Range ambiguity cancellation for continuous-wave indirect ToF image sensors

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Outline

- **Introduction**

- **Motivation**

- **Proposed Scheme**

- **Measurement Results**

- **Conclusion**

Introduction

■ **Short-range 3D applications**

- Face detection

- Hand gesture recognition

■ **Critical requirements with indirect time-of-flight (ToF) sensors**

- Minimal motion artifacts

- High frame rate

- Depth precision and accuracy
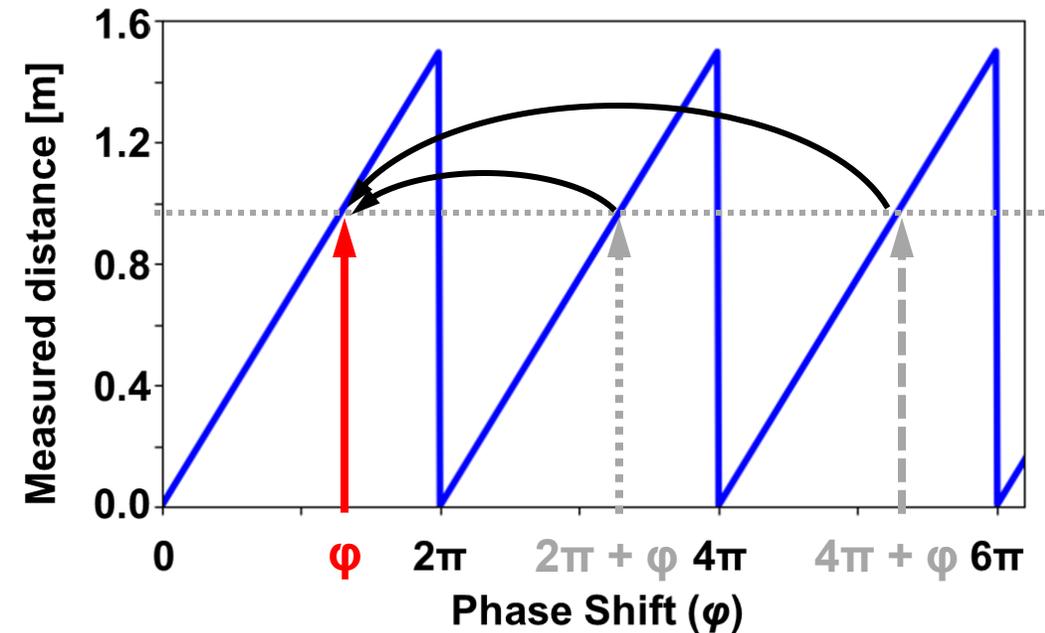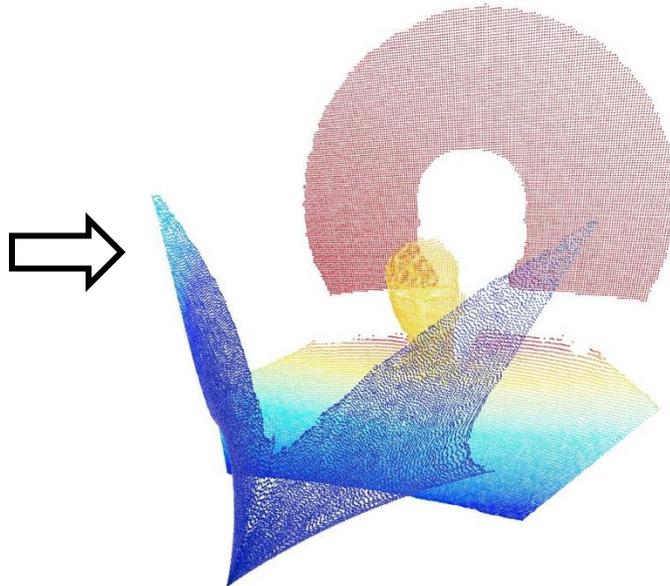
- **No phase wrapping errors (abnormal operation)**

Introduction

■ **What is the phase wrapping error in the indirect ToF?**

Object

3D point cloud

Motivation

- ■ **Prior methods for addressing the phase wrapping error**

  - Dual-frequency modulation method [Payne, '09]
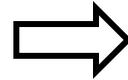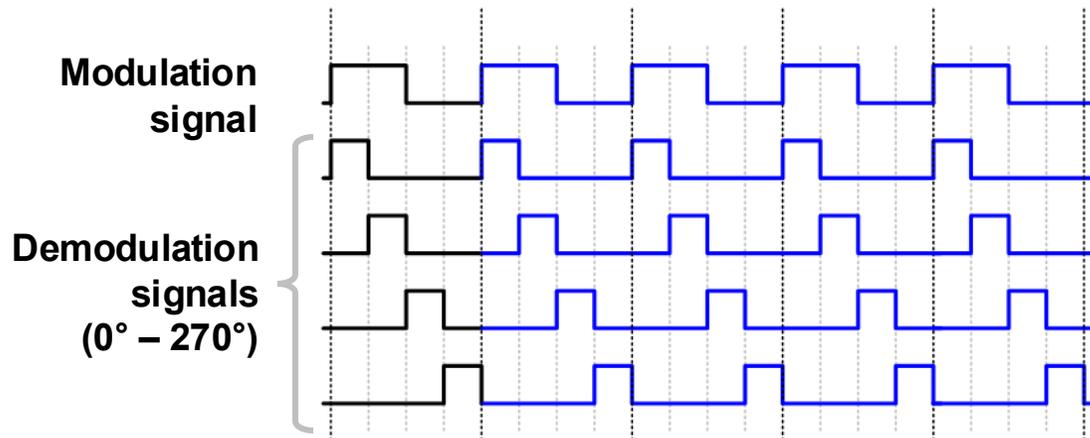
  - Time-gating architecture [Kawahito, '22]

