MICHIGAN STATE
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Distributed Interferometric Radar for Radial and Angular Velocity Measurement

2024 IEEE International Symposium on Antennas and Propagation and ITNC-USNC-URSI Radio Science Meeting

WE-A6.1P.1 | Focused session on challenges, advances and future trends on emerging applications of radar imaging

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delta
Distributed Electromagnetics
Theory and Applications

emrg
Electromagnetics Research Group
Michigan State University

Outline

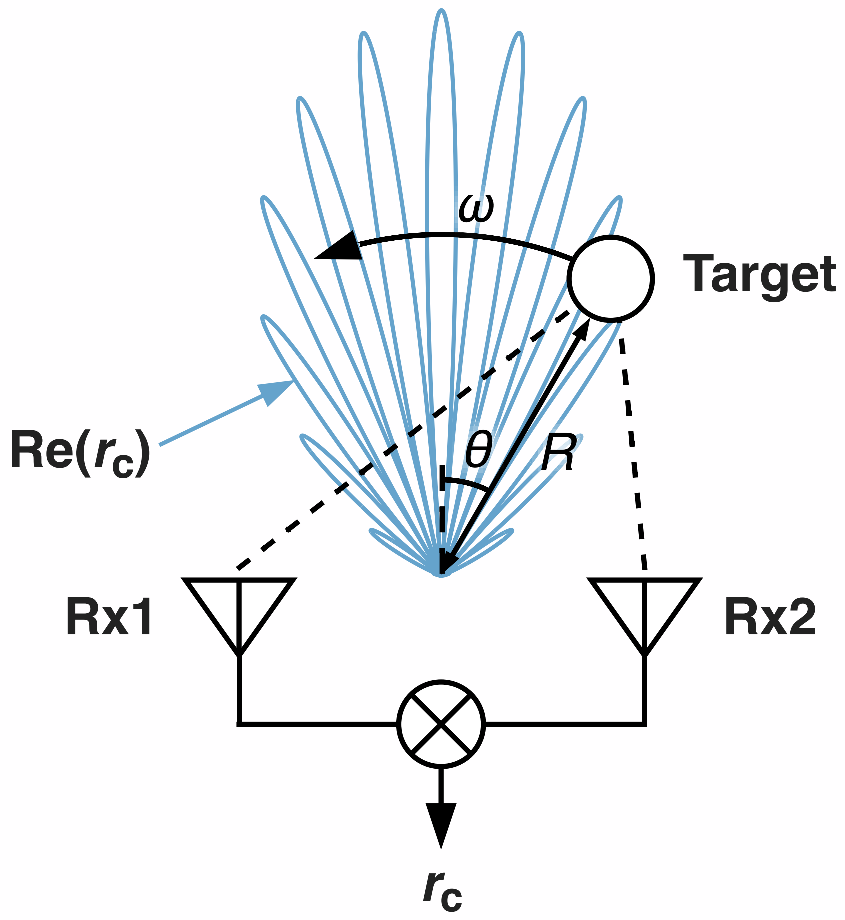
1. Overview and Motivation
2. Radar Interferometer Measurement Technique
3. Coordination Technique
4. Experimental Configuration and Measurement Results

Interferometric Distributed Aperture Sensing

Active distributed aperture interferometry utilizes grating or “fringe” patterns of sparse array to measure:

1. Instantaneous angular velocity for traditional radar sensing and tracking
2. Scene spatial frequency intensity for incoherent microwave/millimeter-wave imaging

Single-Baseline Aperture Interferometer



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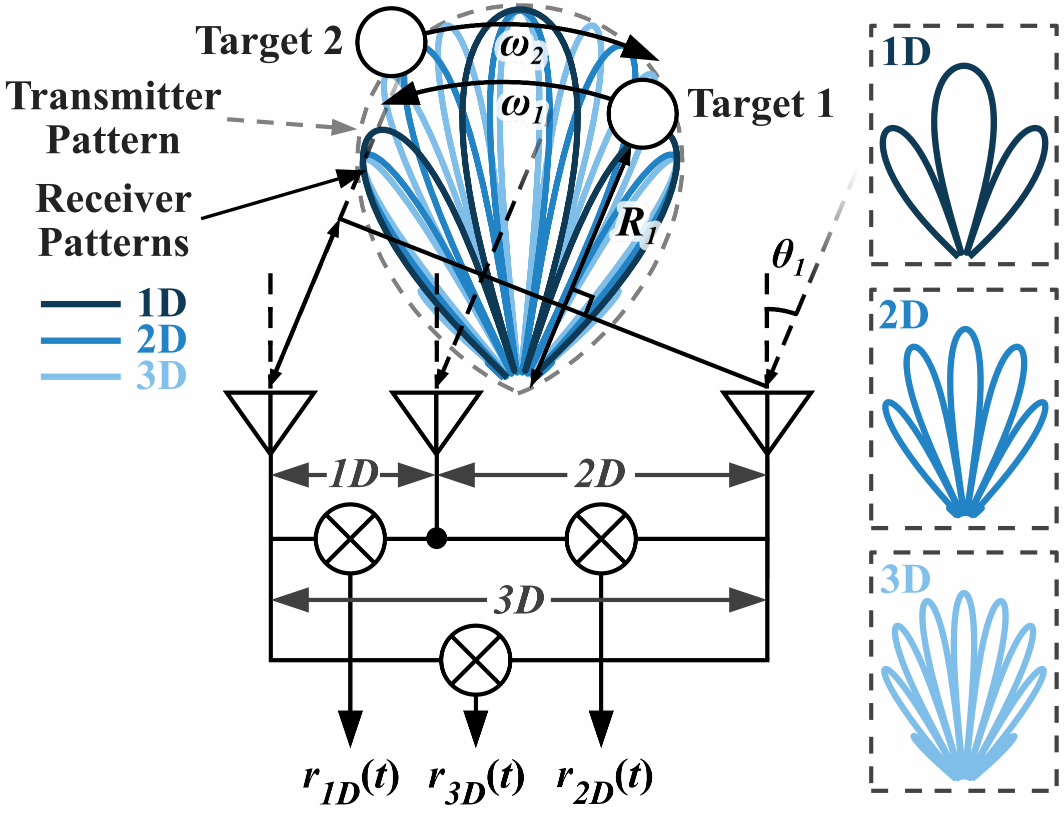
Using multiple baselines, multiple targets may be tracked, or multiple spatial frequencies may be measured

Multi-Baseline Aperture Interferometer



J. Merlo, E. Klinefelter, S. Vakalis and J. A. Nanzer, "A Multiple Baseline Interferometric Radar for Multiple Target Angular Velocity Measurement," in IEEE Microwave and Wireless Components Letters, vol. 31, no. 8, pp. 937-940, Aug. 2021, doi: 10.1109/LMWC.2021.3079842.

