Addressing Practical Challenges in Acoustic Sensing To Enable Fast Motion Tracking

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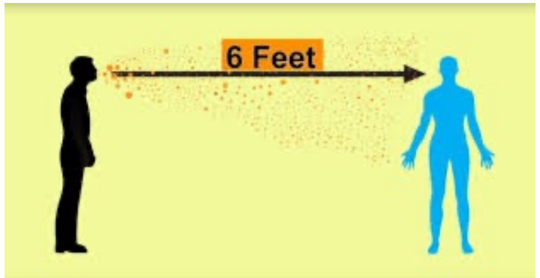
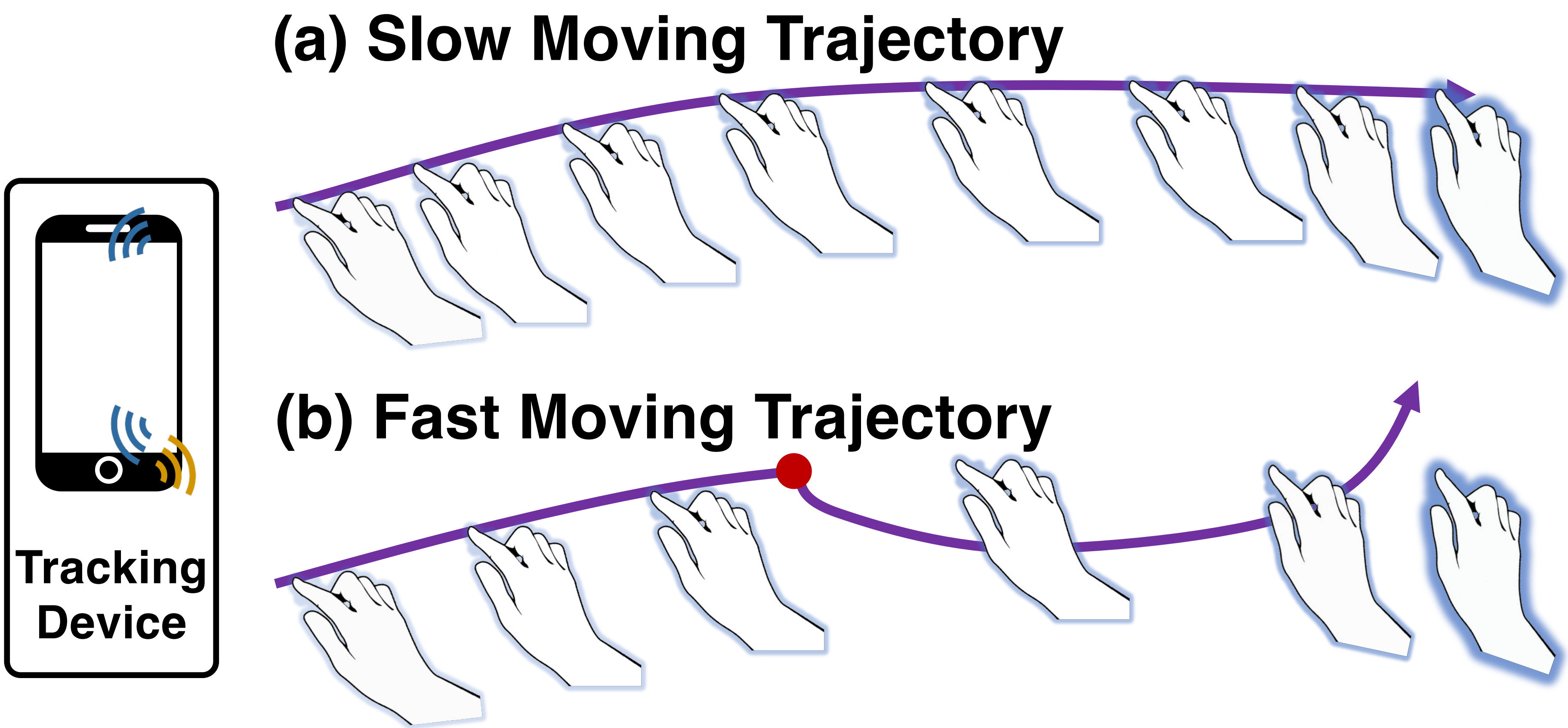
Acoustic sensing are becoming pervasive and popular



Acoustic Tacking

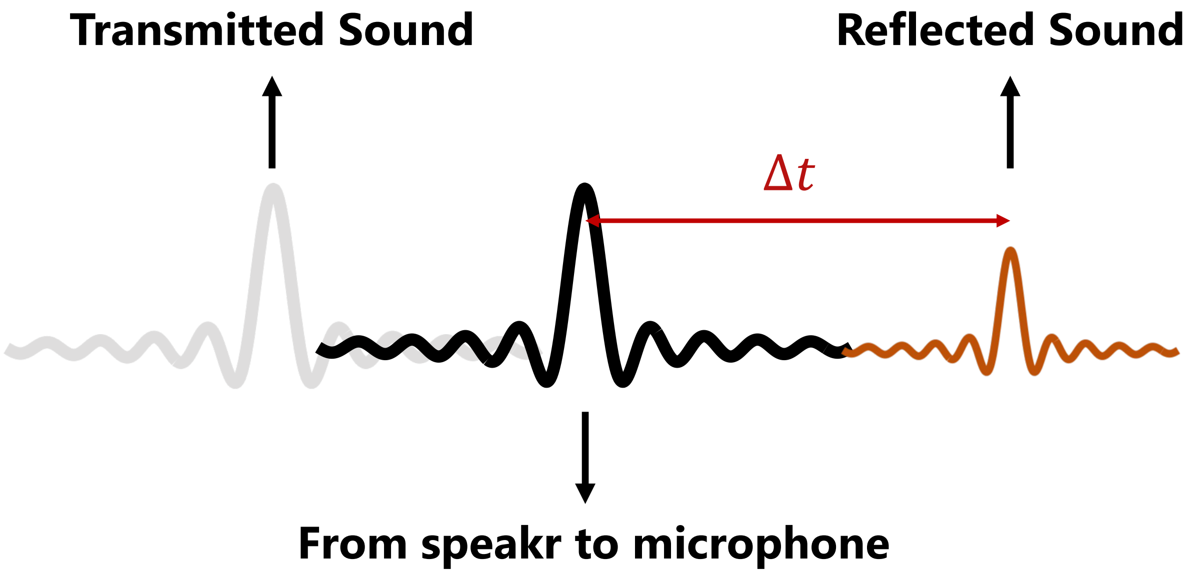
Tracking the motion of a target with the reflected sound

Fast Motion Problem



Fast motion causes the failure

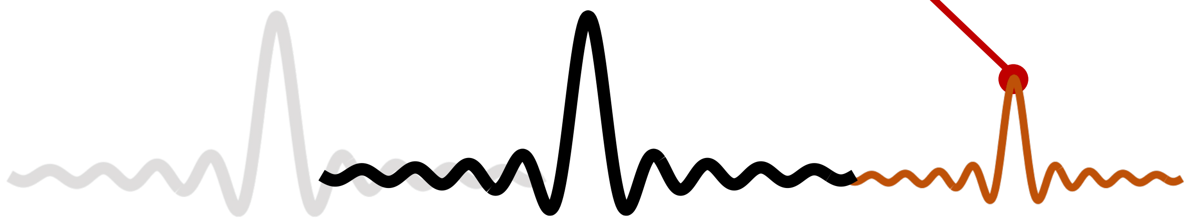
Coarse-grained tracking with time delay



The resolution is limited due to bandwidth and sampling rate

Fine-grained tracking with phase

$$p = Ae^{-j\frac{4\pi f_c d}{c}}$$



1mm displacement will cause 0.73rad phase change!