- ■ **The demerits of prior schemes**

  - Low frame rate

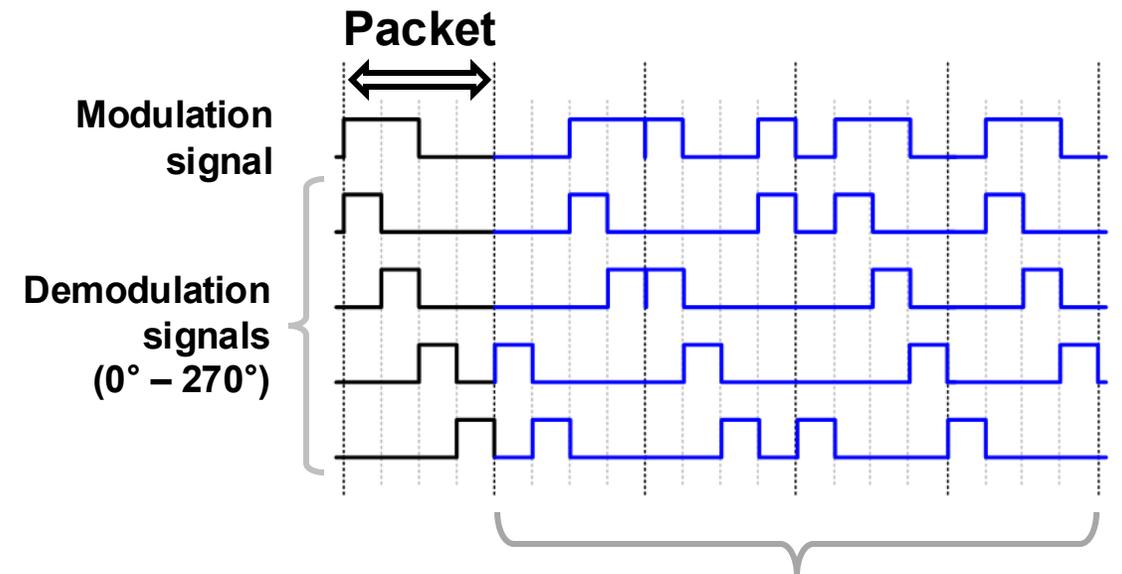 - Motion artifact

  - High power consumption

Proposed Scheme

- **Target: short-range application (φ < 2π)**
- **Key point: To eliminate phase information exceeding 2π inherently through the random packet modulation**

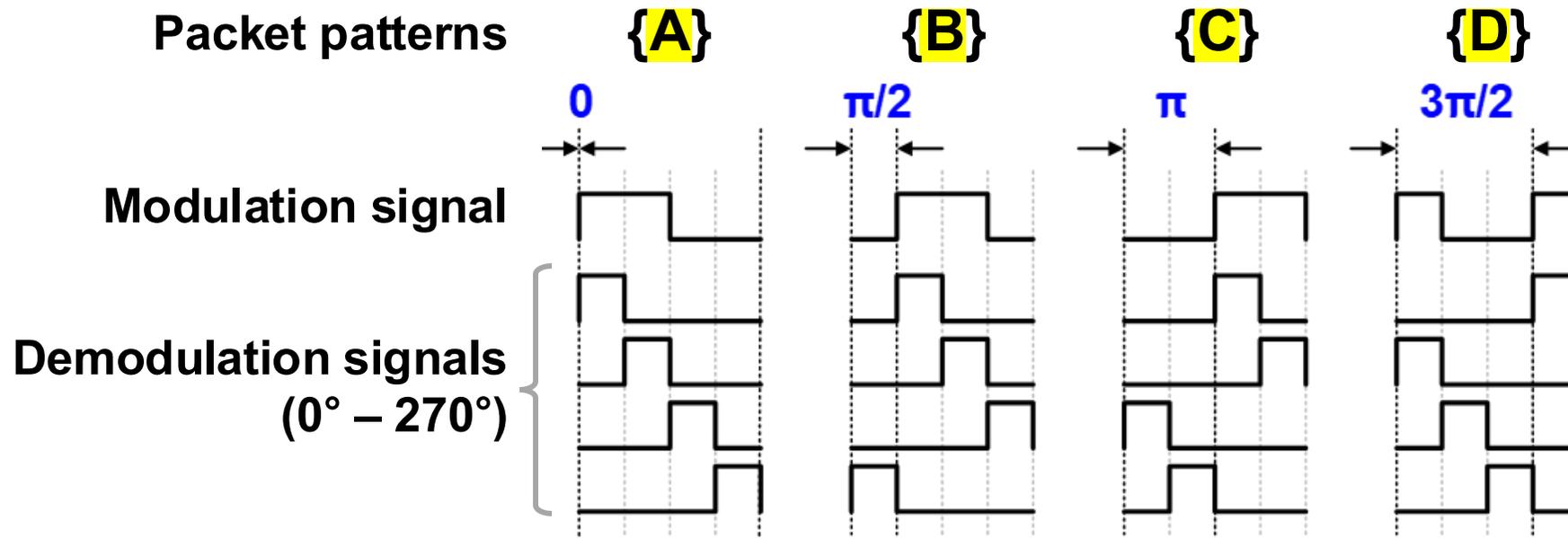< Conventional >

< Proposed >

Modulation signal

Demodulation signals (0° – 270°)

Packet

Random packet pattern demodulation

Proposed Scheme

■ **How to make the random packet patterns?**

Packet patterns　　**{A}**　　　**{B}**　　　**{C}**　　　**{D}**

Modulation signal

**Demodulation signals
(0° – 270°)**

- Four different packets: {A}, {B}, {C} and {D} are matched with 0, π/2, π and 3π/2 delays
- Packet length (PL): the number of repeating patterns
  - e.g., when PL = 3, the packet patterns would be {A}, {A}, {A}, {D}, {D}, {D}, {B}, {B}, {B}, …