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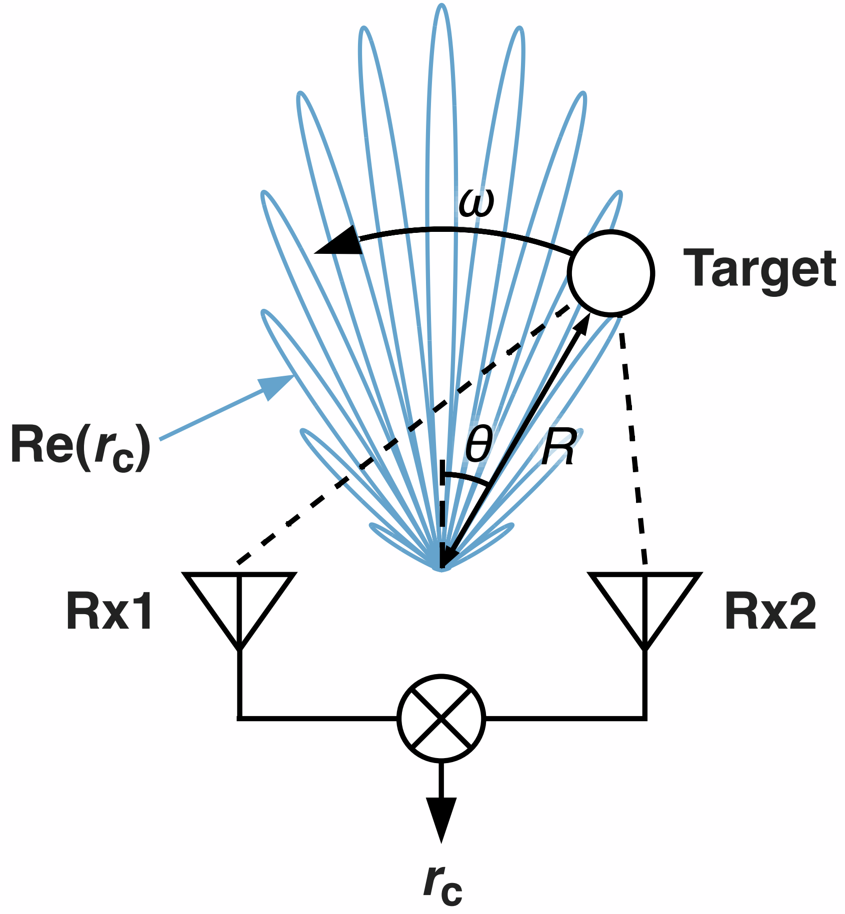
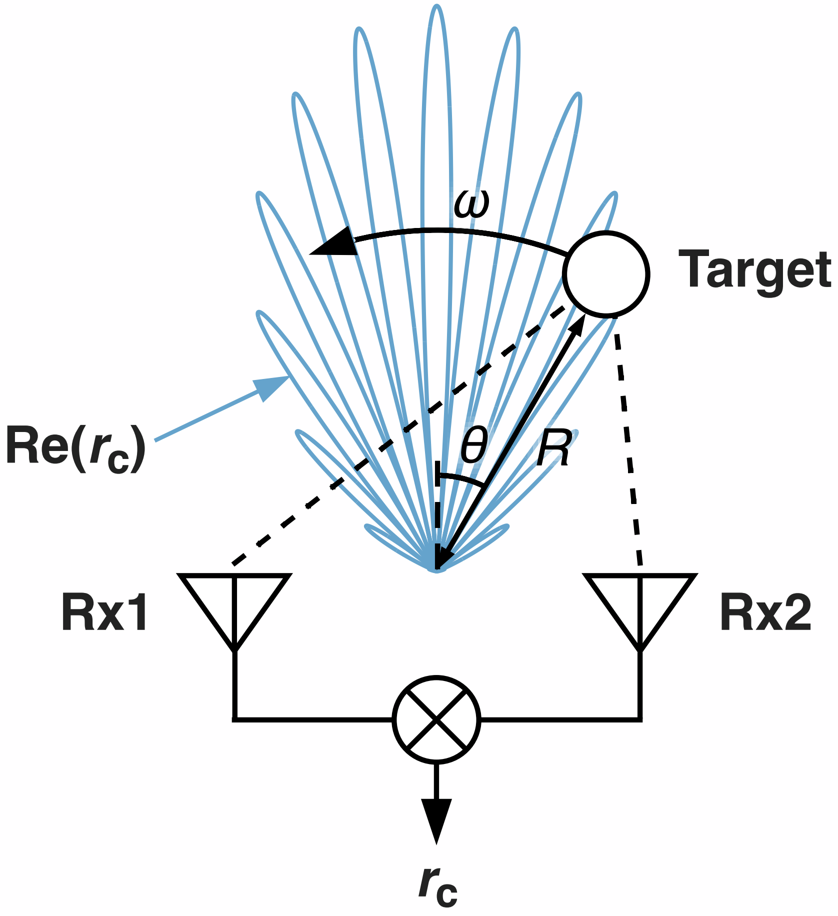


Wireless Distributed Aperture Interferometric Sensing

Traditional Aperture Interferometer



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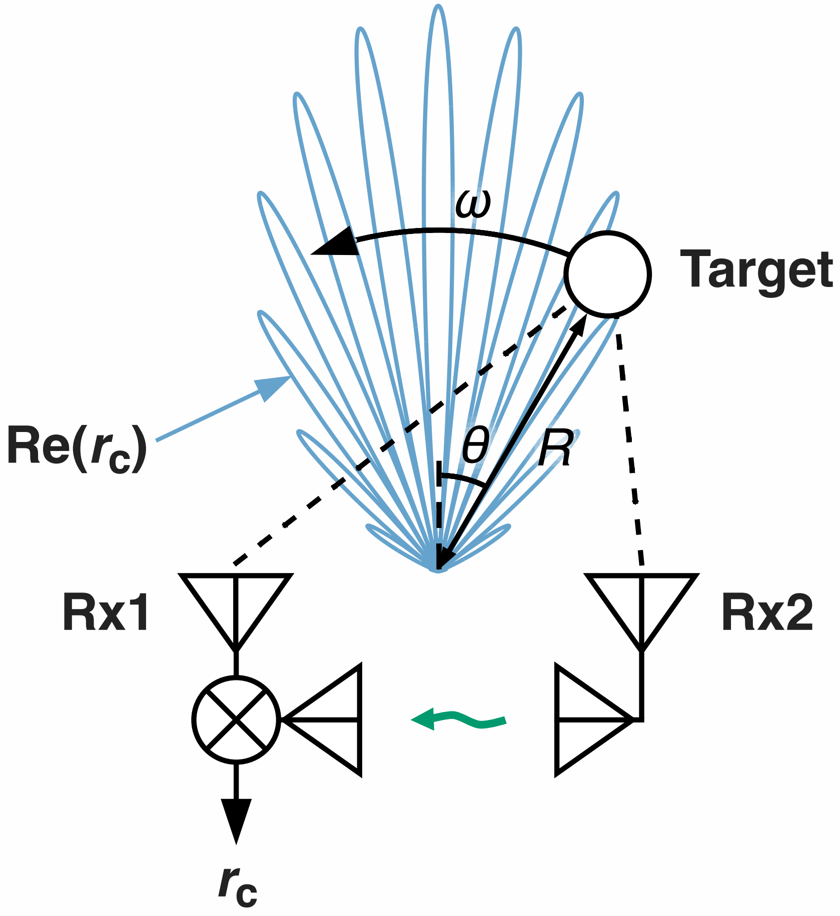