Phase-based tracking provides much higher accuracy

Challenges

1. Under-Sampling of phase caused by fast motion

2. Low SNR will exacerbate the fast motion tracking

Challenges

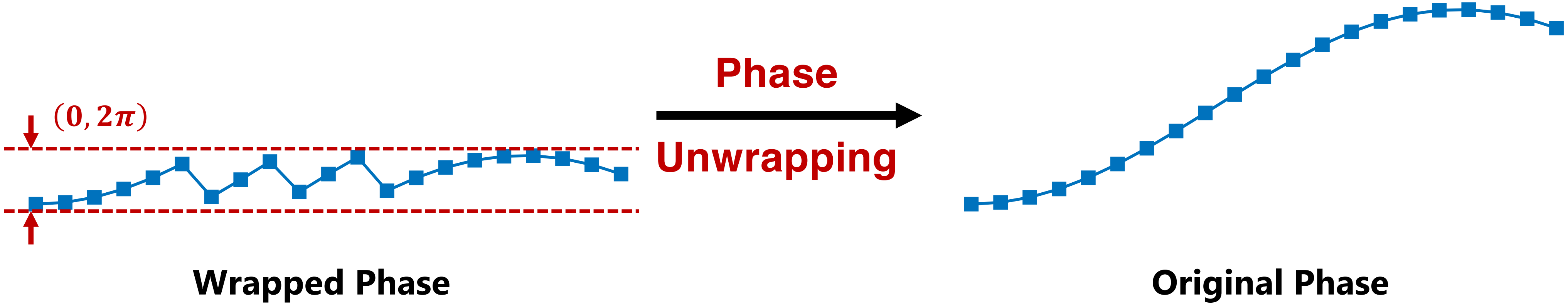
1. Under-Sampling of phase caused by fast motion

2. Low SNR will exacerbate the fast motion tracking

However, phased-based tracking encounters an issue...

$$\angle p = \frac{4\pi f_c d}{c} \gg 2\pi$$

The measured phase is wrapped in $(0, 2\pi)$



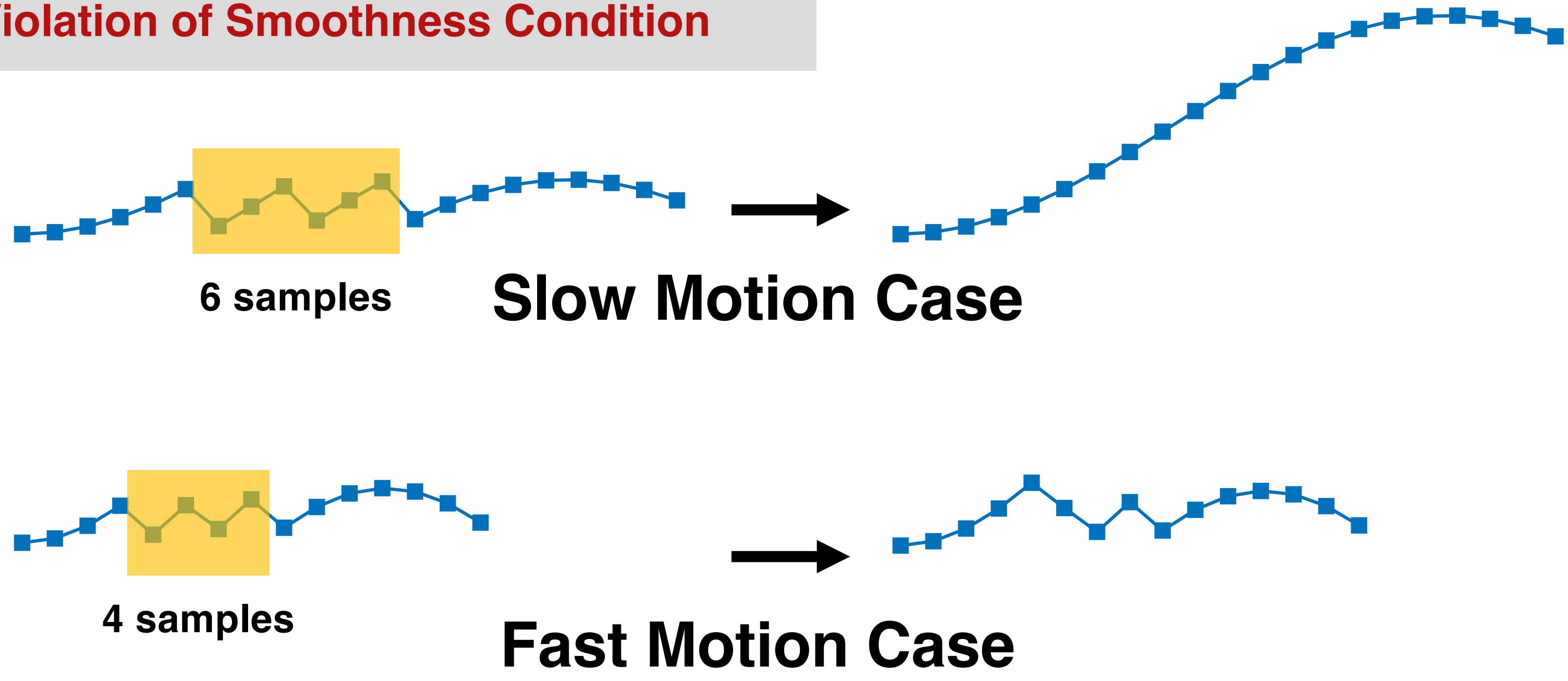
But, phase unwrapping limits the speed of motion…

Smoothness Condition:

$$|\Delta\phi| \leq \pi$$

Major Challenge – Fast Motion Tracking

Insufficient phase samples cause
The Violation of Smoothness Condition



Fast motion causes the violation of smoothness condition

Theoretical Analysis

Speed Limitation – From smoothness condition

$$\Delta\phi = \frac{4\pi f_c T}{c} \frac{|d[n] - d[n-1]|}{T} \leq \pi$$

Sample one phase measurement at each period

$$|v[n]| \leq \frac{c}{4 f_c T}$$

$$|v| \leq 0.43\ m/s$$

V.S.

$$|v_{Human\ Arms}| \leq 2.7\ m/s$$

For a typical acoustic system

- c: sound speed – 343m/s
- f_c : carrier frequency – 20kHz
- T : period – 0.01s

Our Intuition

Motions can be fully described by many properties

- **Distance**
- **Velocity**
- **Acceleration**
- **…**

Can we track fast motions with other properties, instead of distance?

