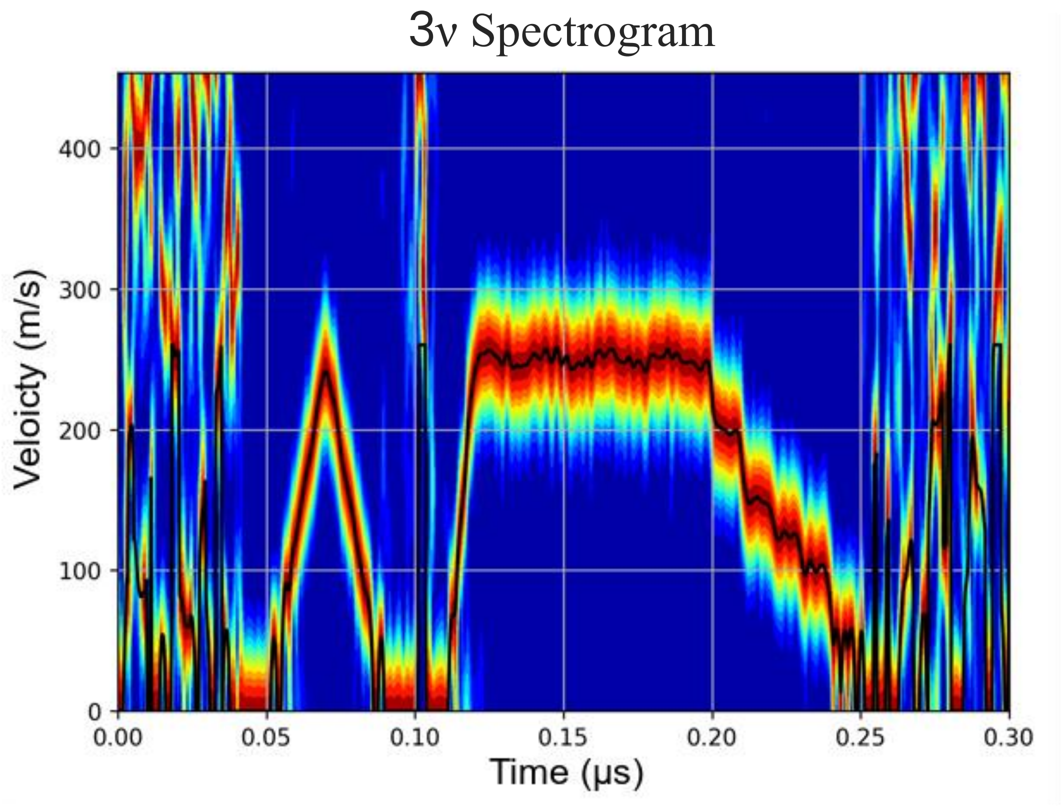


σ = 3.75 m/s

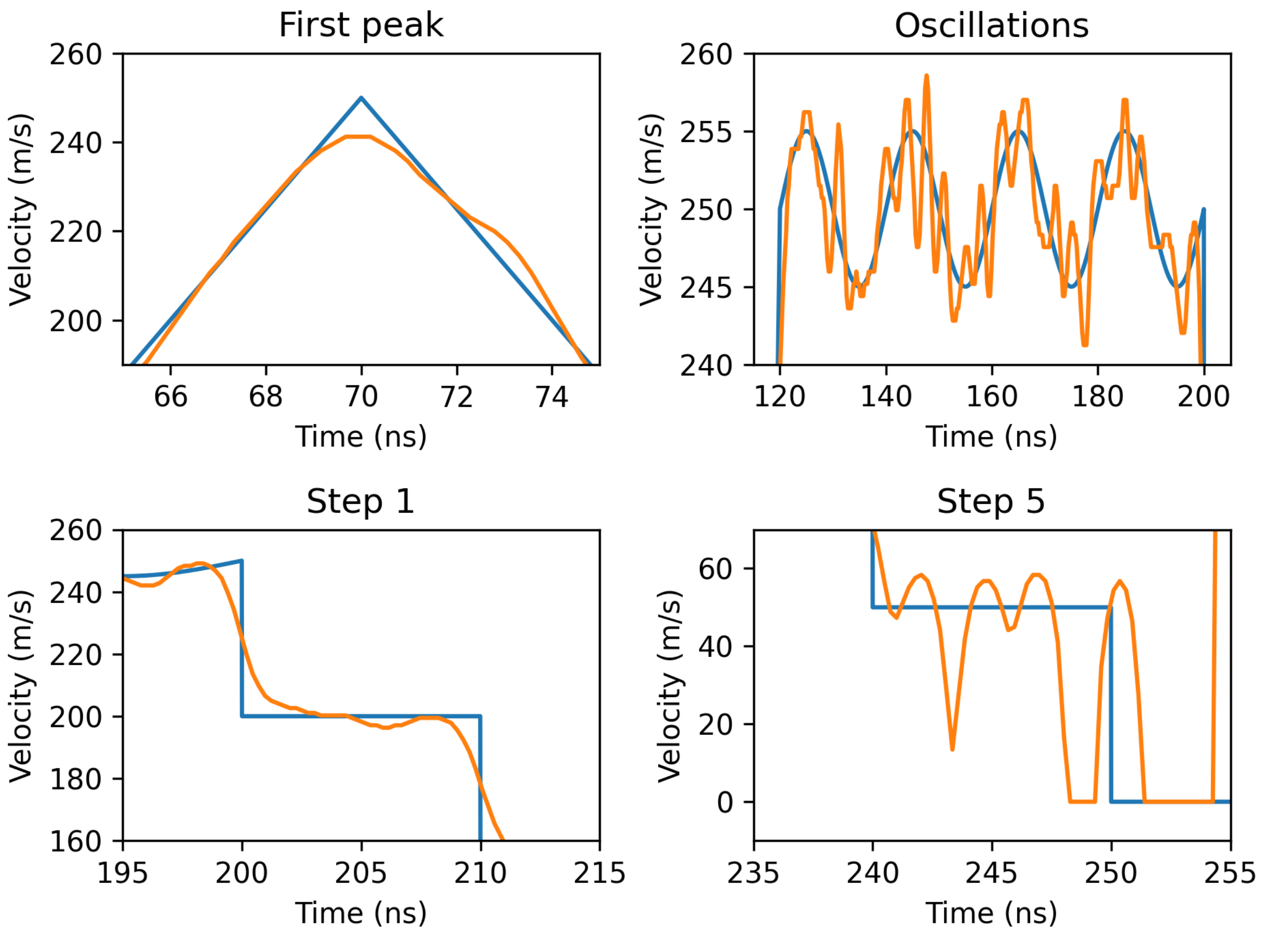
~1 m/s higher than FS-PDV

- Closer to the sharp transitions
- Oscillations too noisy

3ν 1550 nm Triature

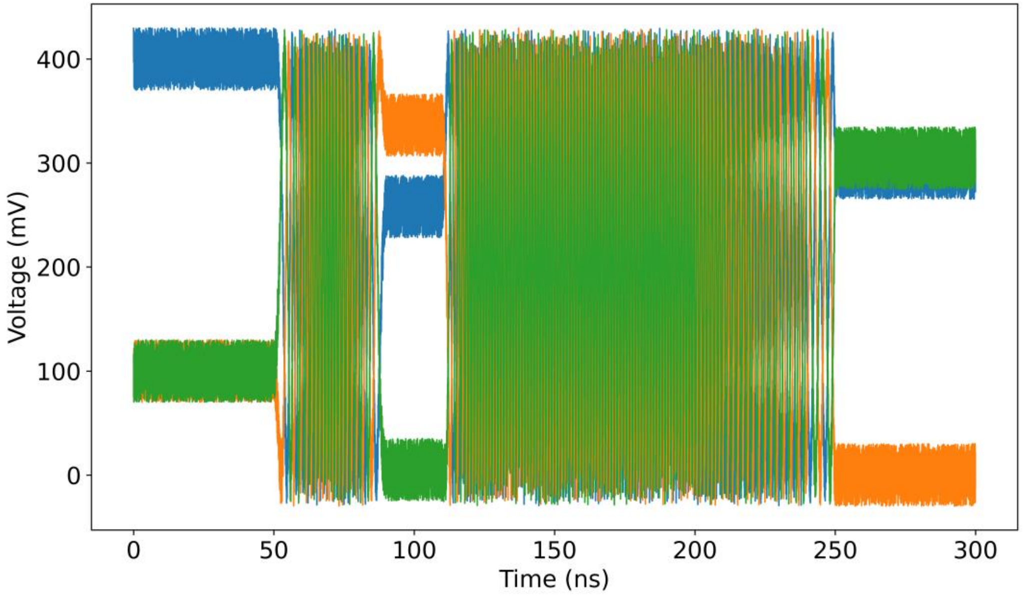


σ = 11.3 m/s



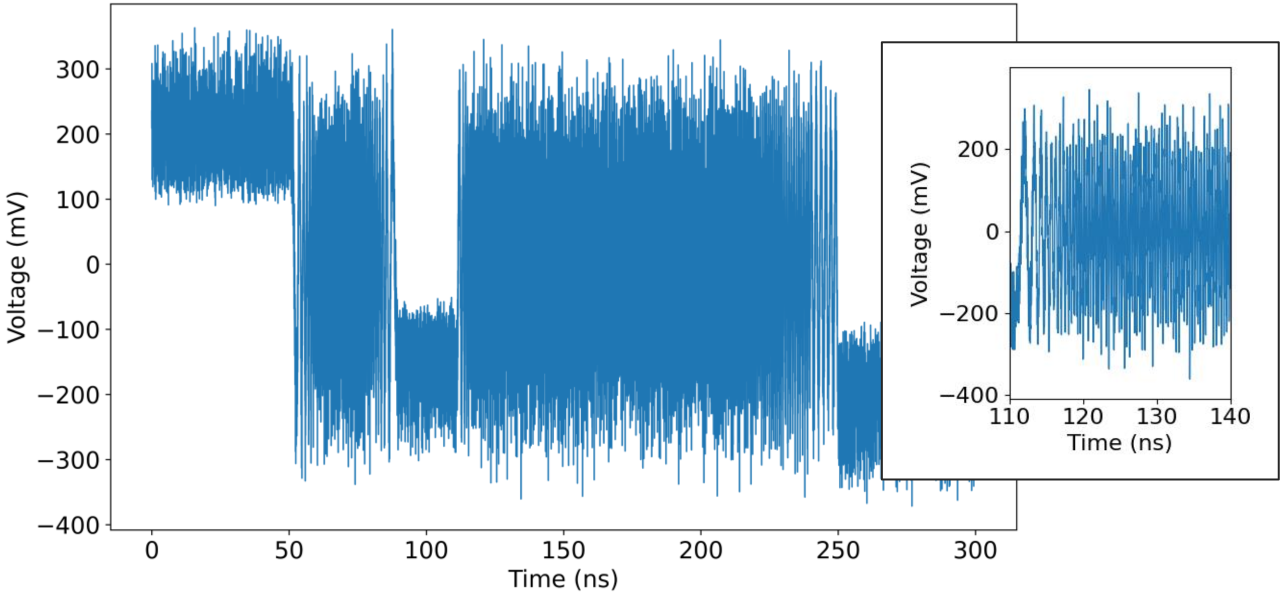
No significant improvement compared to the 1550-nm FS-PDV
It could be better for higher velocities (>1000 m/s)