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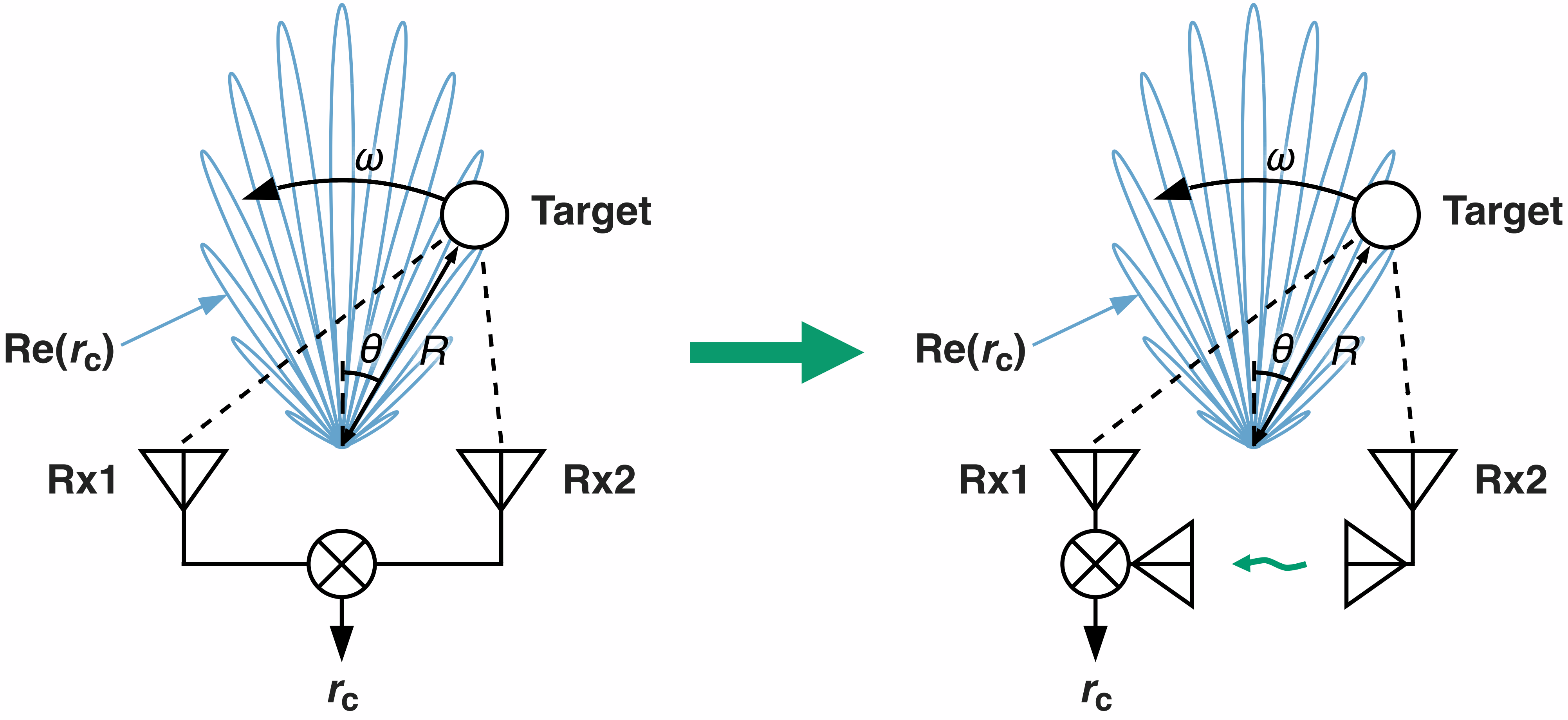

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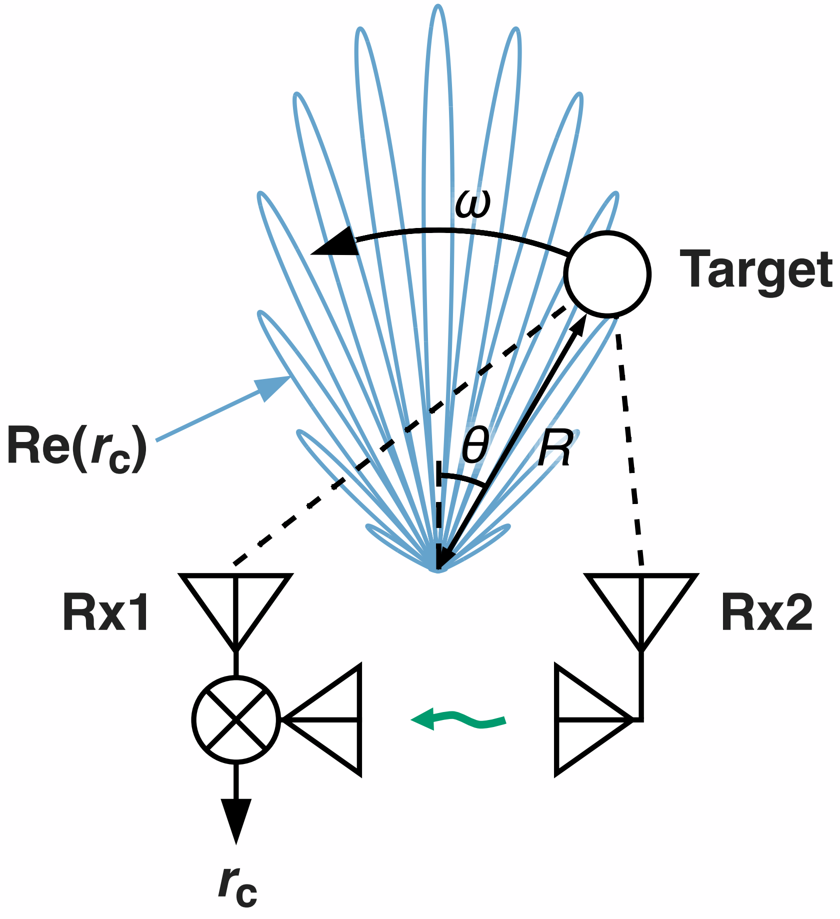
Wireless Aperture Interferometer



Benefits

- Many small nodes make up array
  - Reduced deployment cost
  - Decreased thermal management requirements
  - Resilient to antenna / node failure

- Larger array sizes possible
  - Increased targets possible to track
  - Increased spatial frequencies for imaging

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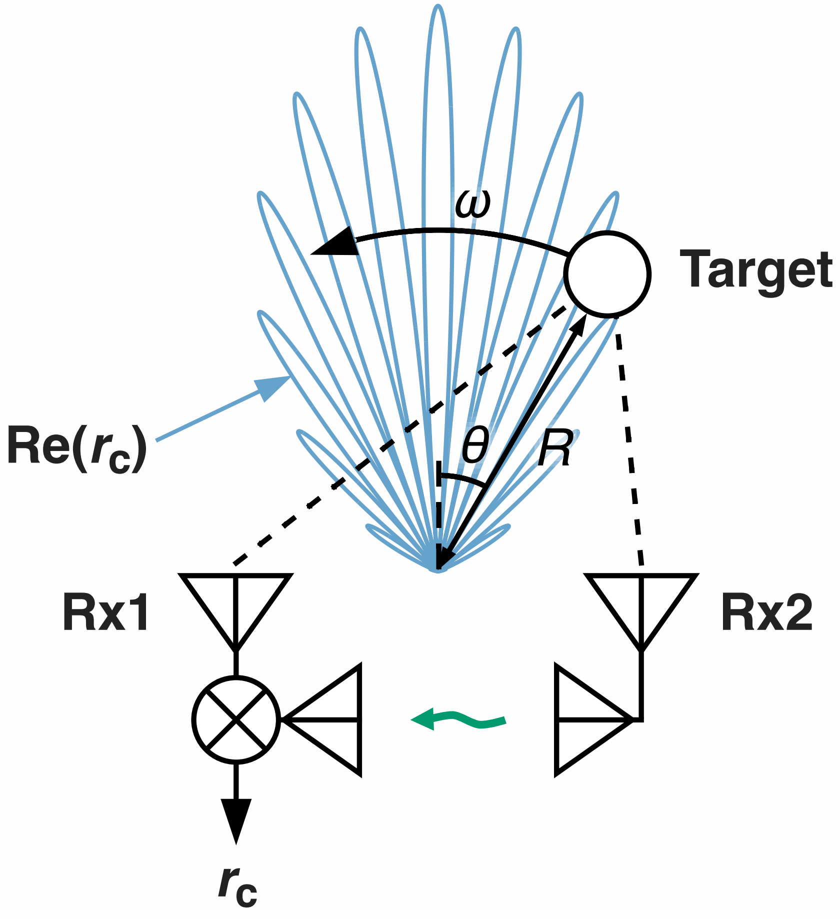