Our Core Solution

Compute Phase Derivative:

$$p'[t] = \frac{p[t]}{p[t-1]}$$

$$= |p'[t]| e^{-j\frac{2\pi f_c T}{c} v(t)}$$

Phase is relative to velocity!

Use Phase Derivative to Measure Velocity

Our Core Solution

Unwrap Phase Derivative

$$\Delta\phi = \frac{4\pi f_c T^2}{c}\frac{|v[n]-v[n-1]|}{T} \le \pi$$

$$|a[n]| \le \frac{c}{4 f_c T^2}$$

$$|a| \le 43\ m/s^2$$ **V.S.** $$|a_{Human\ Arms}| \le 30\ m/s^2$$

For a typical acoustic system

c: sound speed – 343m/s

f_c : carrier frequency – 20kHz

T : period – 0.01s

Challenges

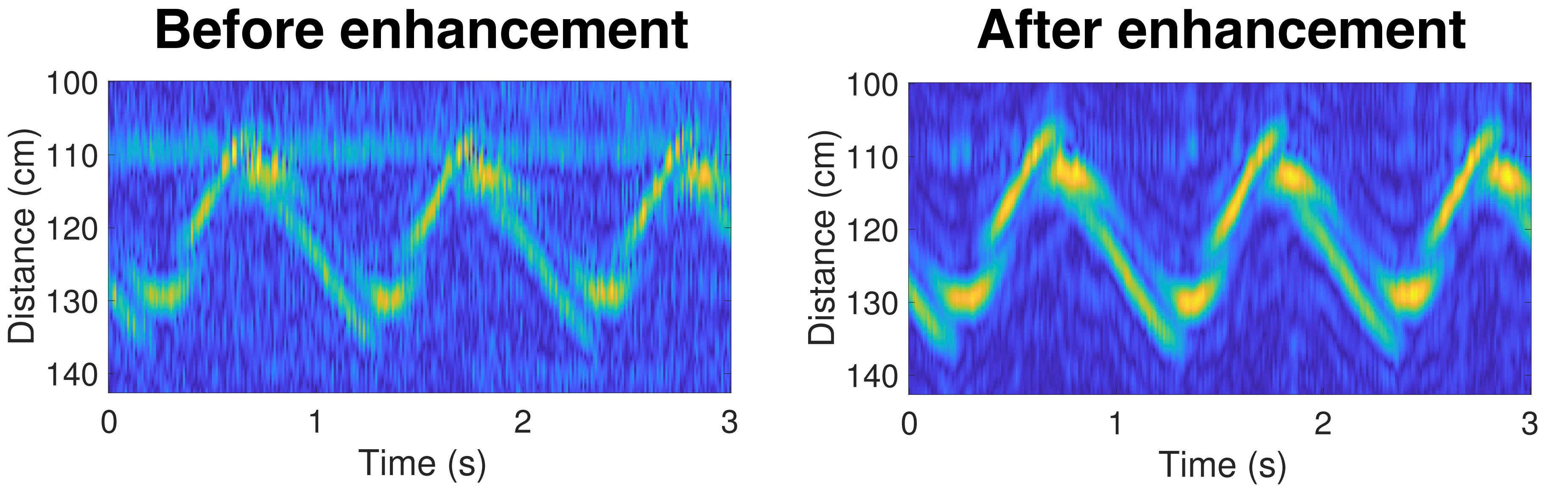
1. Under-Sampling of phase caused by fast motion ✓

2. Low SNR will exacerbate the fast motion tracking

   Many factors will decrease SNR

   - Signal attenuation
   - Doppler effect
   - Hardware imperfection

Enhance Signal Strength

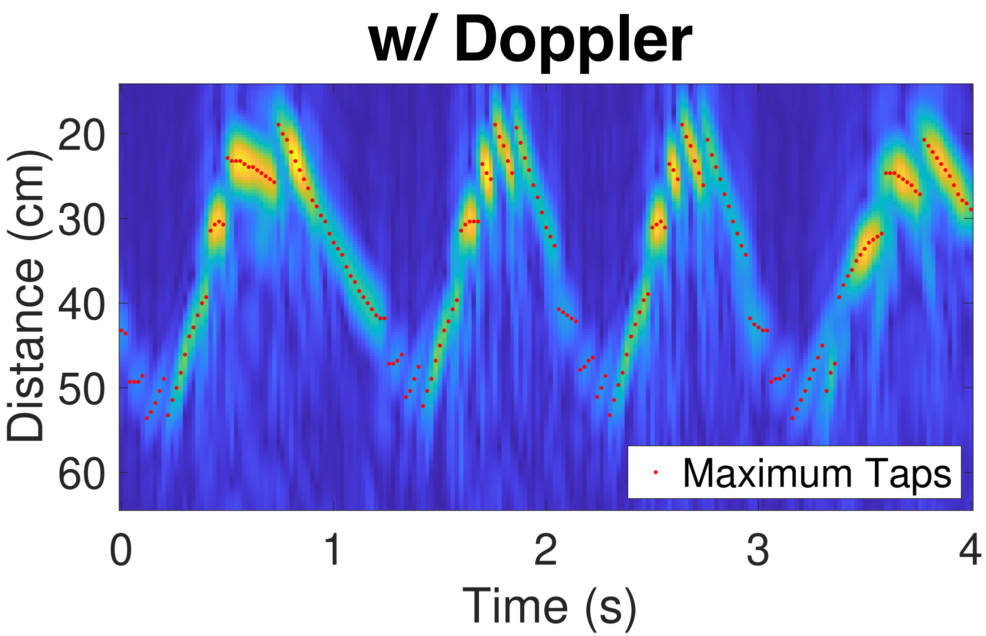


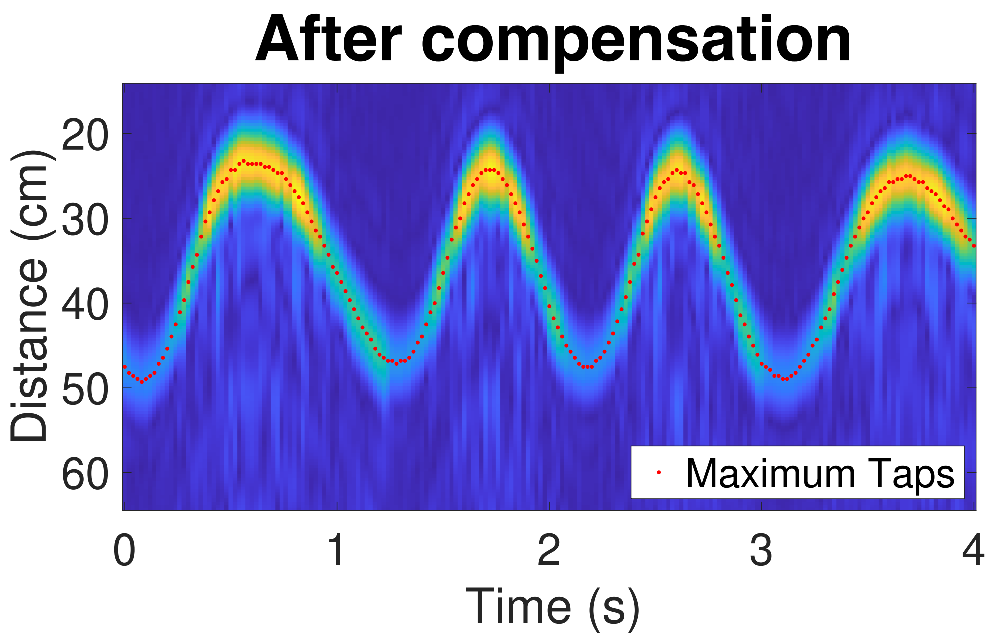
SNR enhancement:

1. **Model the channel transfer function**
2. **Apply maximum entropy principle**

Enhance SNR when moving fast in a longer range

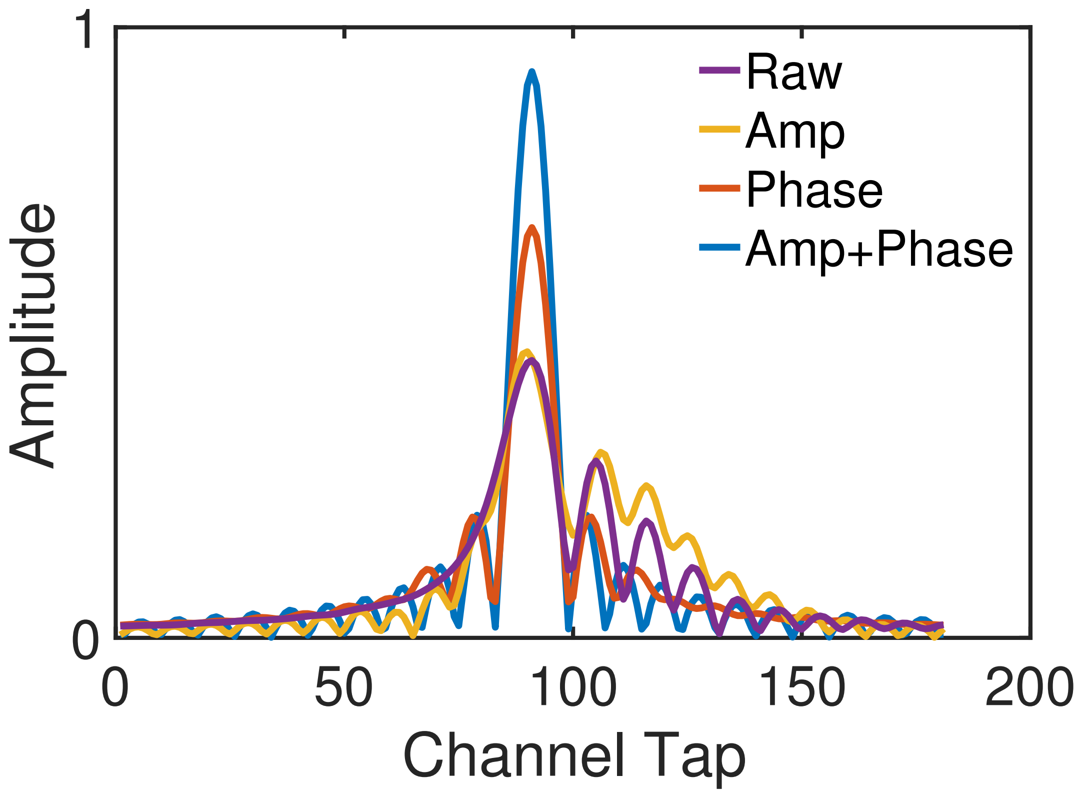
Compensate Doppler Effect





Fast motion distorts pulses and therefore decreases SNR

Hardware Imperfection



Hardware frequency response will decrease SNR

Final Algorithm