532 nm Triature signals



$$\lambda_{eff.@532} = 177.3\ nm$$

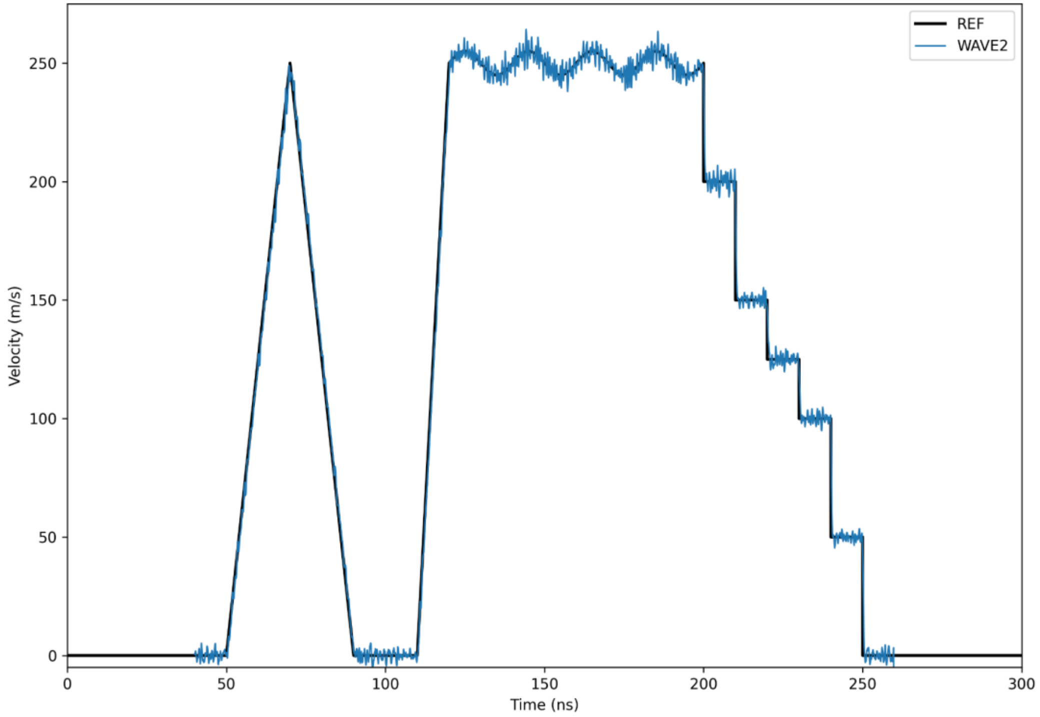
3ν signal



The noise level has increased but the fringes are clearly visible

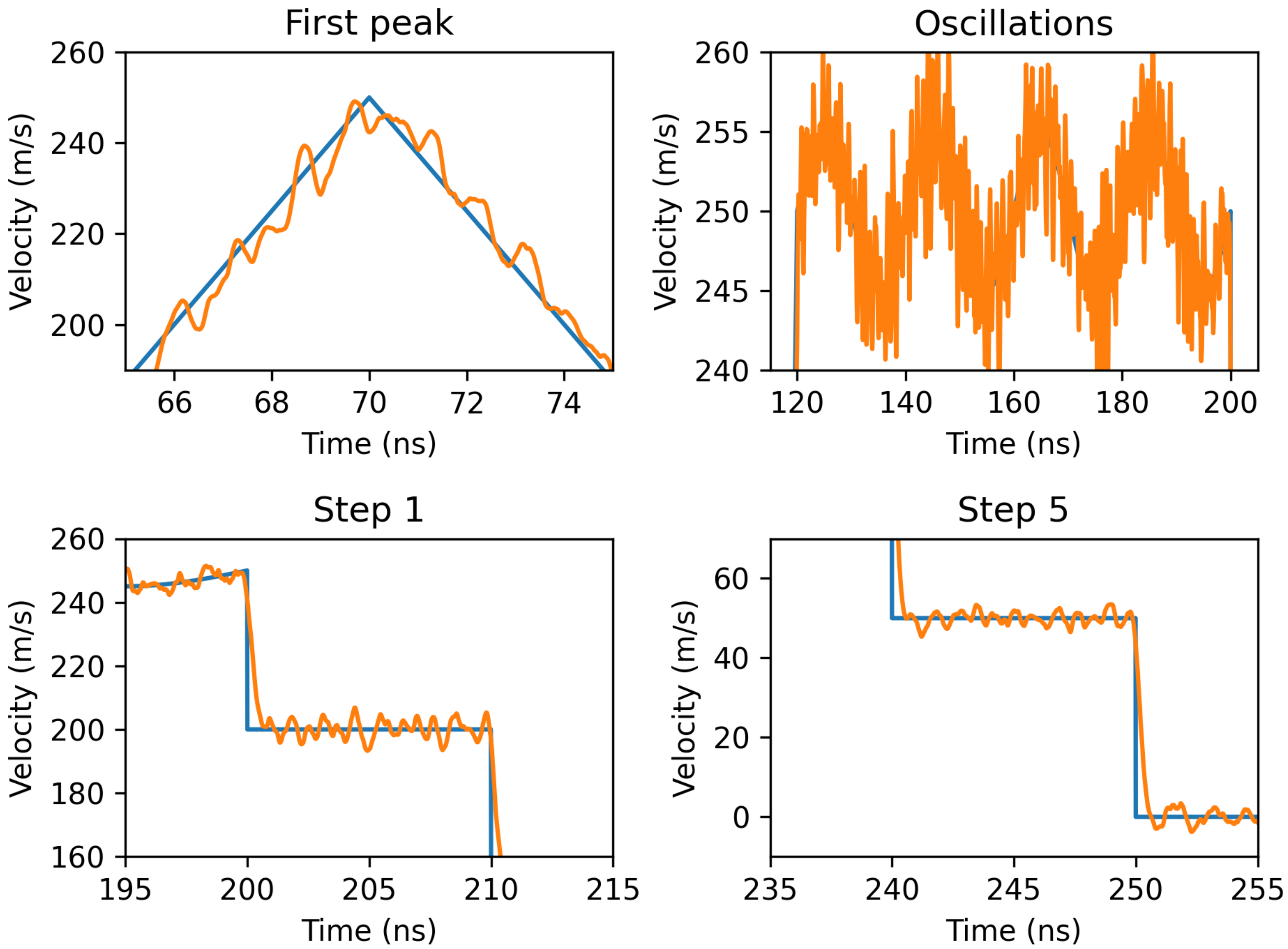
Note: 1550 / 177.3 = 8.74 => effective WL 8.7 times smaller than @ 1550 nm