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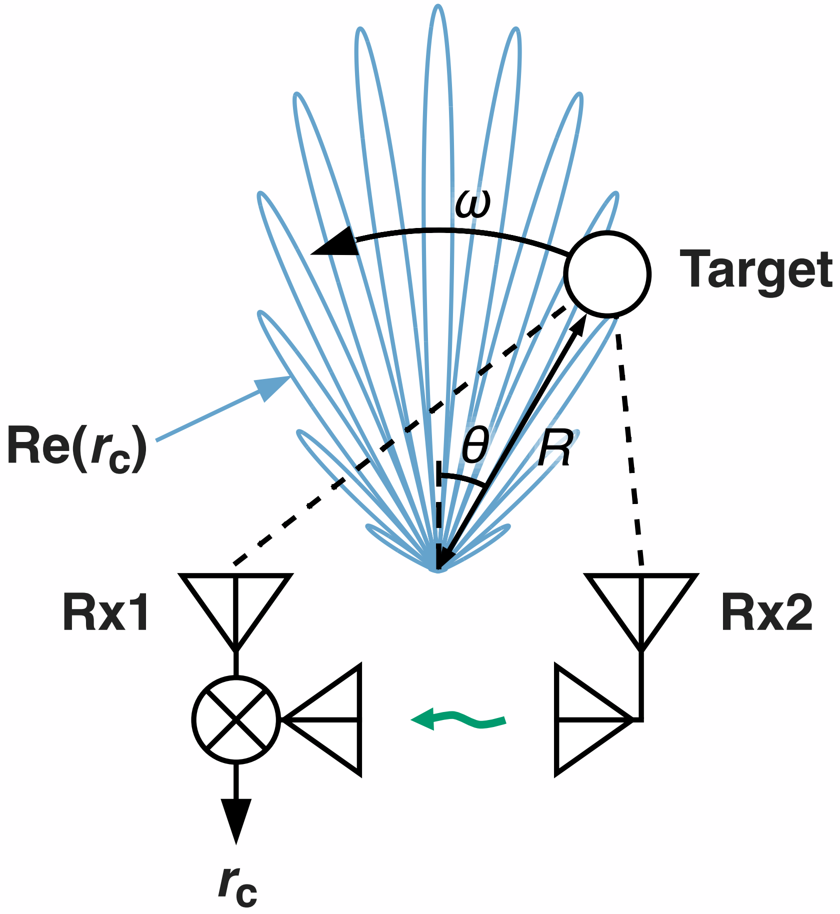


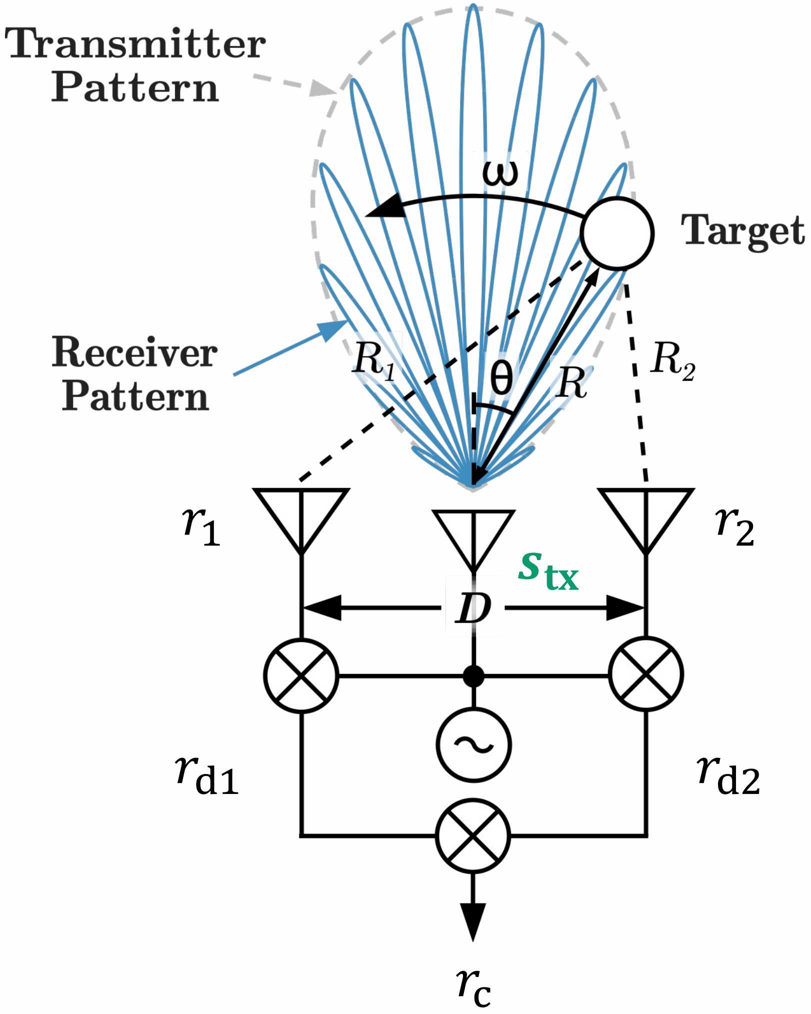
Challenges

- Stringent coordination requirements for
  - Time
  - Frequency
  - Element Position

Interferometric Radar Techniques

Continuous-wave transmit signal

$$s_{\mathrm{tx}}(t) = A(\theta)\exp(j2\pi f_0 t)$$



Interferometric Radar Techniques

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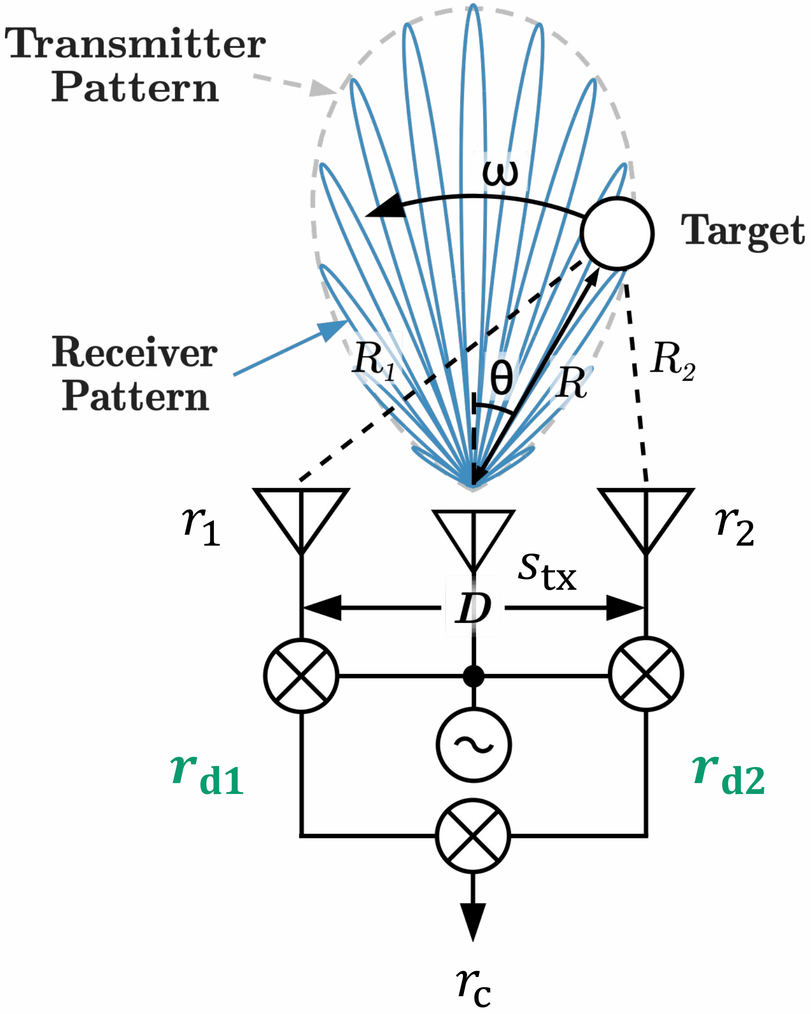
Baseband signals