Compensate frequency response

↓

SNR enhancement

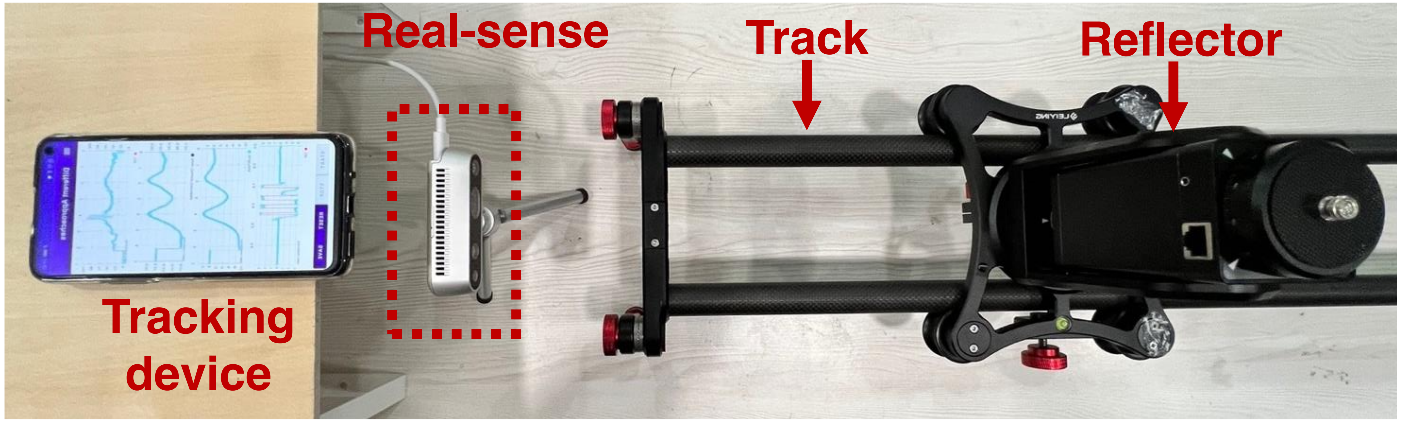
↓

Doppler compensation

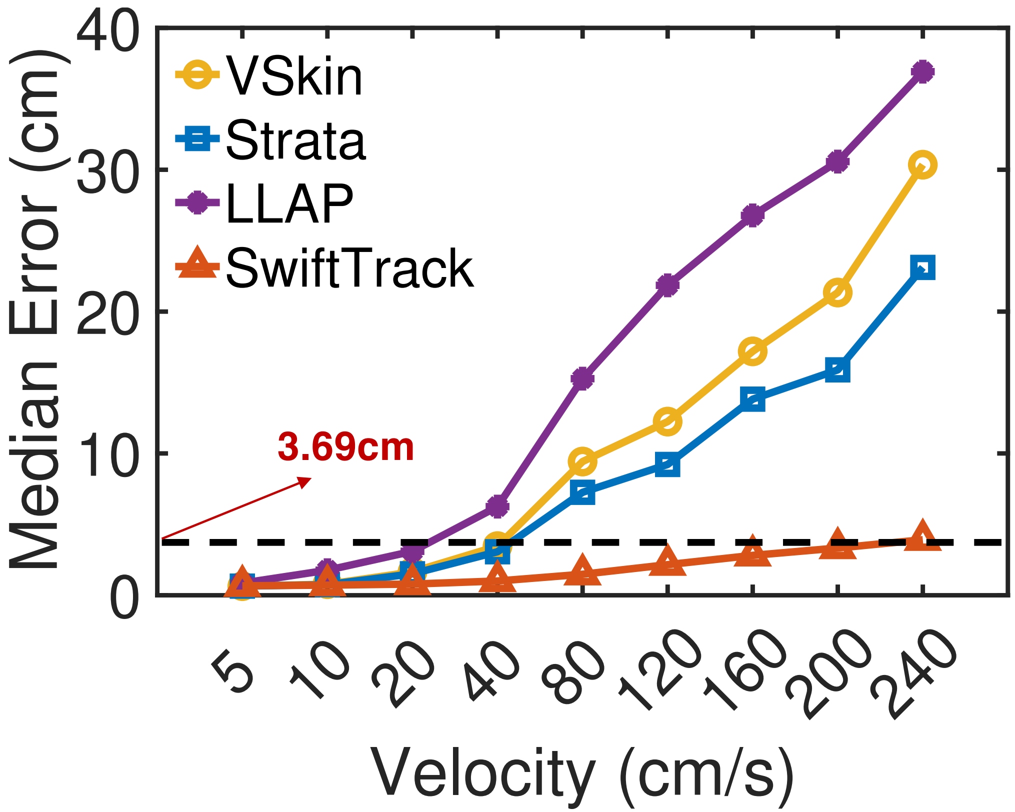
↓

Phase derivative

Experiment Setup

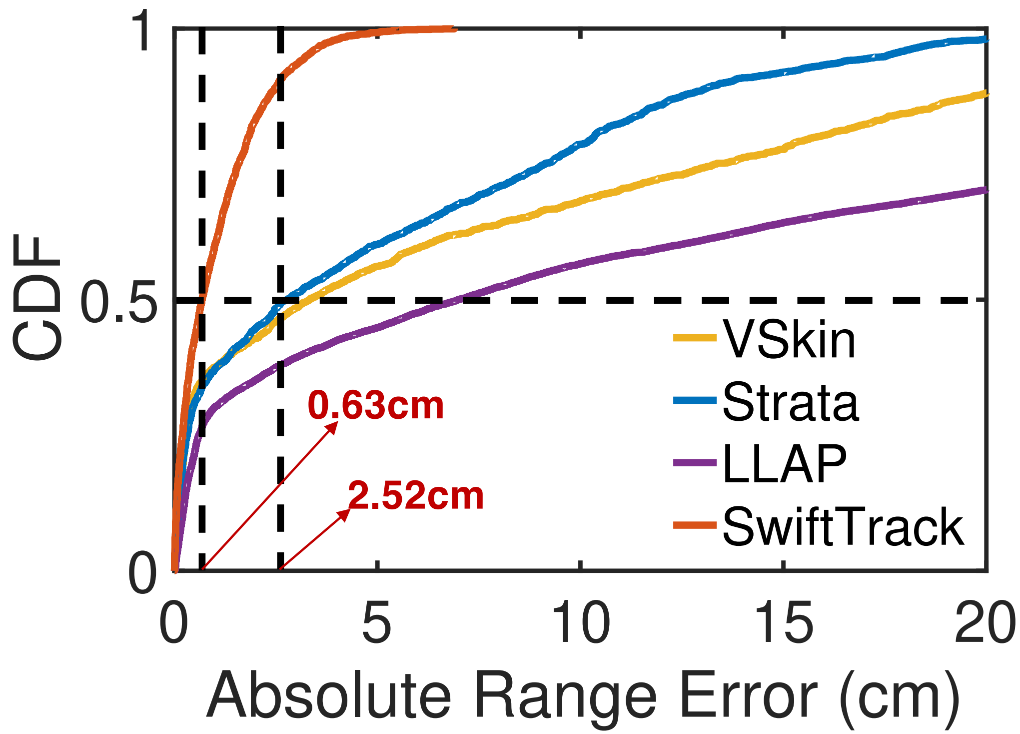


Evaluation: Vary Velocity



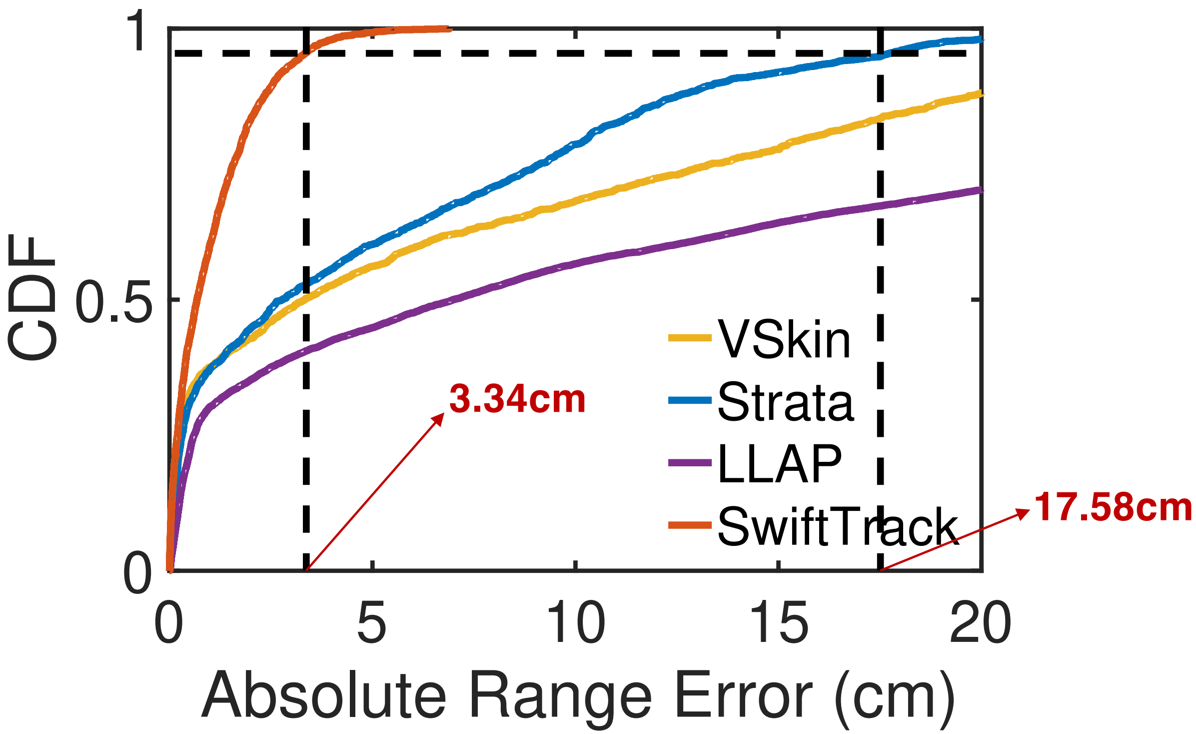
3.69cm tracking error at 240cm/s moving speed