Proposed Scheme

- **0 ≤ phase shift < 2π, with PL = 2**

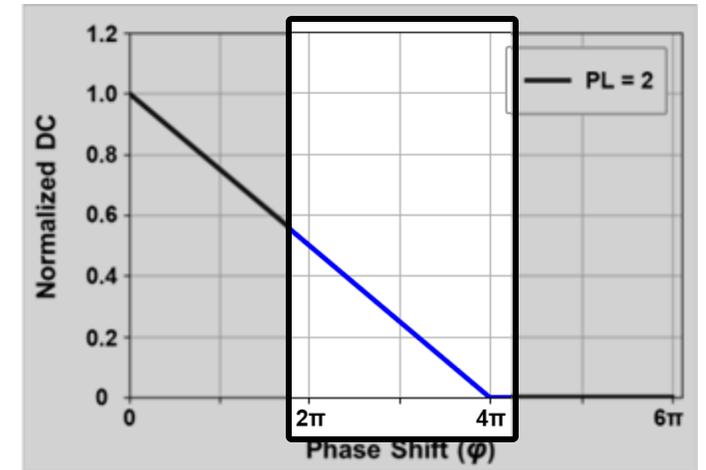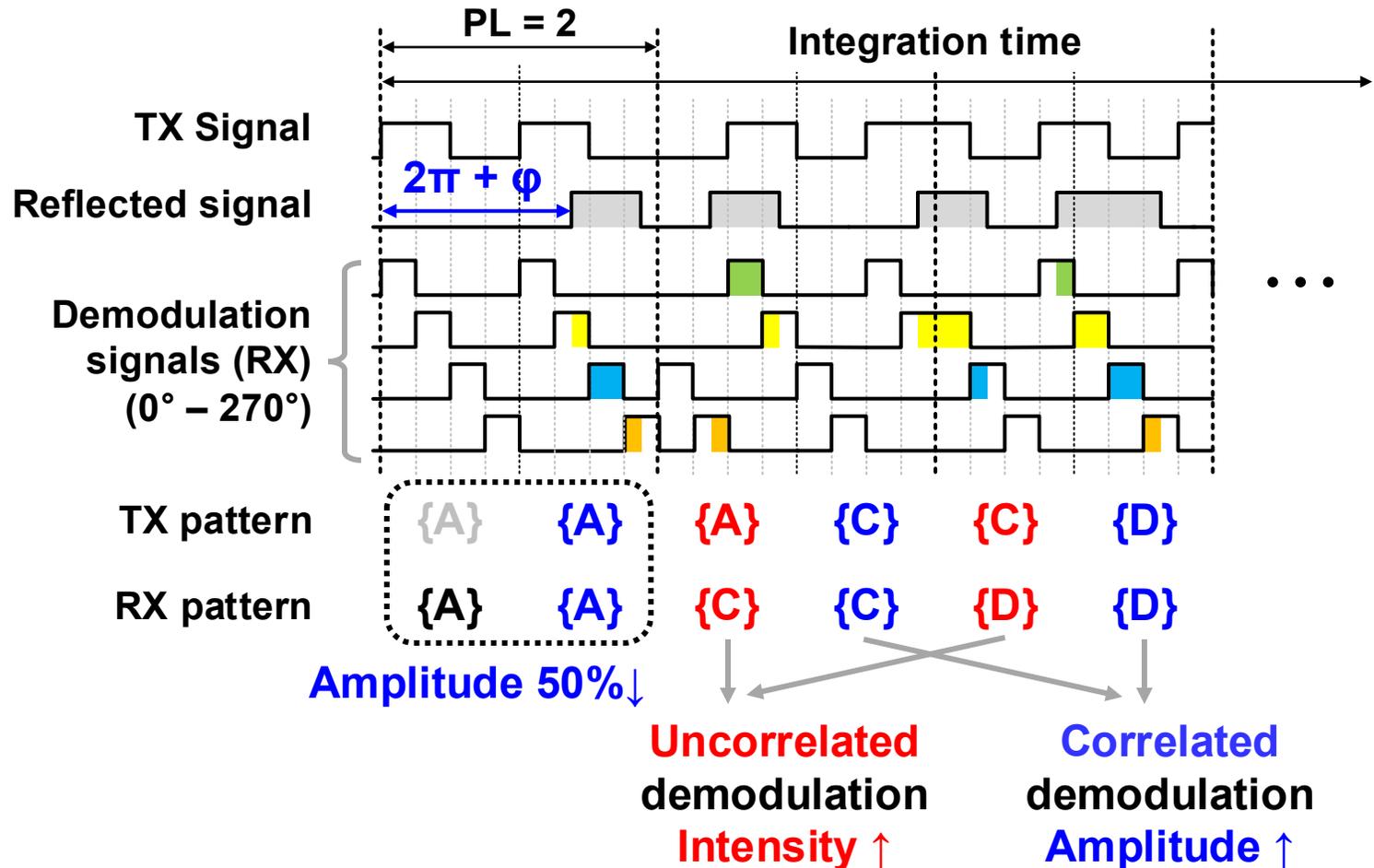Reflected signal **correlated** to demodulation signal
Amplitude ↑↑↑
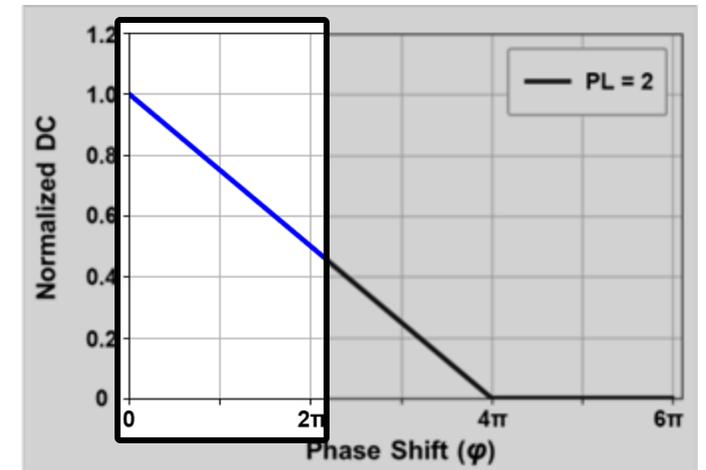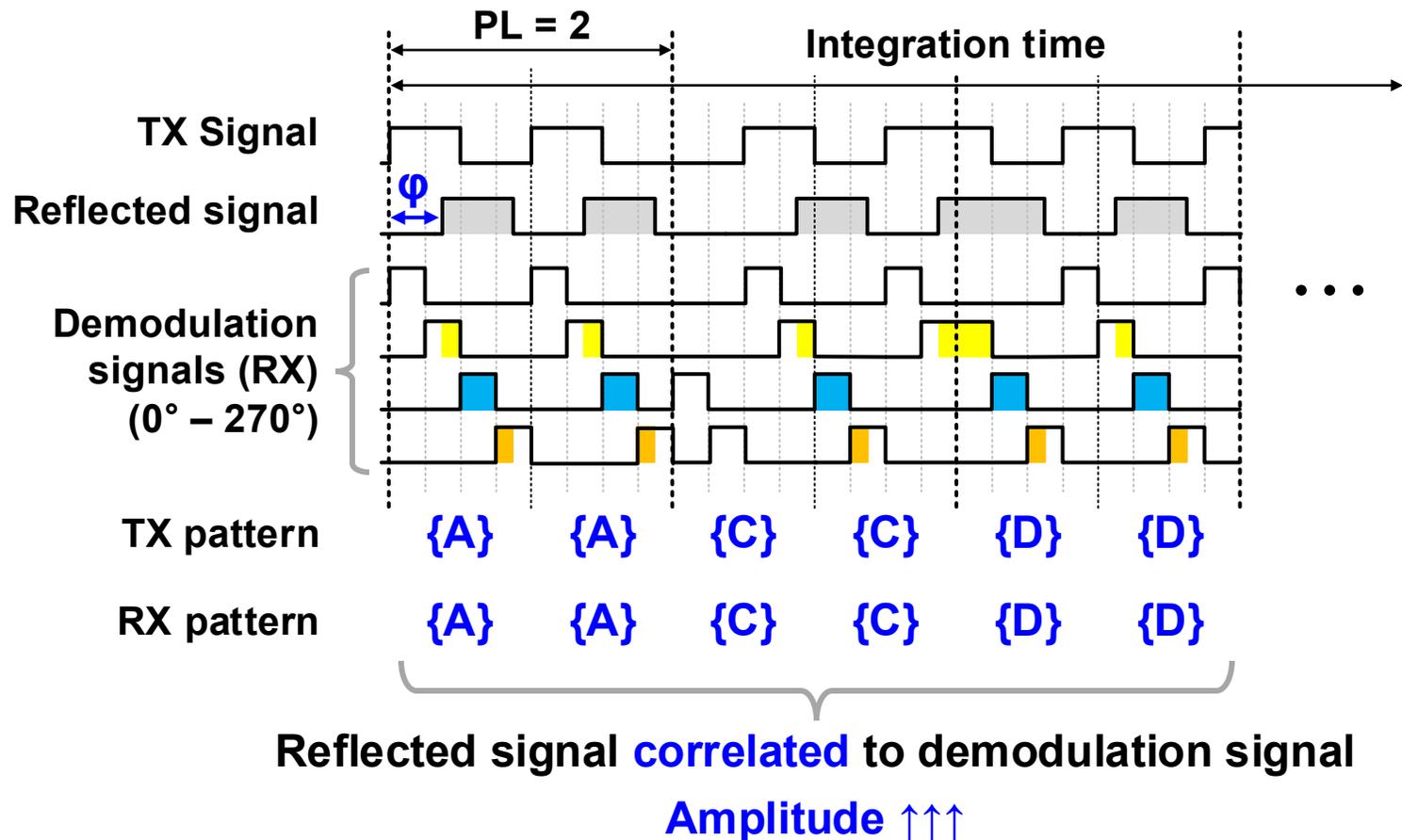
**Demodulation contrast (DC)
= Amplitude / Intensity**