$$r_{\mathrm{d}n}(t) = A(\theta)\exp(-j2\pi f_0 \tau_{\mathrm{d}n})$$



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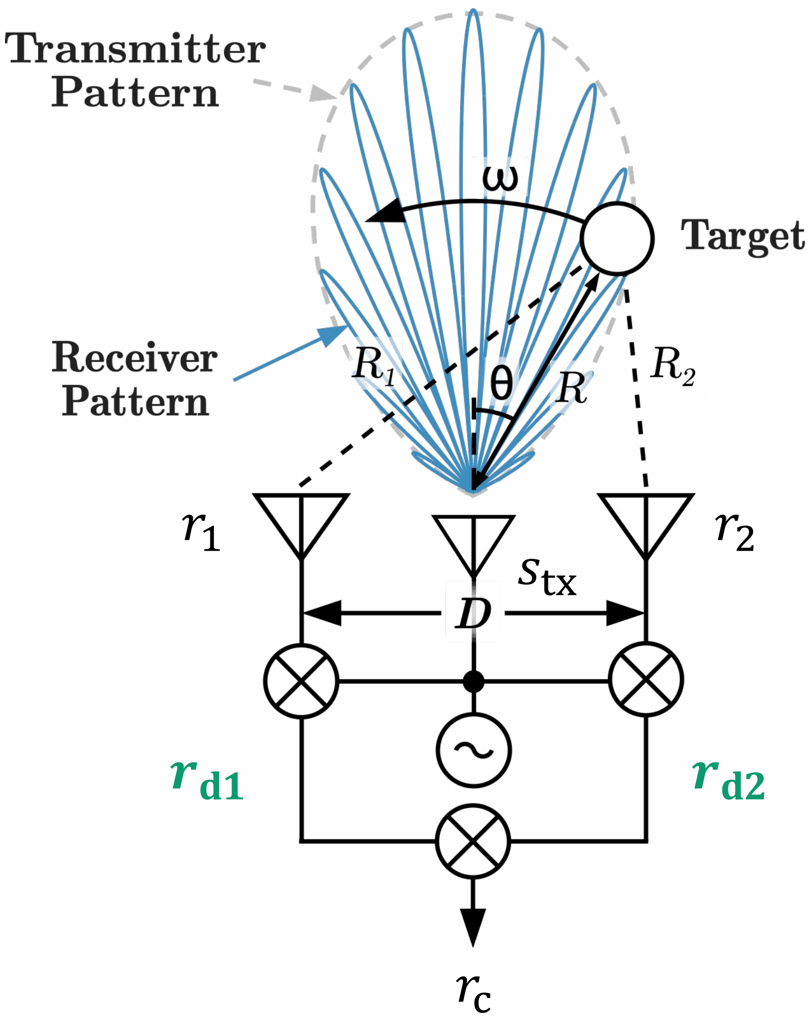
Radial rate measurement (Doppler)

$$f_{\text{d}n}(t) = \frac{1}{2\pi}\frac{d\phi_{\text{r}_{\text{d}n}}(t)}{dt} = -\frac{d}{dt} f_0\tau_{\text{d}n} = \frac{2v_{\text{r}n}}{\lambda}$$

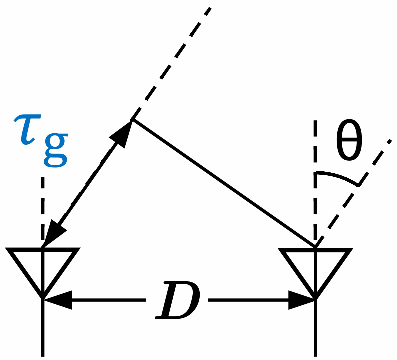
$$\Rightarrow \quad \boxed{\hat{v}_{\text{r}n} \approx -f_{\text{d}n}\frac{\lambda}{2}\ (\text{m/s})}$$



Interferometric Radar Techniques

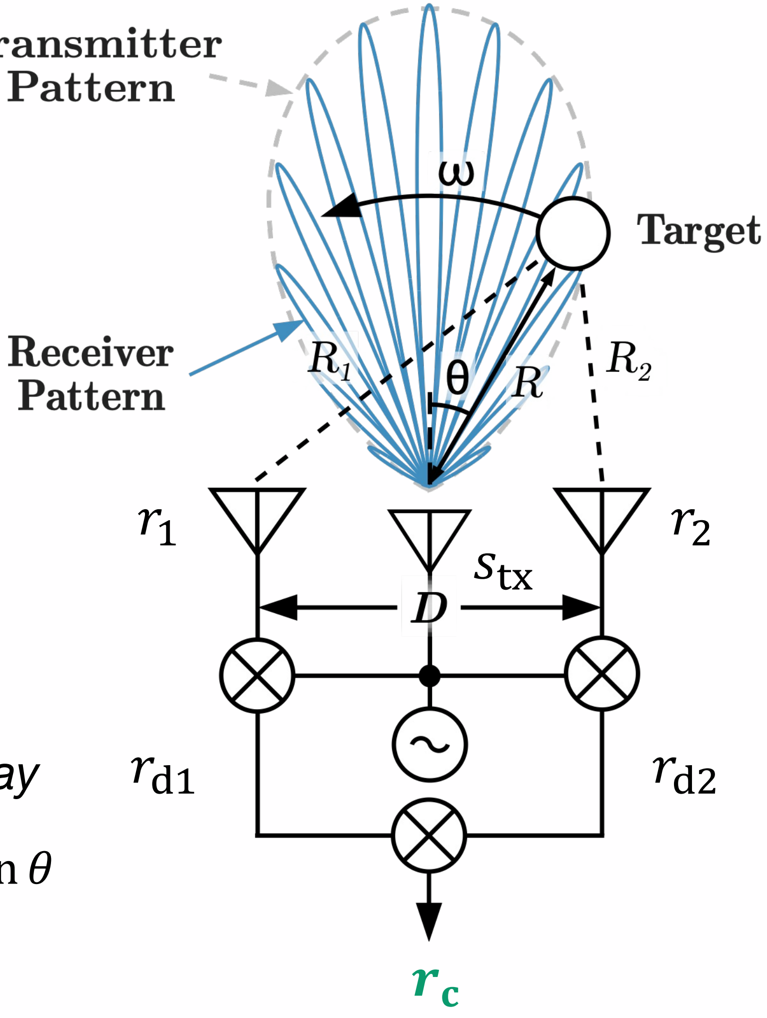
Correlator output

$$
\begin{aligned}
r_c(t) &= r_{d1}(t) \cdot r_{d2}^{*}(t) \\
&= A(\theta)\exp\left(j2\pi f_0 \tau_g\right) \\
&= A(\theta)\exp(j2\pi D_\lambda \sin\theta)
\end{aligned}
$$



Geometric Time Delay

$$\tau_g = \tau_{d2} - \tau_{d1} = \frac{D}{c}\sin\theta$$



J. A. Nanzer, "Millimeter-Wave Interferometric Angular Velocity Detection," in IEEE Transactions on Microwave Theory and Techniques, vol. 58, no. 12, pp. 4128-4136, Dec. 2010, doi: 10.1109/TMTT.2010.2086467.