Evaluation: Overall accuracy



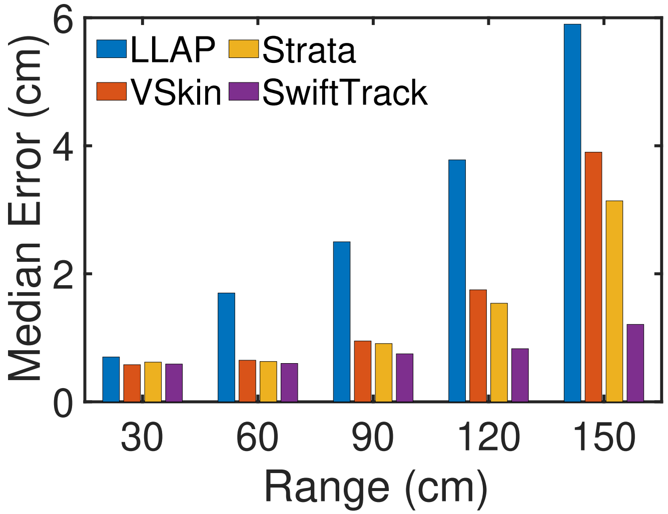
Median error is reduced from 2.52cm to 0.63cm

Evaluation: Overall accuracy



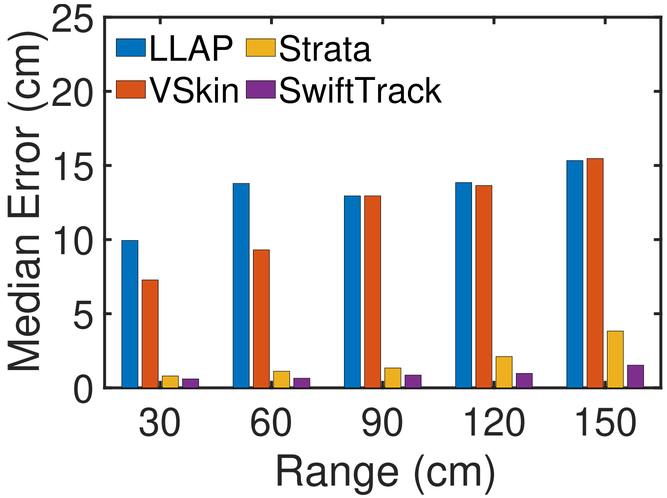
95th percentile error is reduced from 17.58cm to 3.34cm

Evaluation: Vary Range



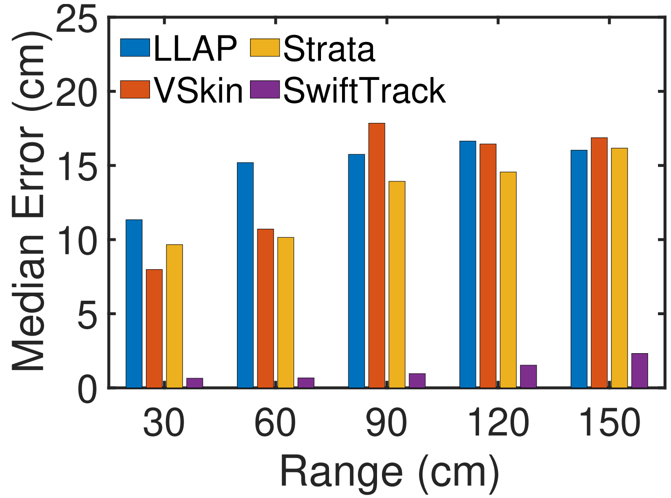
Low speed

$\leq 20cm/s$



Medium speed

$20cm/s$ - $80cm/s$

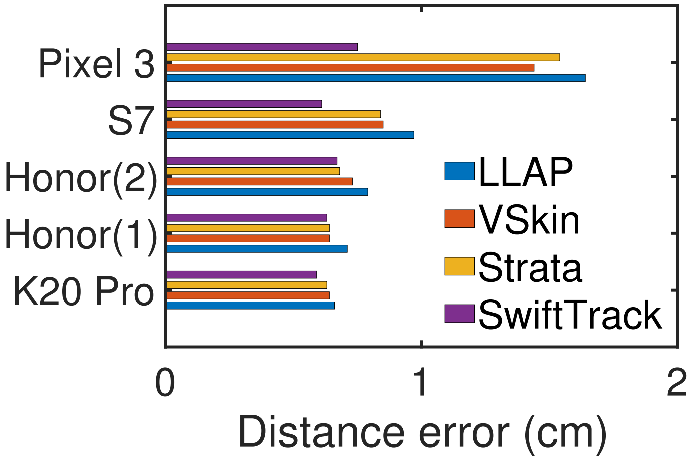


High speed

$\geq 80cm/s$

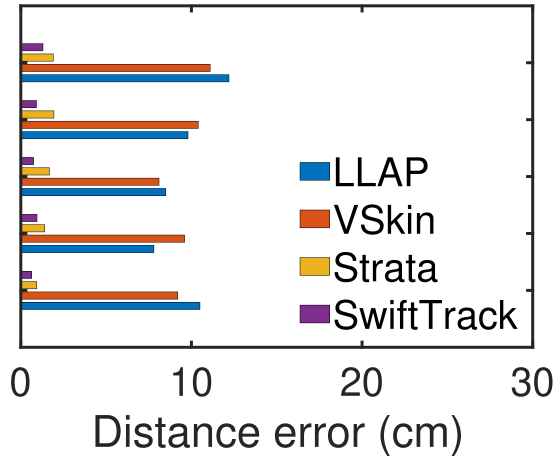
2.37cm tracking error at 150cm with high moving speed

Evaluation: Vary Devices



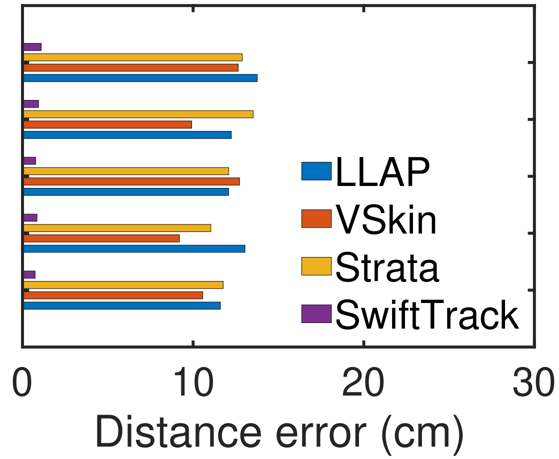
Low speed

$\leq 20cm/s$



Medium speed

$20cm/s$ - $80cm/s$



High speed

$\geq 80cm/s$

More stable performance on all devices

Conclusion

Our paper enables fast motion tracking with acoustic signals:

- ✓ **Show the root cause of fast motion problem in acoustic tracking**
- ✓ **Phase derivative based solution to deal with under-sampling**
- ✓ **Address other challenges to enhance the performance of fast motion tracking, which can also be used for general tracking purpose.**

Thank you!