High DC

Proposed Scheme
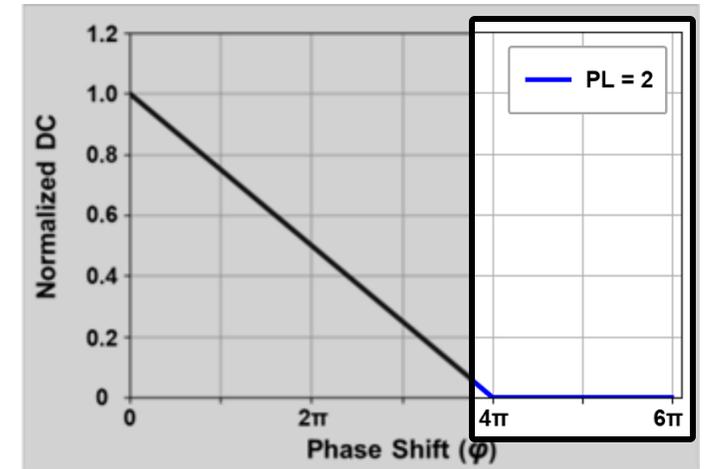
- **2π ≤ phase shift < 4π, with PL = 2**

**Demodulation contrast (DC)
= Amplitude / Intensity**

Mid DC

Proposed Scheme

■ 4π ≤ phase shift, with PL = 2