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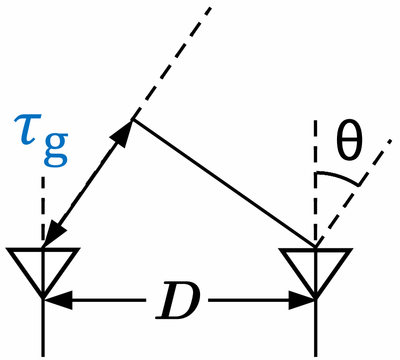
Angular rate measurement

$$\text{Using } \omega = \frac{d\theta}{dt} \implies \theta = \omega t + \theta_0$$

$$f_\omega = \frac{1}{2\pi}\frac{d\phi_{r_c}(t)}{dt} = \omega D_\lambda \cos\theta$$

$$\Rightarrow \quad \boxed{\widehat{\omega} \approx \frac{f_\omega}{D_\lambda}\ \text{(rad/s)}}$$



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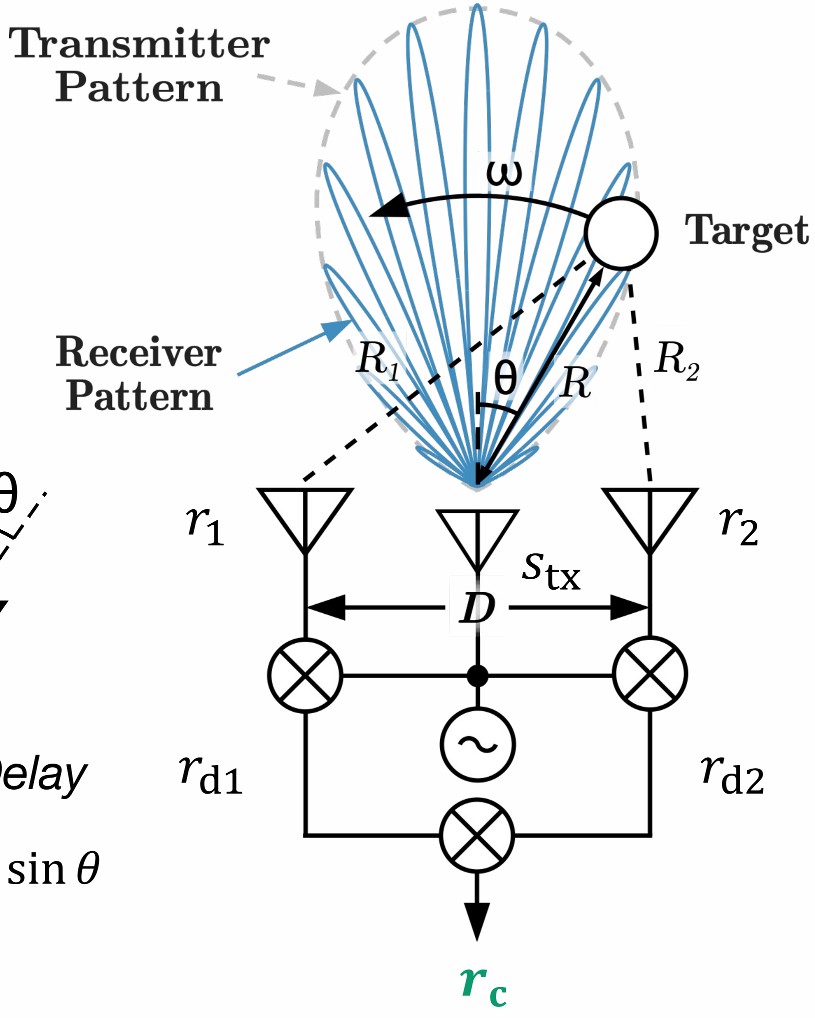

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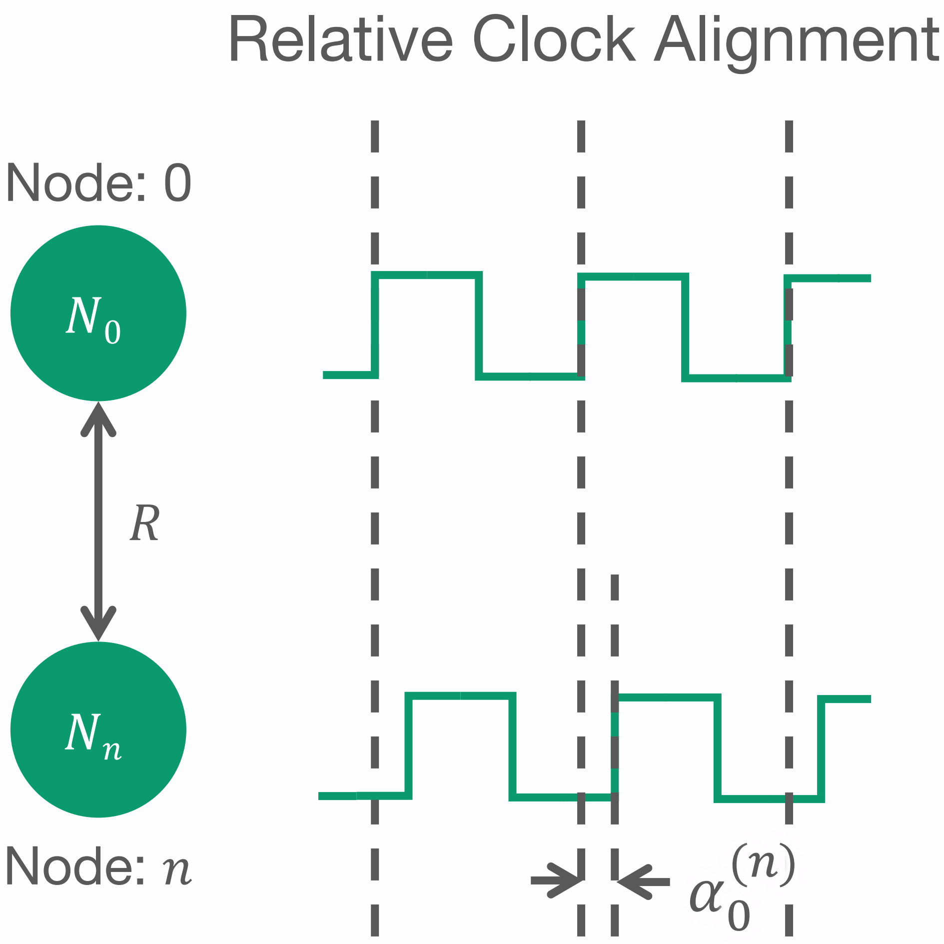
System Clock Model