532 nm Triature Phase Analysis



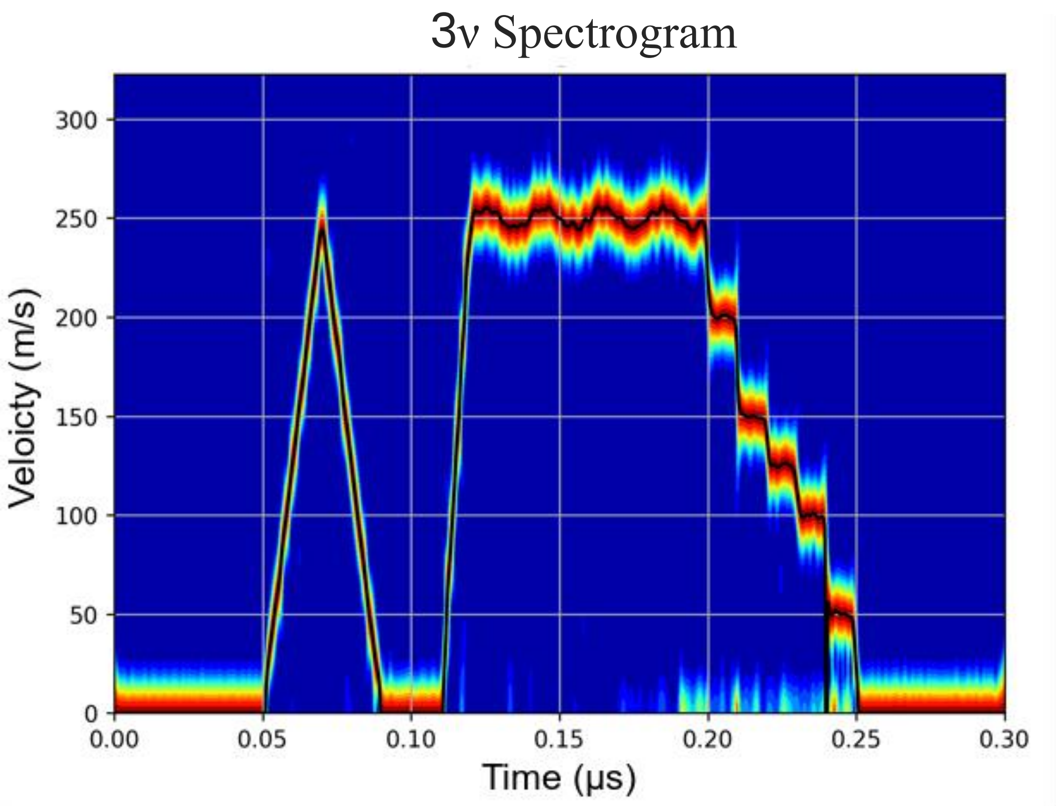
σ = 3.3 m/s

Same standard deviation than the 1550 nm FS-PDV



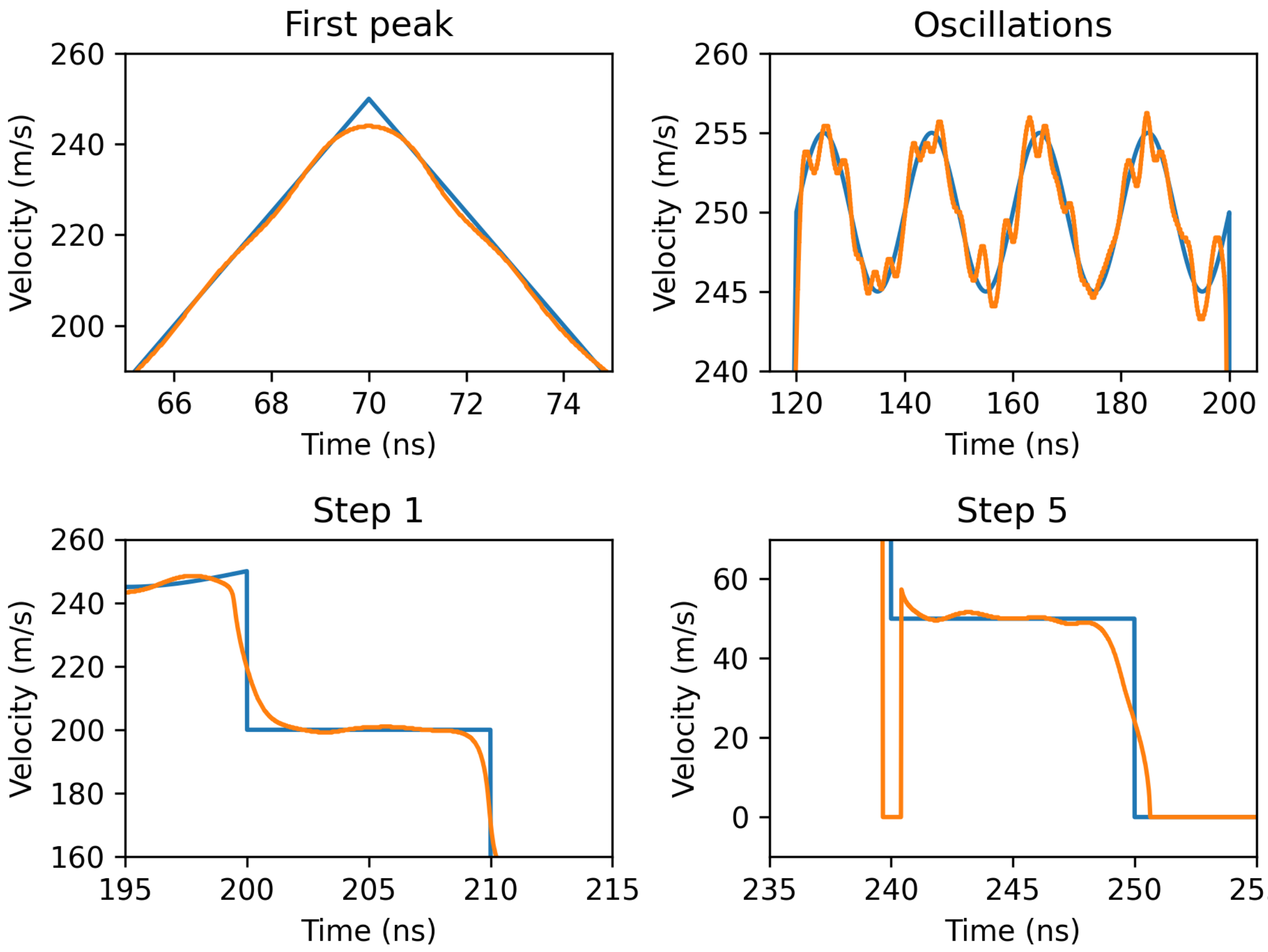
- Very close to the sharp transitions
- Oscillations noisy but could be improved by averaging