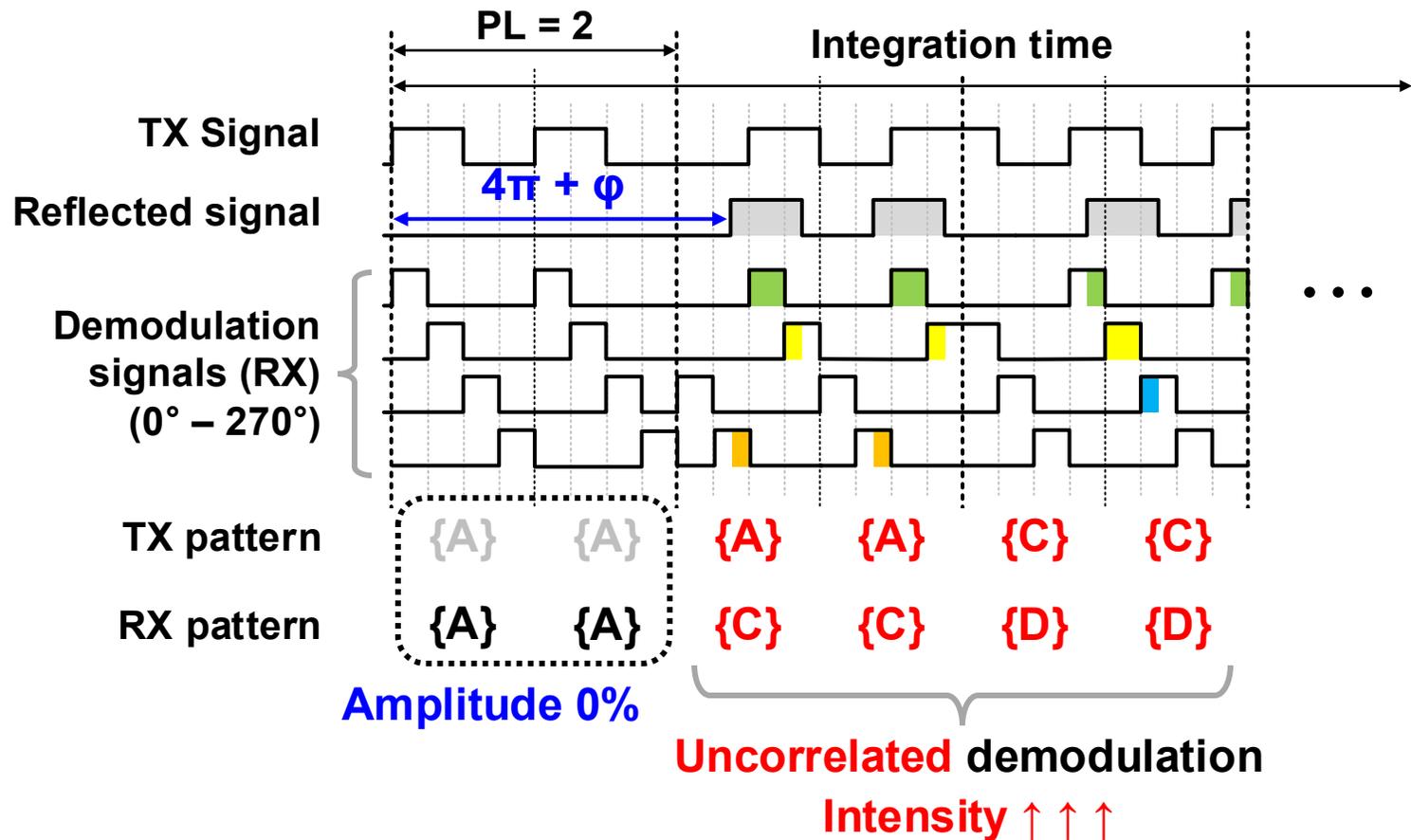
Proposed Scheme

■ **Normalized demodulation contrast**
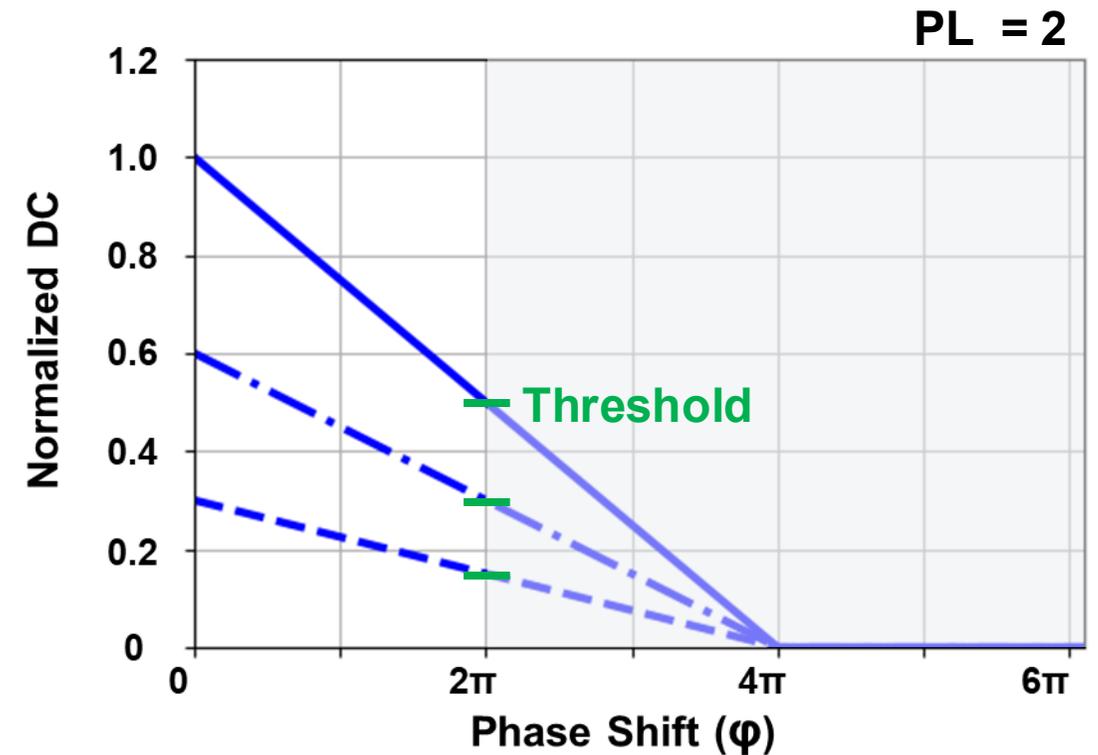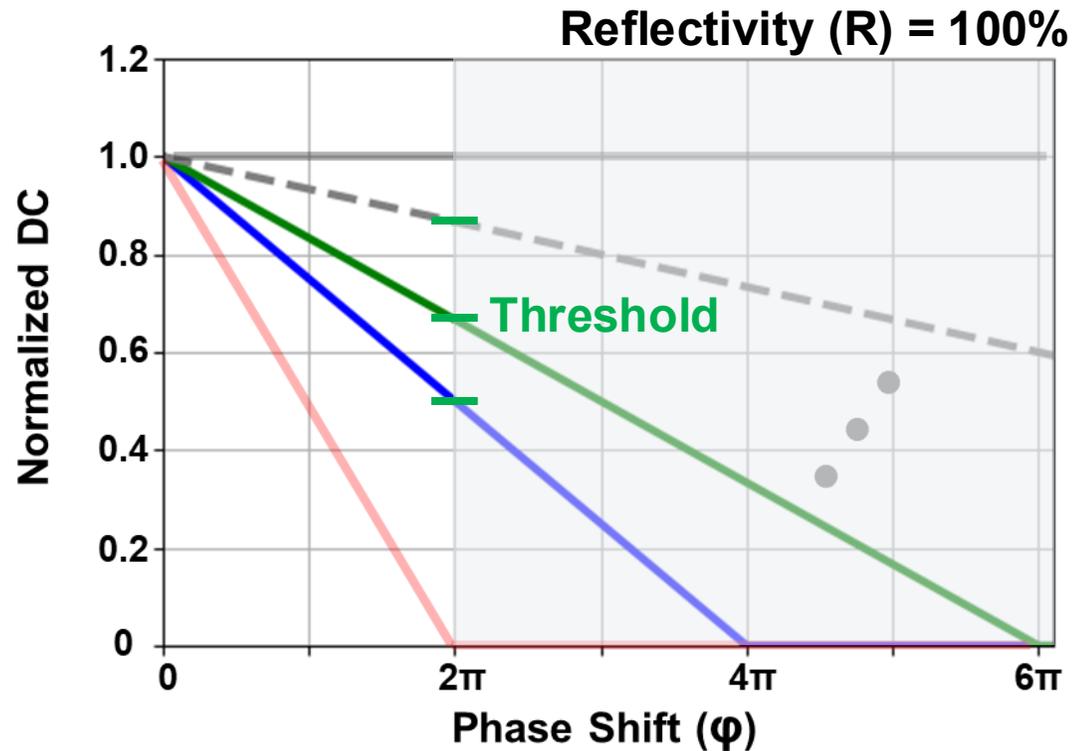
Proposed Scheme