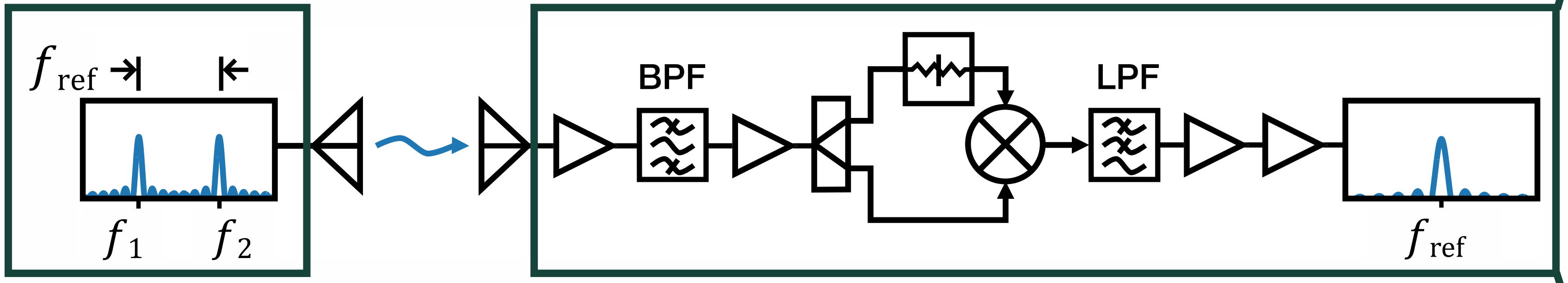
- Local time at node n:

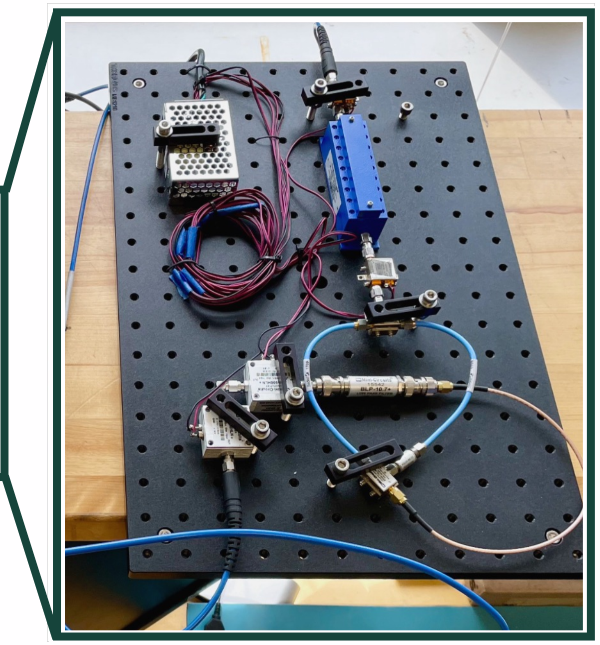
$$T^{(n)}(t) = \sum_{k=0}^{K} \alpha_k^{(n)} t^k + \nu^{(n)}(t)$$

  - K: time model polynomial order
  - $\alpha_k^{(n)}$: kth clock drift coefficient at nth node
  - t : global true time
  - $\nu_n(t)$: other zero-mean noise sources
- Goal:
  - Identify $\alpha_k \; \forall \; n$



Wireless Frequency Syntonization





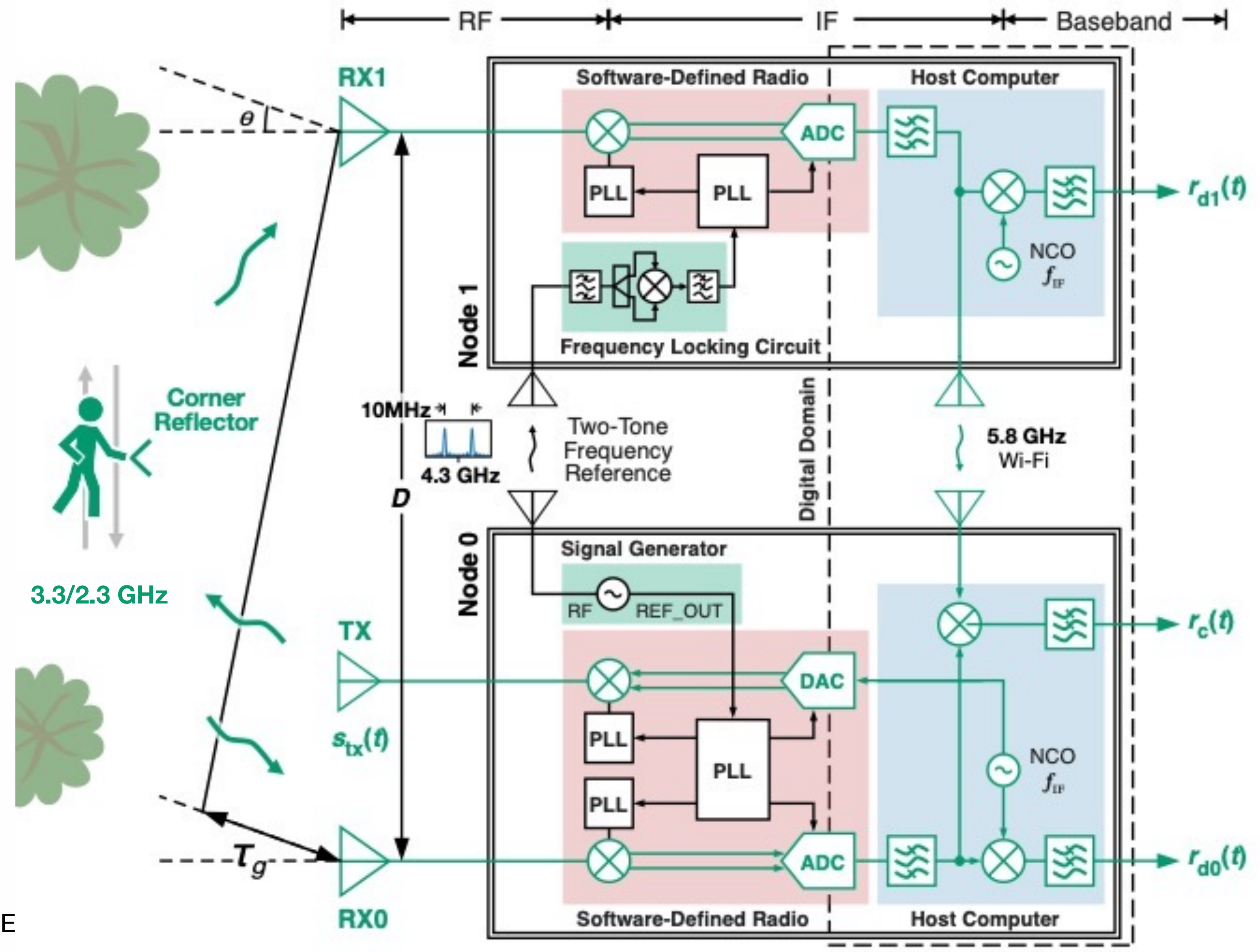
Signal Gen.

Wireless Frequency Transfer Receiver Circuit

- Two-tone transmitter with carrier spacing f_{ref}
- Self-mixing receiver: Mixes received signal with itself, low-pass filters frequencies above f_{ref}
- Fundamental frequency f_{ref} received at output used to discipline local oscillators on the radio nodes (tracks: $\alpha_k^{(n)}$ where $k > 0$)

S. R. Mghabghab and J. A. Nanzer, "Open-Loop Distributed Beamforming Using Wireless Frequency Synchronization," in IEEE Transactions on Microwave Theory and Techniques, vol. 69, no. 1, pp. 896-905, Jan. 2021, doi: 10.1109/TMTT.2020.3022385.