3ν 532 nm Triature



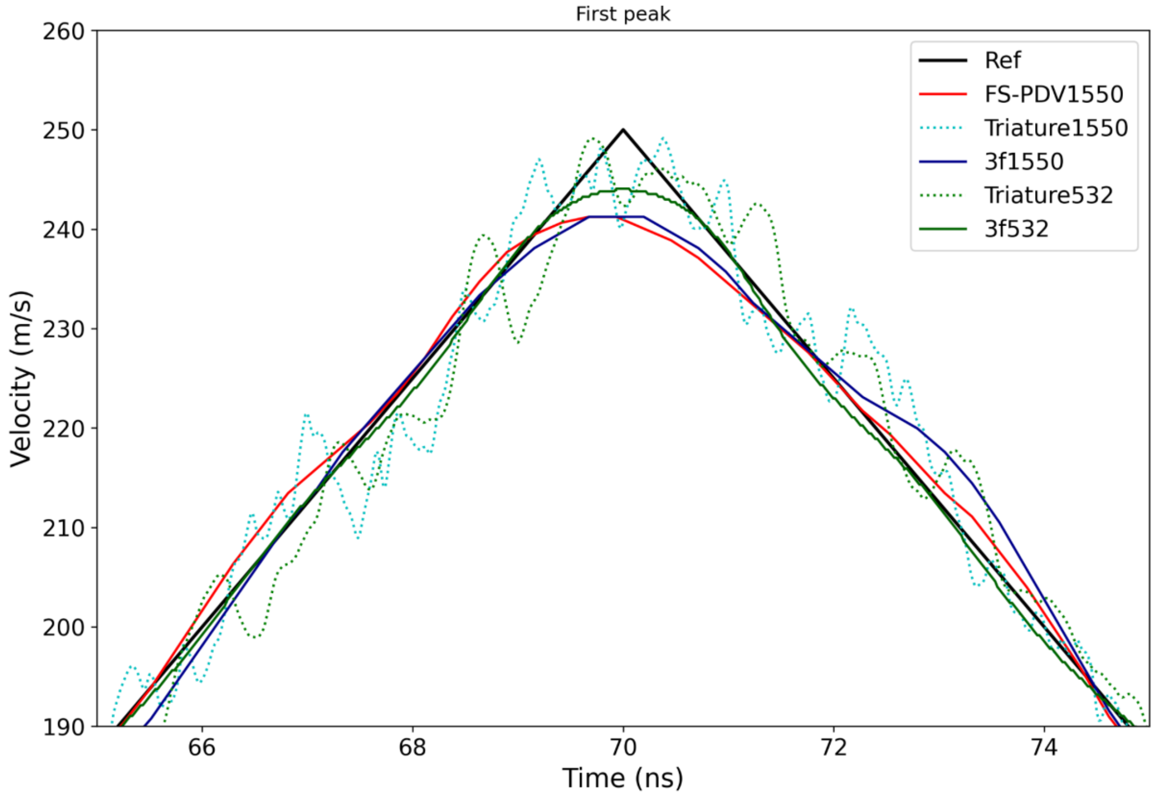
σ = 4.63 m/s

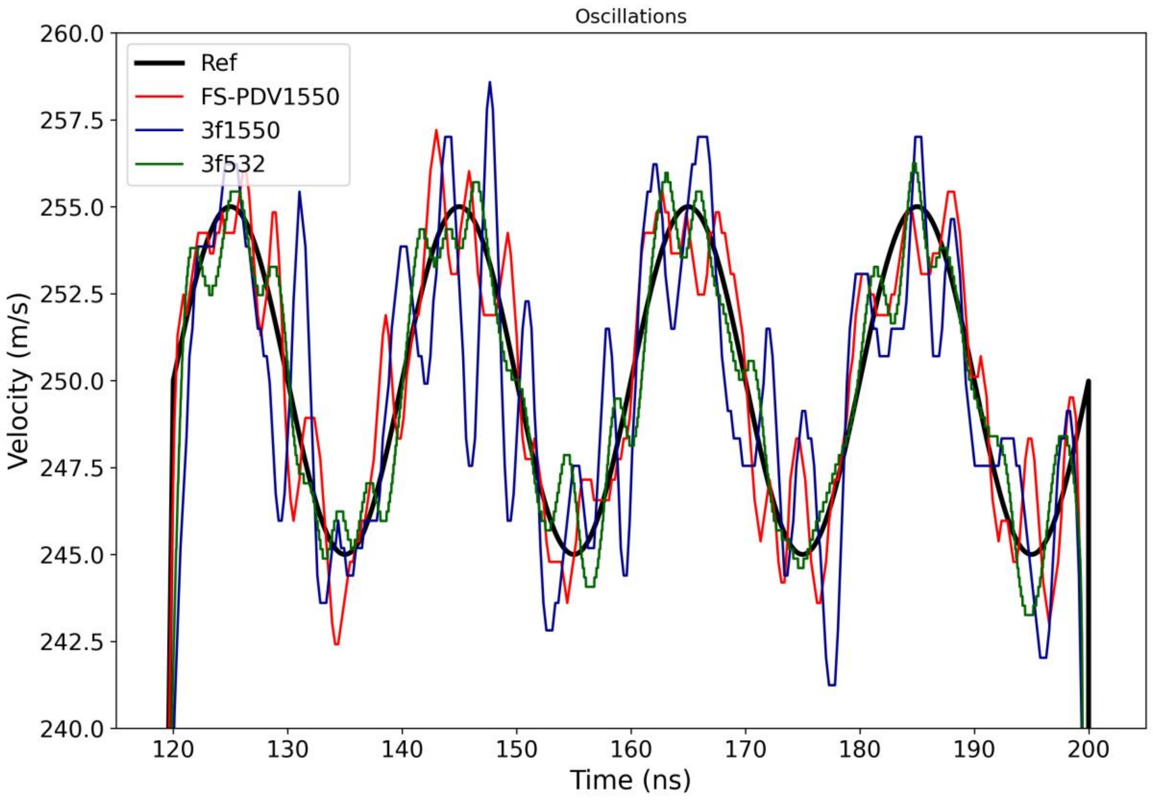
~1.9 m/s higher than FS-PDV



- Smooth and close to the peak and oscillations
- Rather close to the steps except at low velocities