Presenter: Mei Wang

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Please email Yongzhao Zhang if you have any questions!
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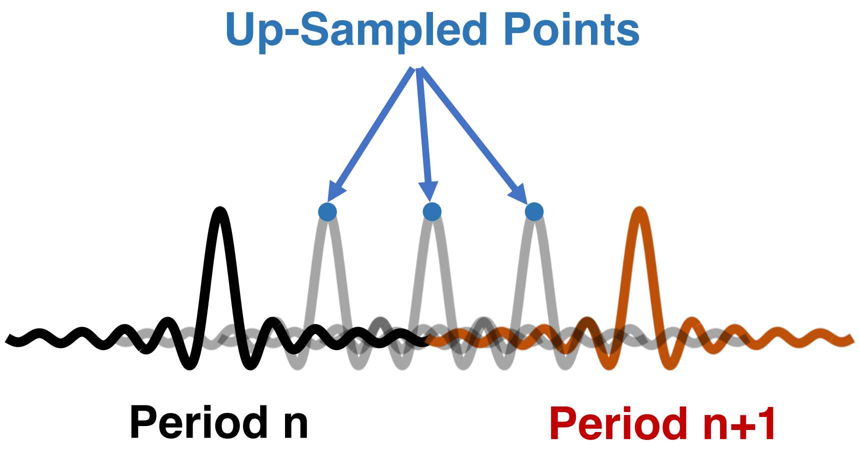
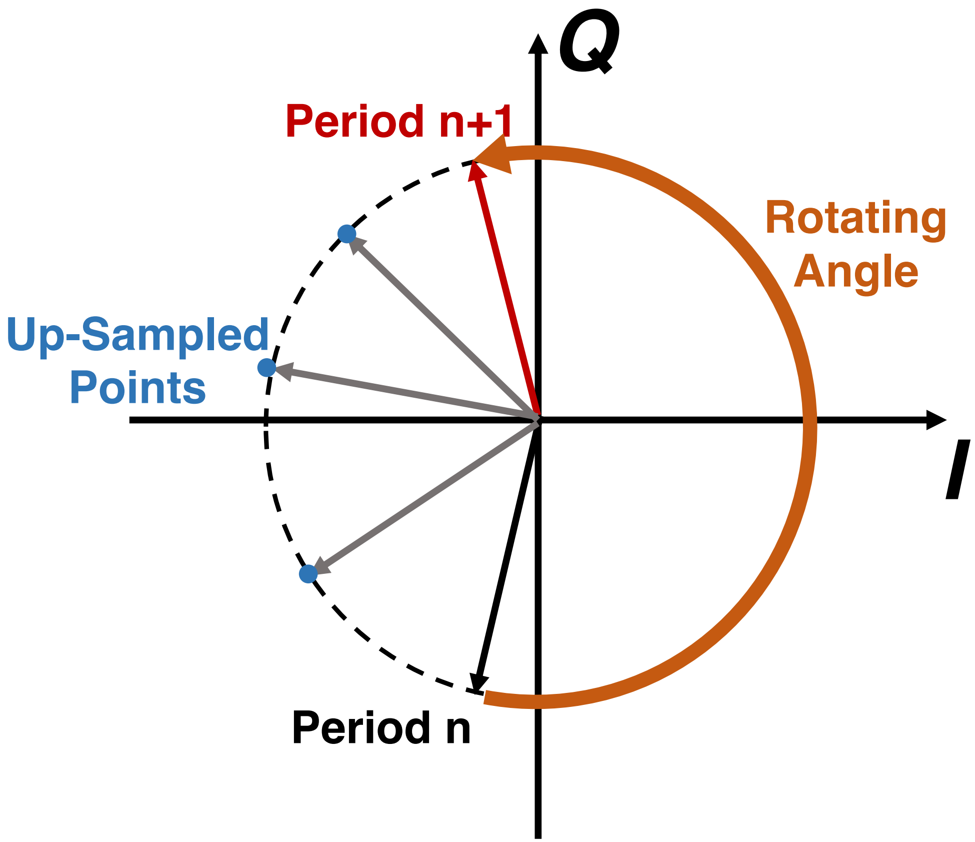




Up-sampling algorithms tend to sample points in the smaller rotating angle.

Fast motion will produce a rotating angle lager than π

$$h[n] = h[n-1]e^{j\phi}$$ **Channel transition model**

STEP 2 $$z[n] = (1-K) \times z[n-1]e^{j\hat{\phi}} + K \times \tilde{h}[n]$$

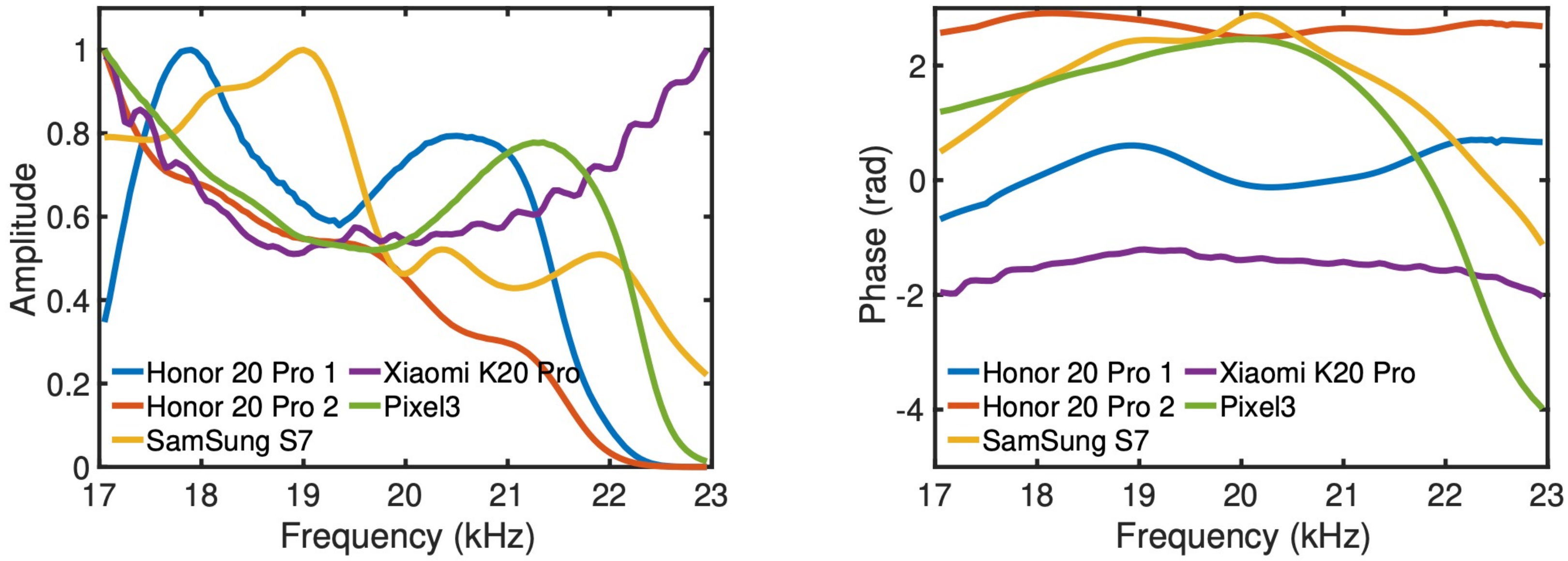
$\tilde{h}$ **is measurement**

z **is smoothed channel**

STEP 1 $$\operatorname*{argmax}_{\phi} H(normalized(|\tilde{h}[n] - \hat{z}[n]| \cdot |\hat{z}[n]|))$$

$\hat{z}[n]$ **is the best estimation from** $\hat{z}[n-1]$

Step 1: find the best estimation from previous result.
Step 2: smooth measurement with estimation.