■ **Normalized amplitude**

$$Normalized\ amplitude$$

$$= amplitude \times Folde\ depth^2$$

Amplitude × **Folded depth²**
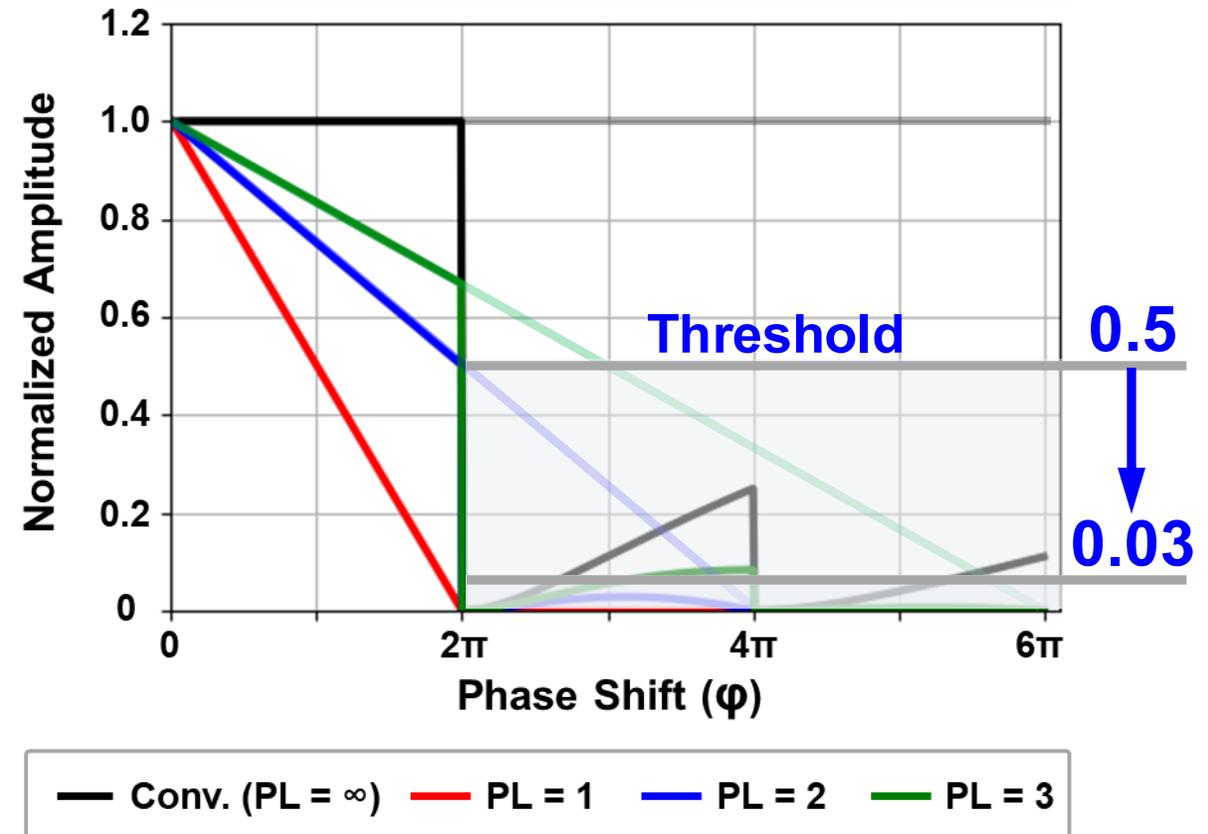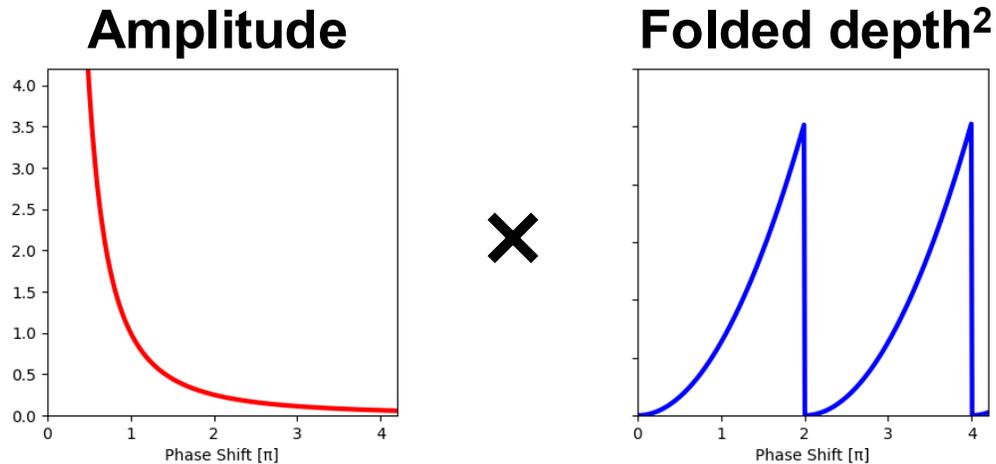
Proposed Scheme