Zooms on the peaks and oscillations





The Triature phase analysis are noisy but closer to the peak

3ν 532 nm is the closest by STFT

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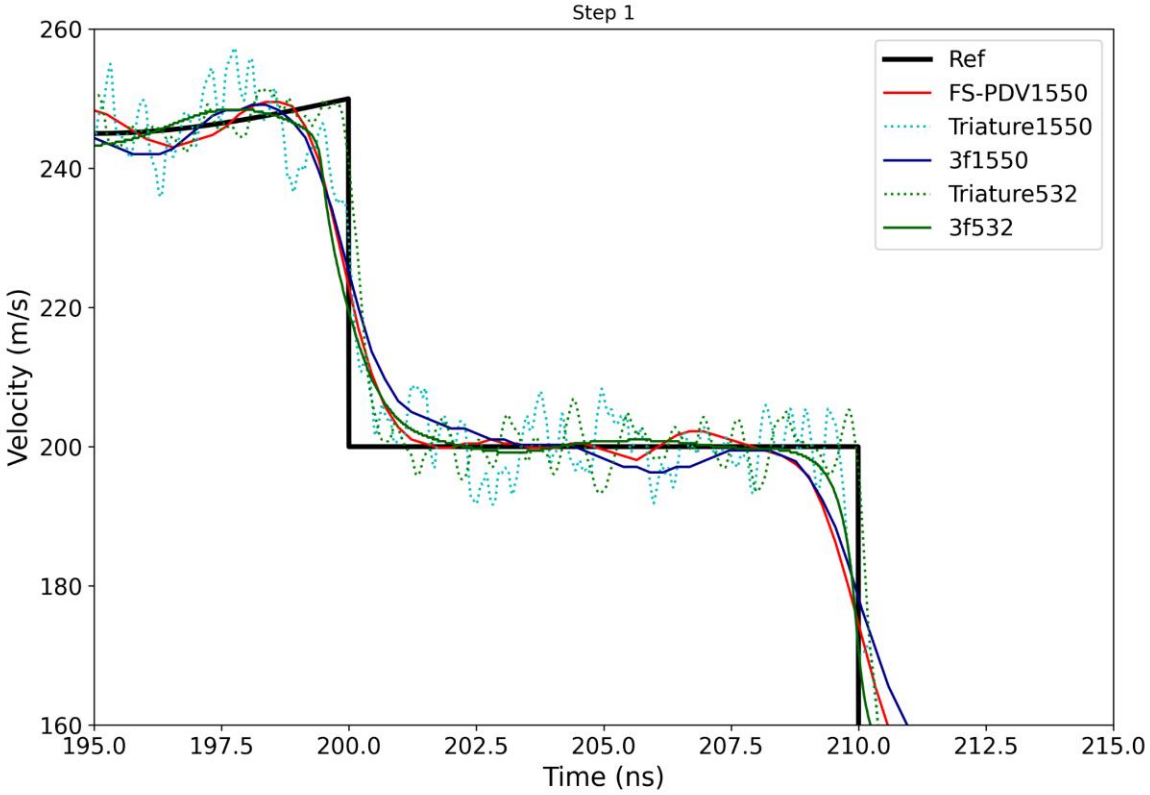
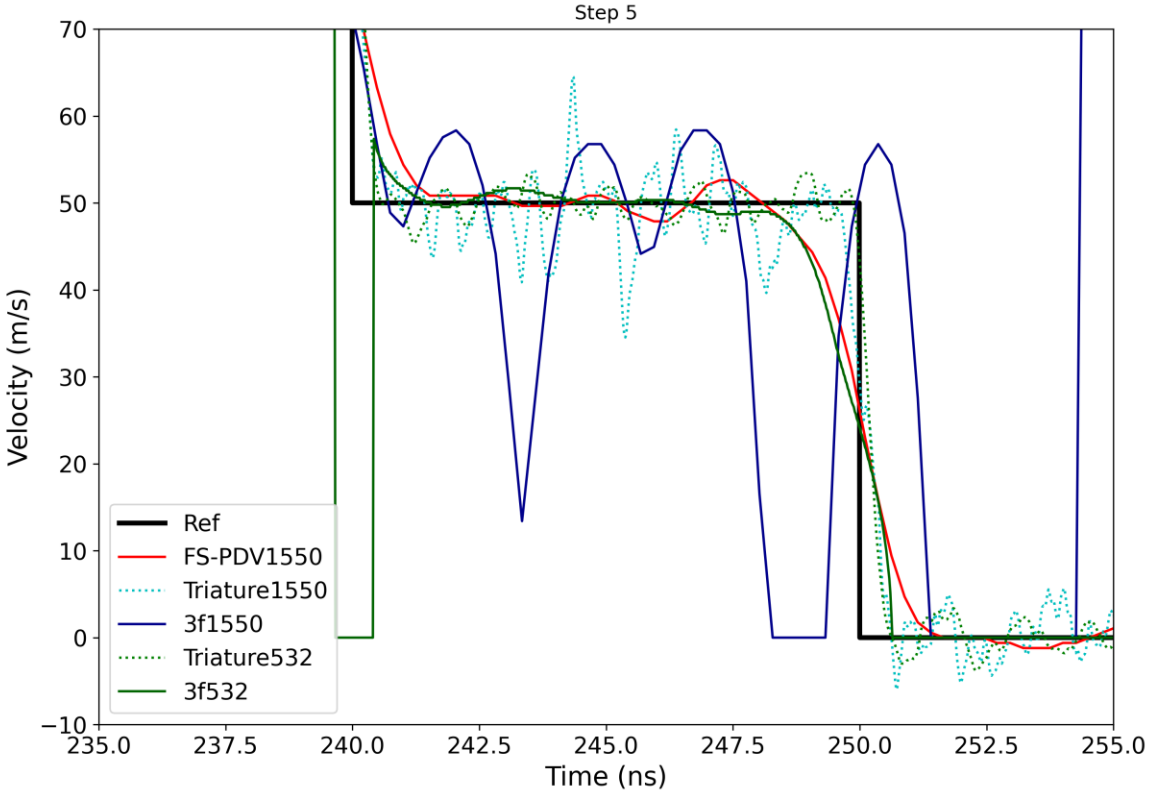
Zooms on the steps