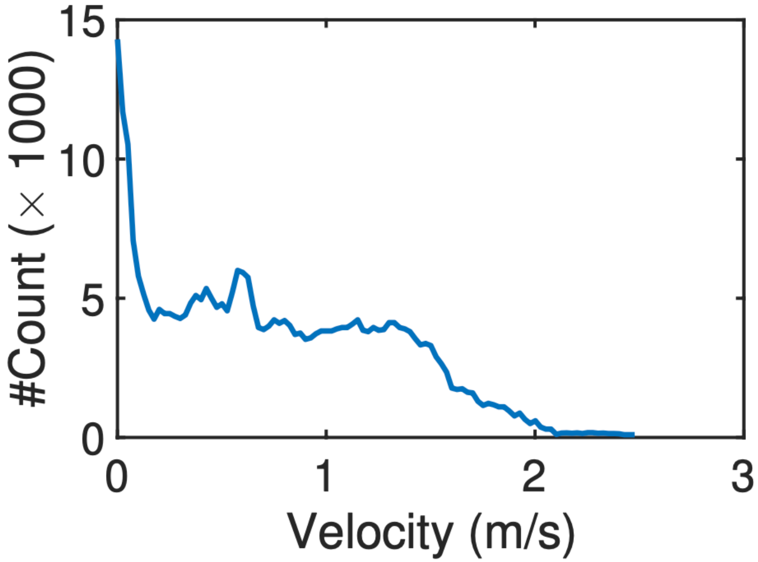


(a) Amplitude response.

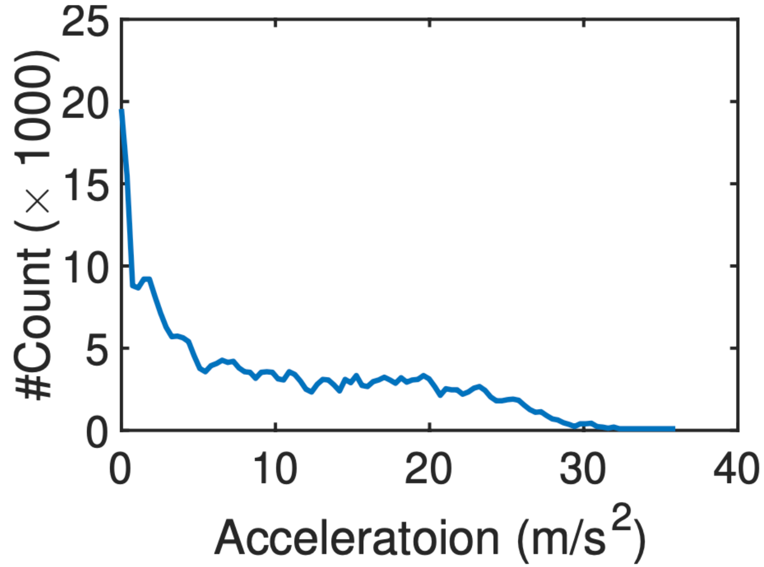
(b) Phase response.

Figure 4: Frequency response of 5 different devices.

Non-linear phase change will distort pulse shape.
Devices with near flat phase response have better performance

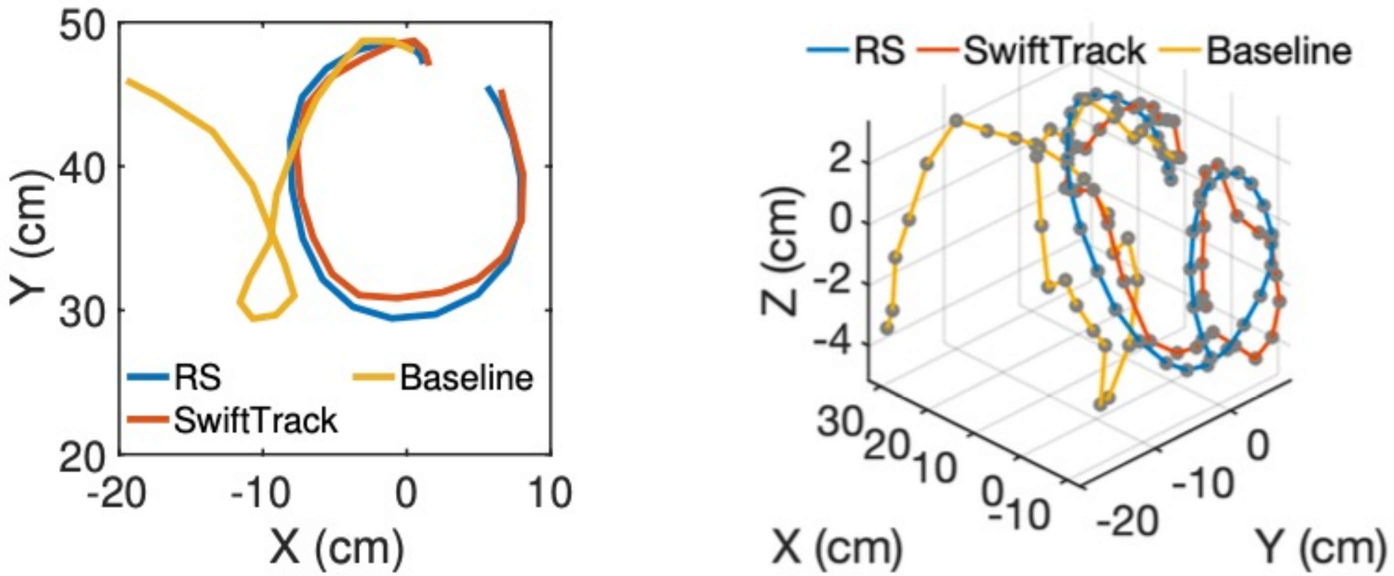


(a) Speed Distribution



(b) Acceleration Distribution

Figure 15: Statistics of collected data.



(a) 2D drawing sample

(b) 3D drawing sample

Figure 16: 2D and 3D drawing samples. "*RS*" represents the trajectories captured by Real-Sense as reference. "*SwiftTrack*" represents the proposed method and "*Baseline*" represents disabling the phase derivative, SNR enhancement, frequency response compensation, and Doppler compensation.