■ **System margin study**

Conventional (PL = ∞)

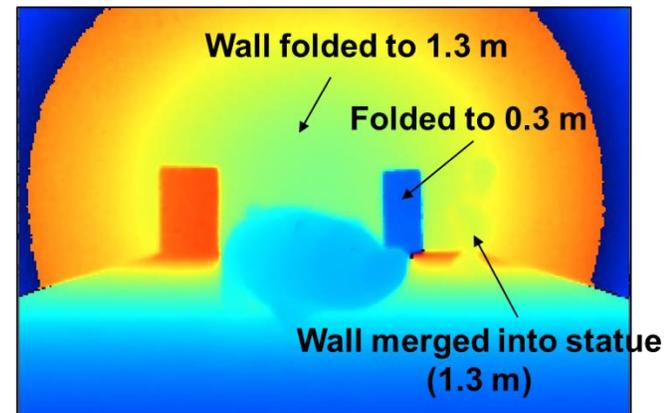Proposed (PL = 2)
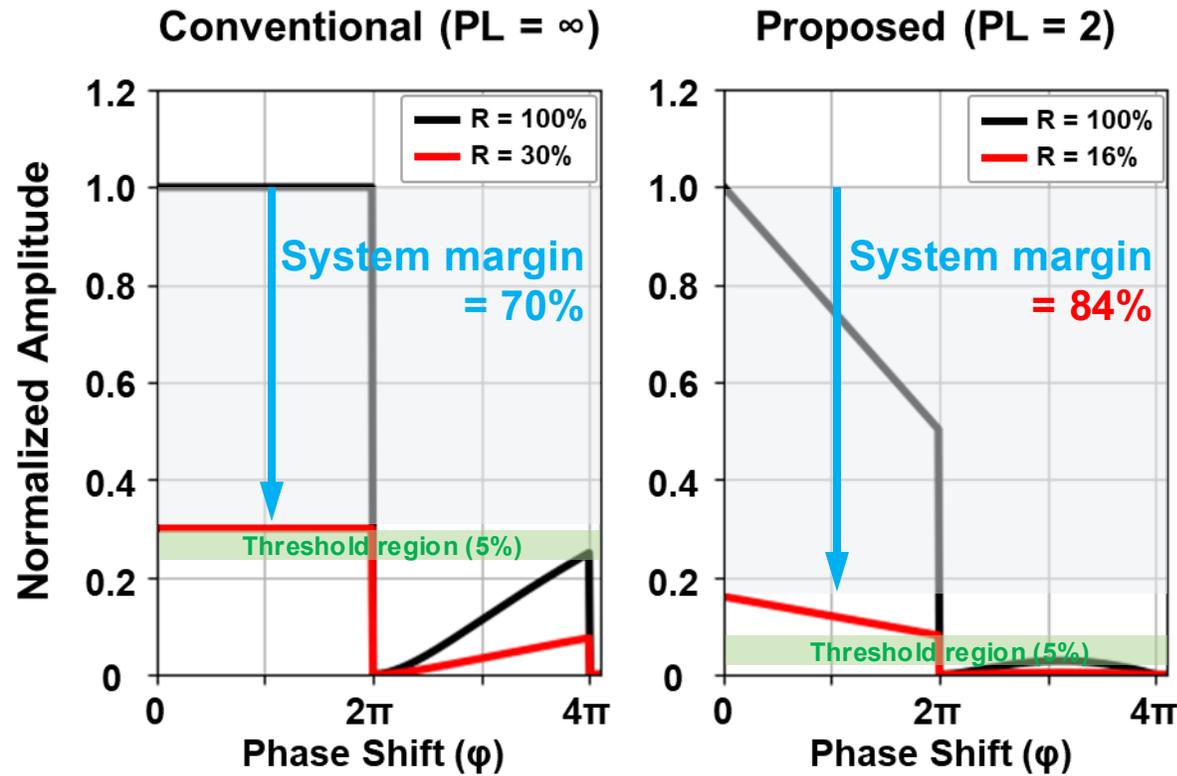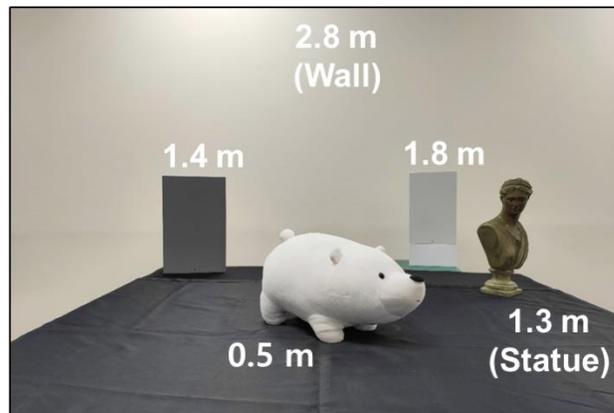
*14%p improved