The phase analysis are noisy, but closer to the edges

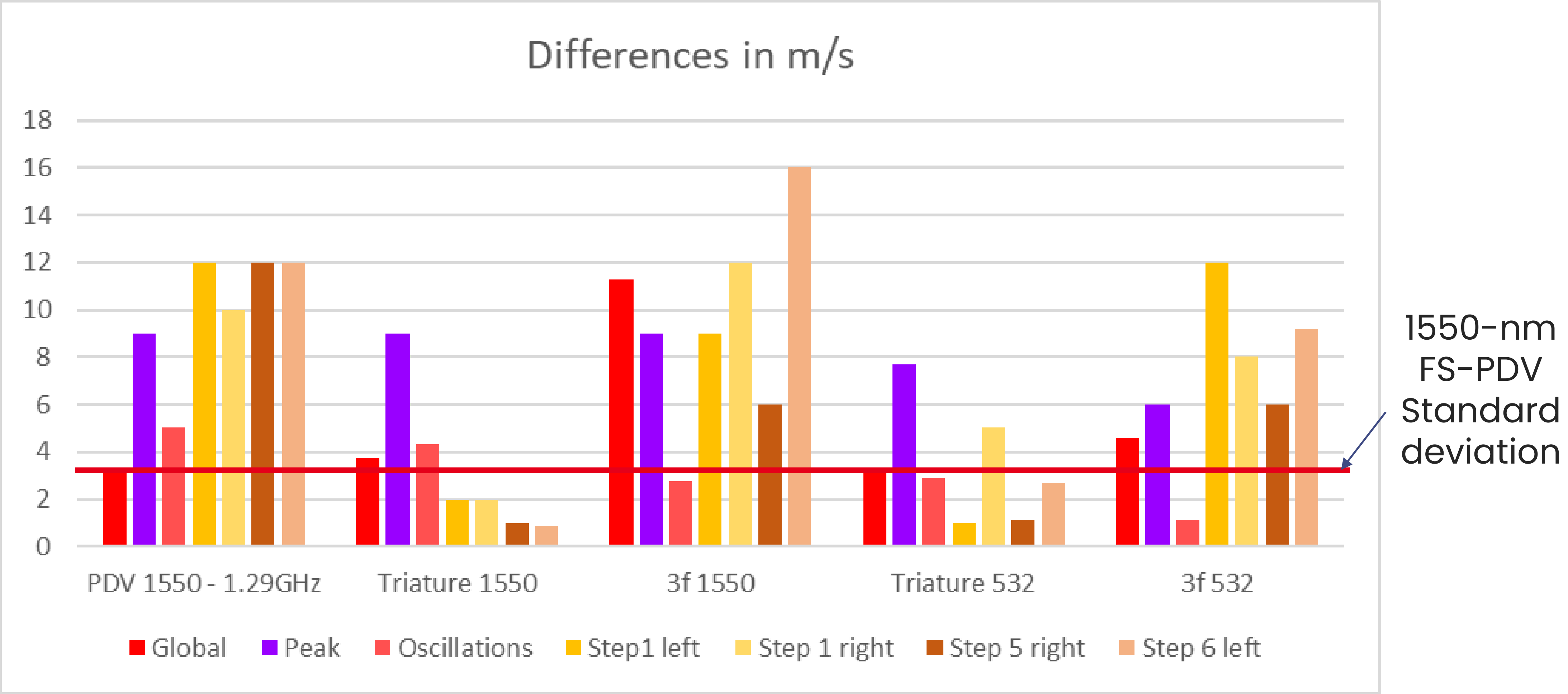
3ν 532 nm is a bit closer by STFT

The phase analysis are noisy, but closer to the edges

For this low velocities (<70 m/s), by STFT, the FS-PDV is the closest

Differences

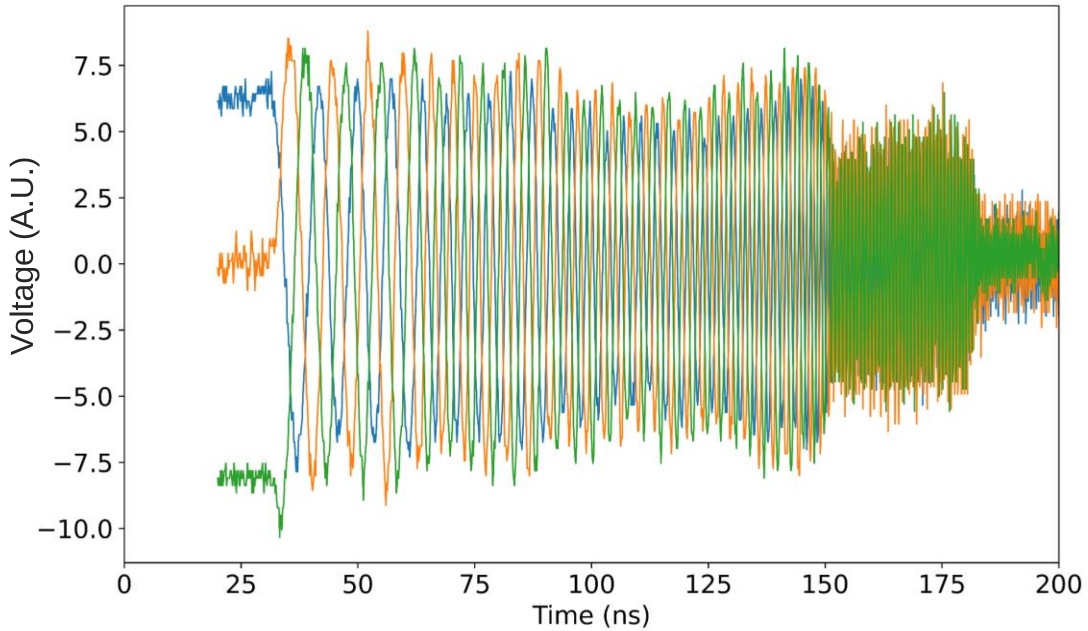
By systems, velocity profile zones and signal processing



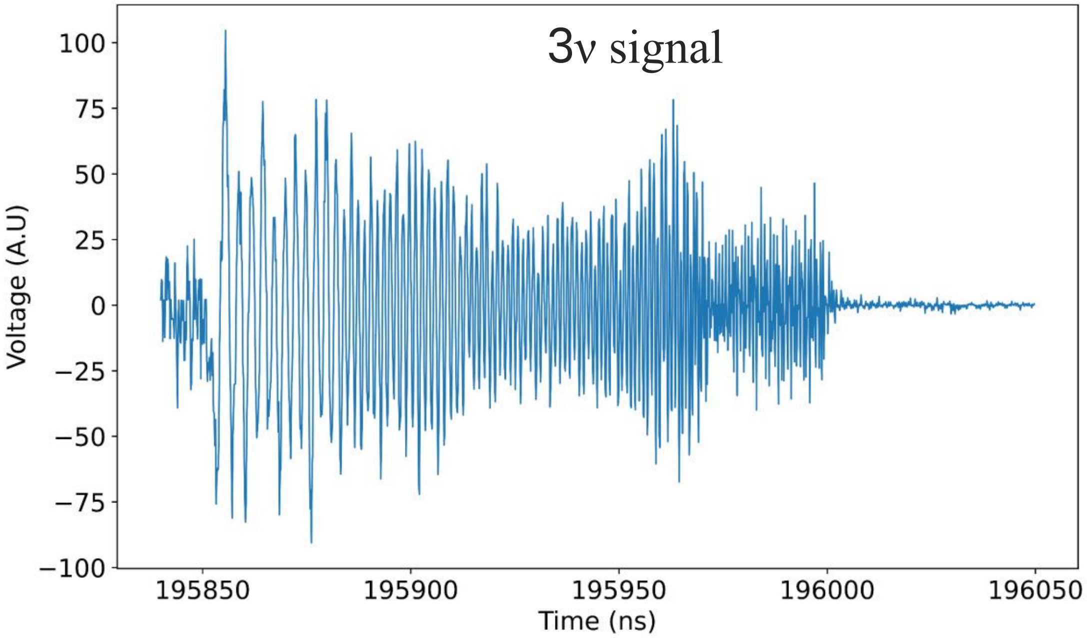
What about "3ν" applied to real data ?

Plate-impact experiment @ 750 m/s

Behind a 50 µm thick gold disk
532-nm triature signals



$$\lambda_{eff.@532} = 177.3\ nm$$

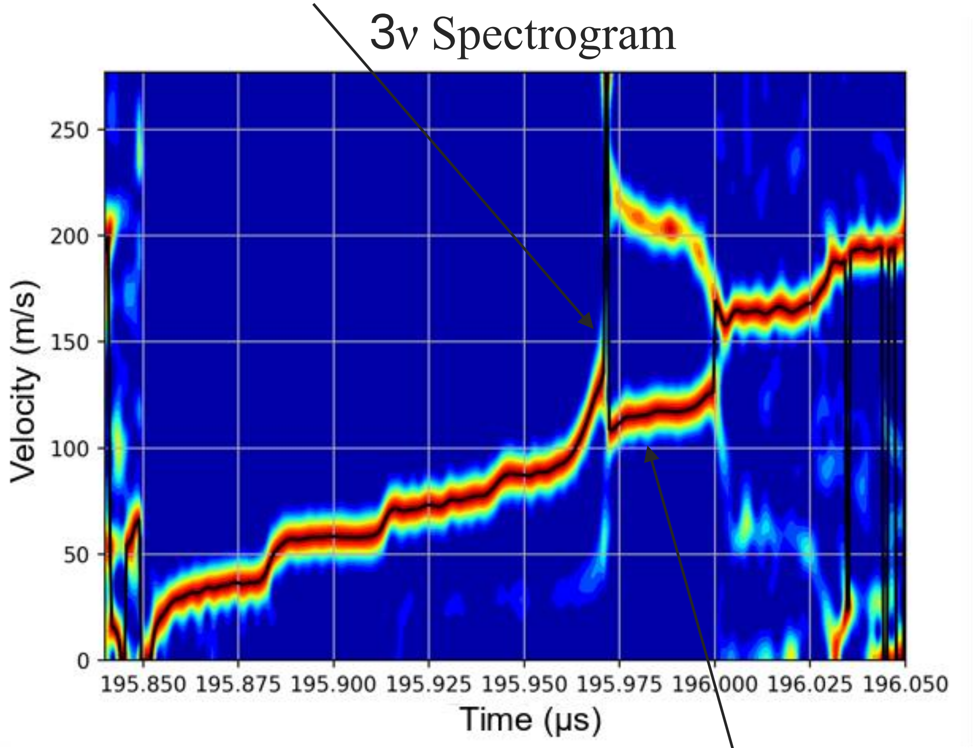


The amplitudes vary a lot due to the 3 multiplications but it doesn't degrade the data. (when zooming, the signal remains sharp)