System margin [%] = 100% − R_black [%]

$$\text{System margin [\%]} = 100\% - R_{black}\text{ [\%]}$$
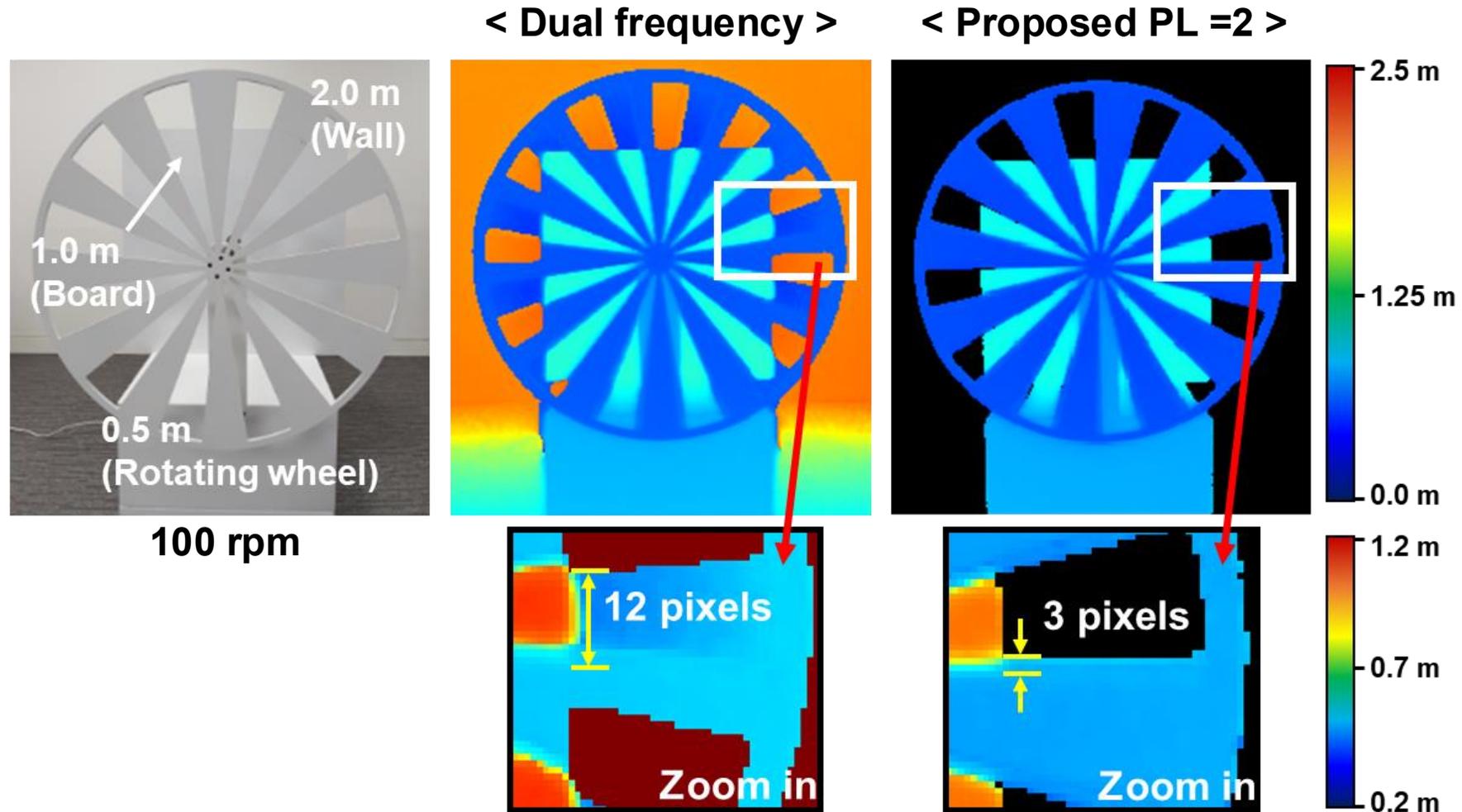
Measurement Results

■ **Proof of cancelling range ambiguity (2D depth image)**

● Unambiguous range = 1.5 m, modulation frequency = 100Mhz
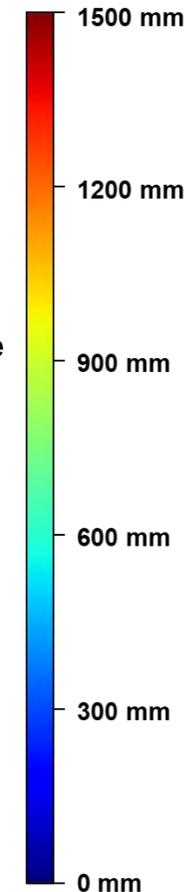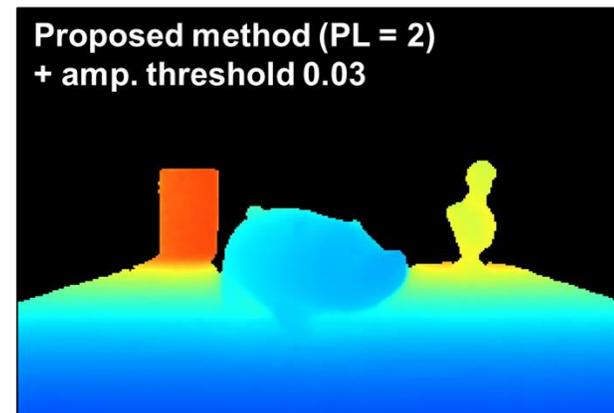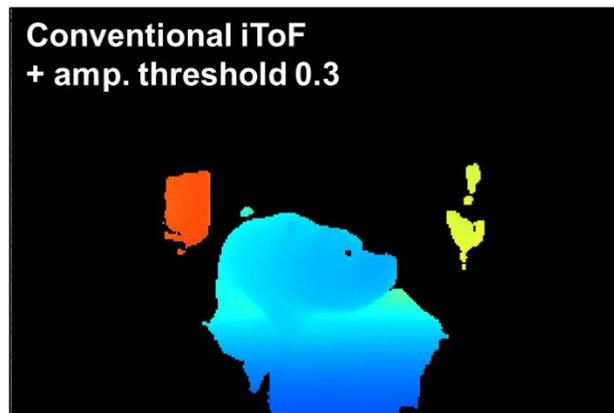
Measurement Results

■ **Proof of reducing motion artifact (2D depth image)**

< Dual frequency >   < Proposed PL =2 >

100 rpm

12 pixels — Zoom in

3 pixels — Zoom in

Conclusion

- ■ **Addressing the phase wrapping errors**

  - ● Random packet pattern modulation with amplitude masking algorithm

  - ● System margin reaches 84%, which is 14%p better than the conventional iToF (when PL = 2, amplitude threshold 0.08 and reflectivity 16%)

- ■ **Minimizing motion artifact**

  - ● Motion artifact performance is improved by 75% (when the spoke wheel is placed at 0.5 meters and rotates 10.5 rad/s)

Thank you