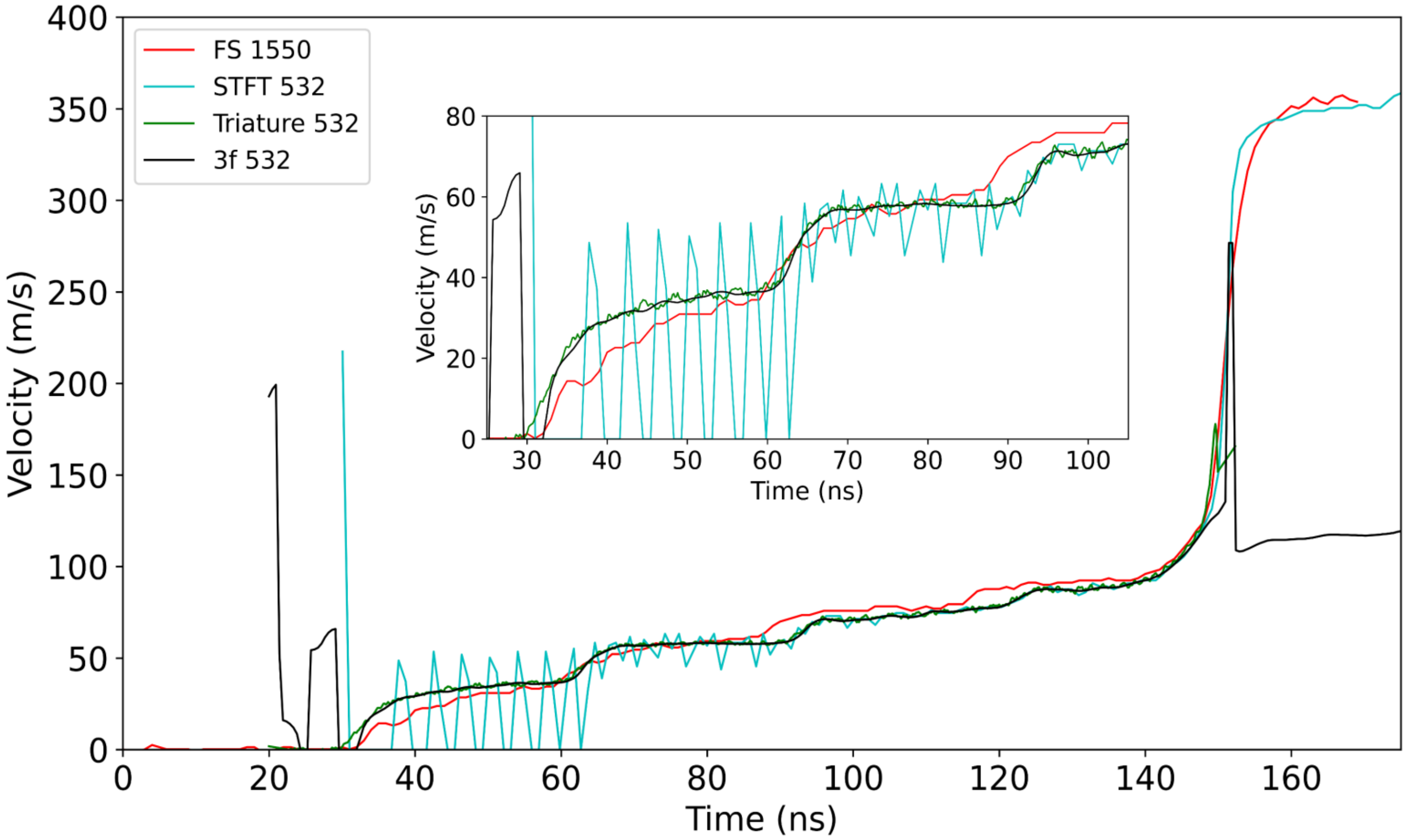
=> Need to normalize the spectrogram

Plate-impact experiment @ 750 m/s

Insufficient sampling



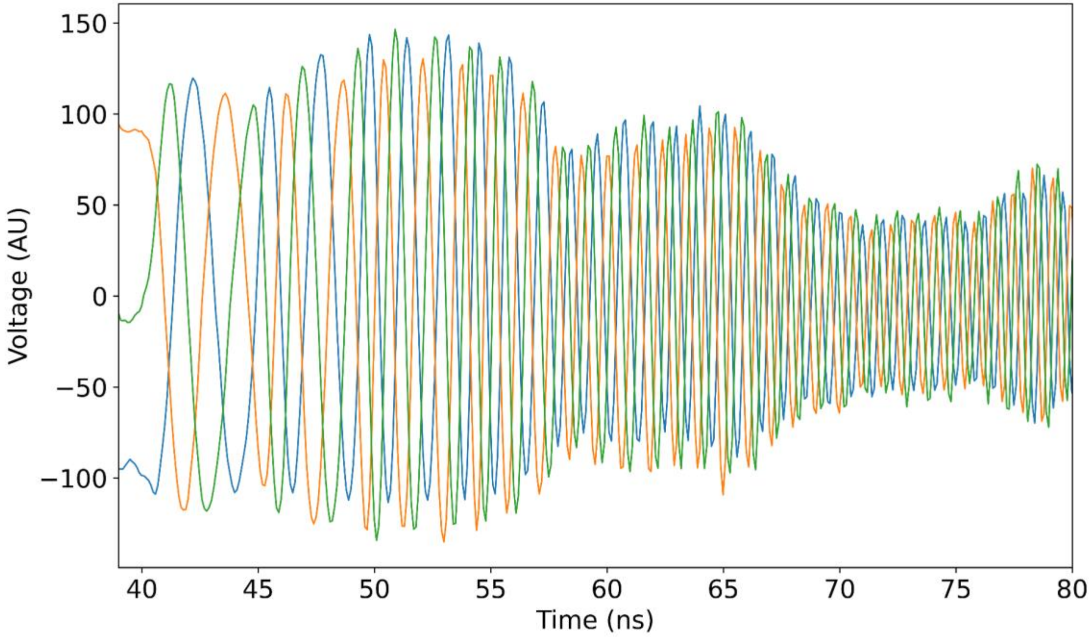
Harmonic 1ν



- Smoother than the triature phase analysis
- Sharper than the 1550 nm FS-PDV

Laser-driven shock experiment

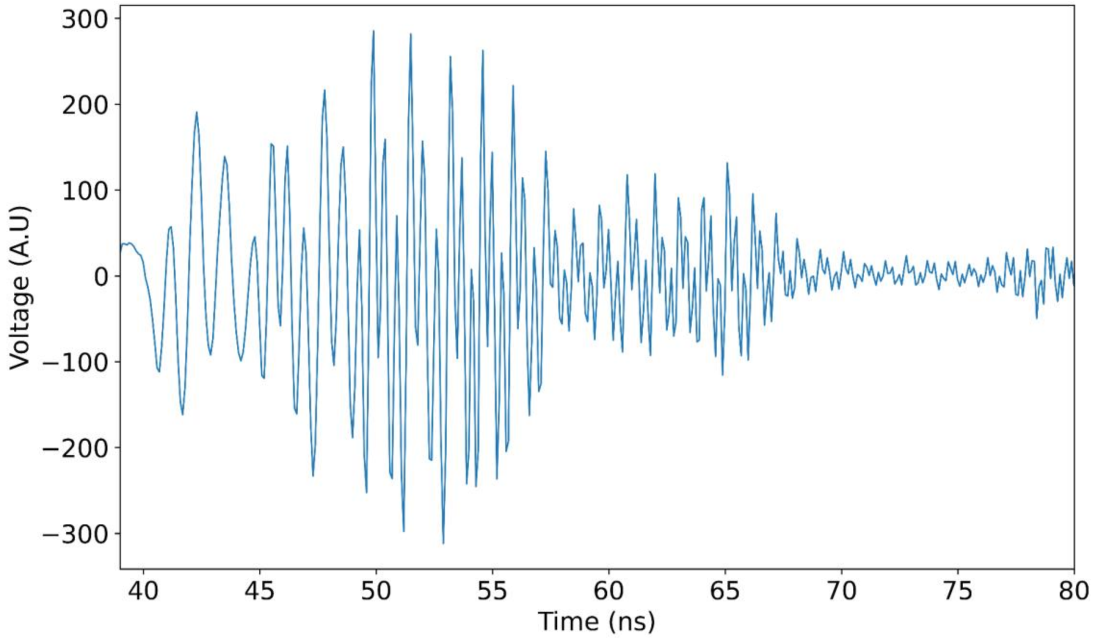
532-nm triature signals



The 3 signals are not perfectly normalized and centered around zeros

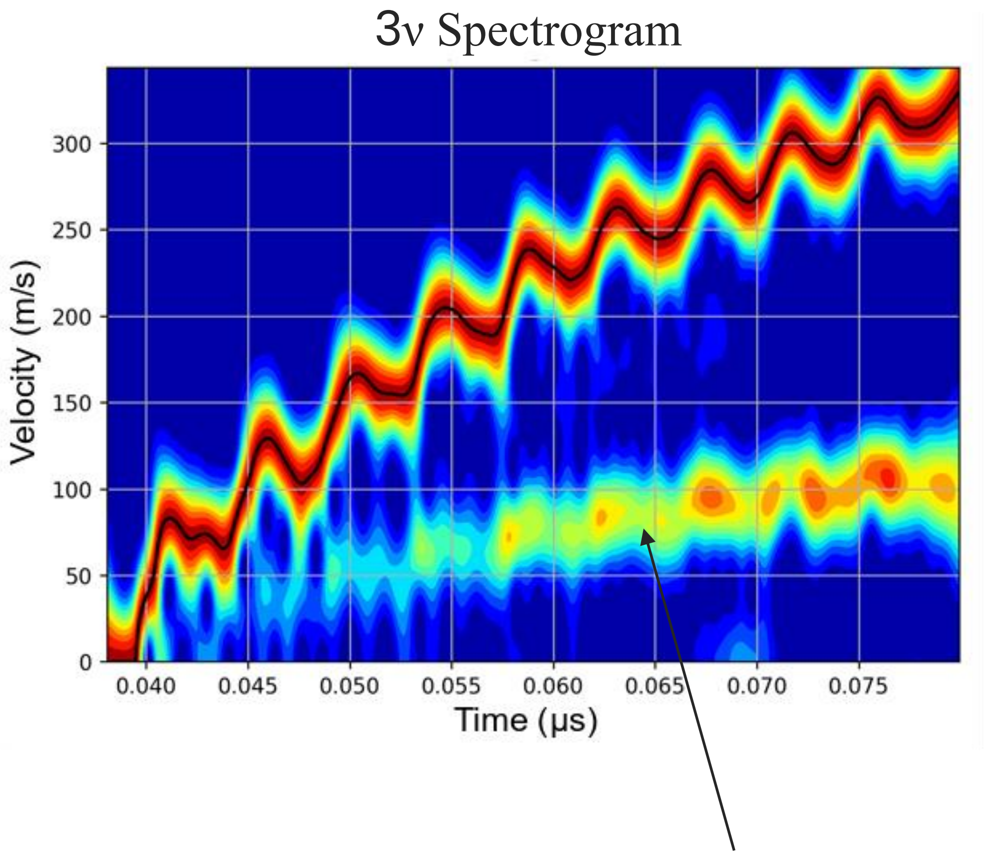
$\lambda_{eff.@532} = 177.3\ nm$

3ν signal

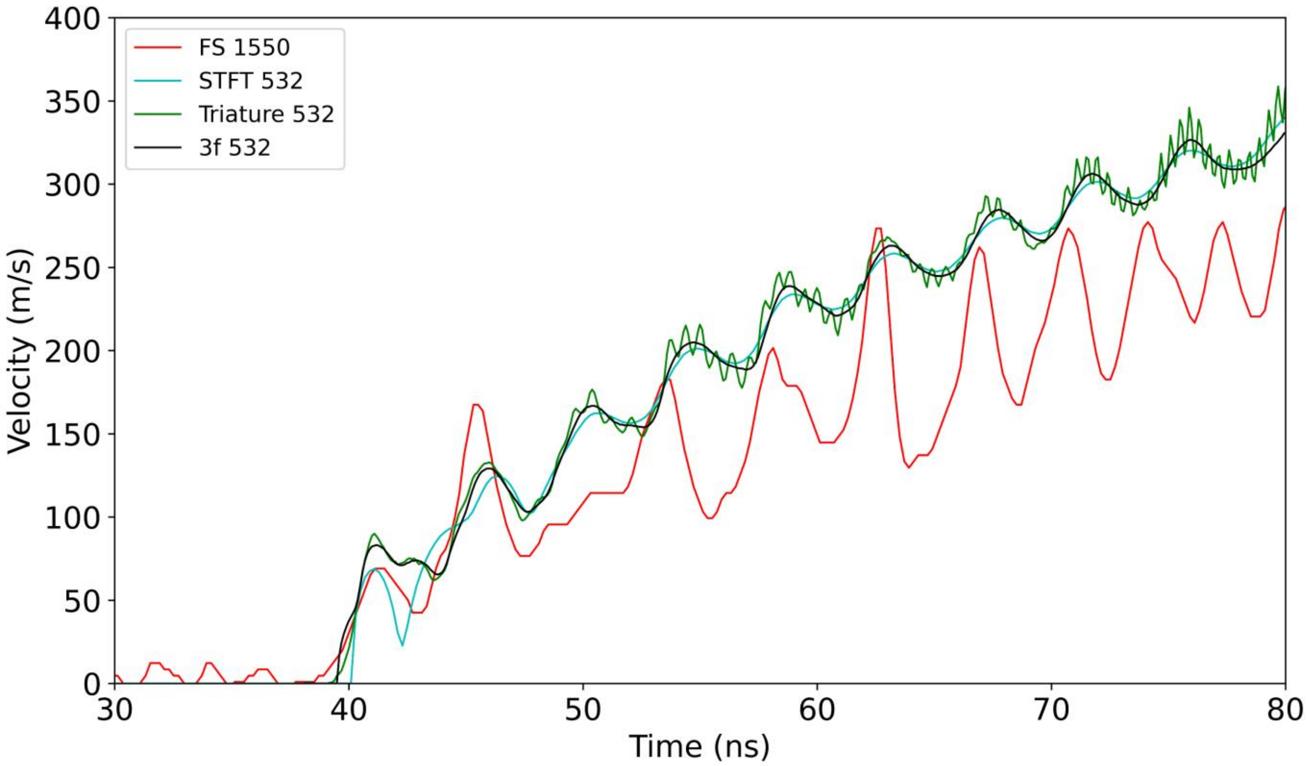


There are variations that will create 1ν harmonics

Choc laser @ 532 nm



Harmonic 1ν



- Smoother than the triature phase analysis
- Sharper than the 1550 nm FS-PDV

Conclusion

- On average, 1550 nm FS-PDV and 532 nm *3v* PDV are very close
- The peak and small oscillations are better measured by the 532 nm *3v* PDV
- *3v* spectrogram gives a less noisy velocity profile than triature signal processing
- Velocity steps are better measured with a triature signal processing (1550 nm or 532 nm)
- The 532 nm Triature PDV with phase analysis or *3v* spectrogram seems to be the most versatile system for this type of velocity profile (according to our simulations)
- The pretreatment to get the 3 signals well centered around zero and normalized is crucial to avoid/limit harmonics in the spectrogram
- Warning : the sampling rate should be chosen according to the virtual wavelength but not the bandwidth.

Outlook:

- Improve the pretreatment automatically
- Explore the limits with more than one velocity and with ejecta particles

Thank you for your attention