System Diagram



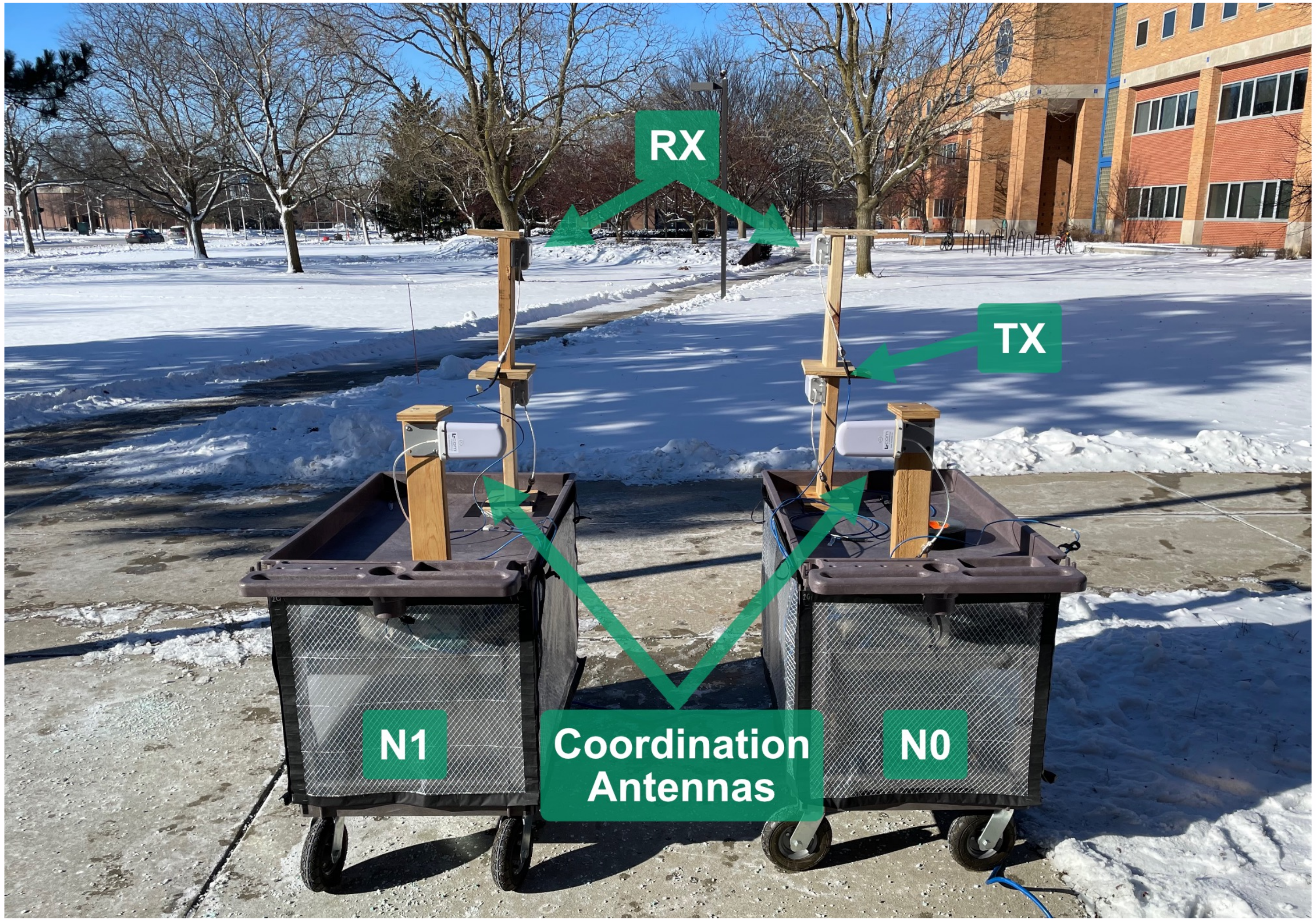
Legend

— Correlation Path

— Frequency Reference Path

- Two Ettus X310 SDRs were used on each node
- Each SDR covered one frequency band (3.3/2.3 GHz)
- Time alignment performed using GNSS PPS

Experimental Setup



Tangential Velocity Measurements

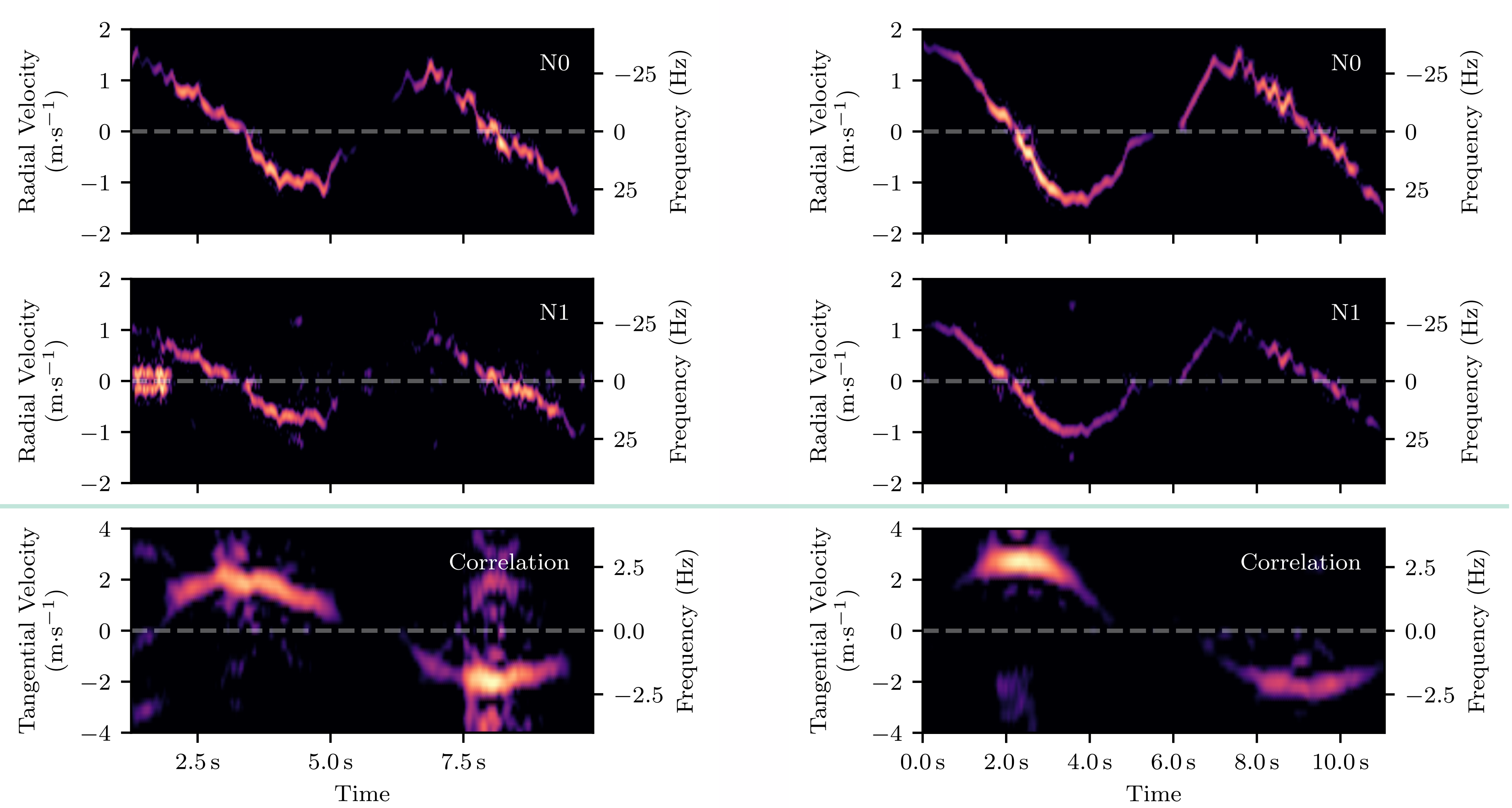
f_c = 3.3 GHz

Pass 1

Pass 2

Radial Velocity

Tangential Velocity



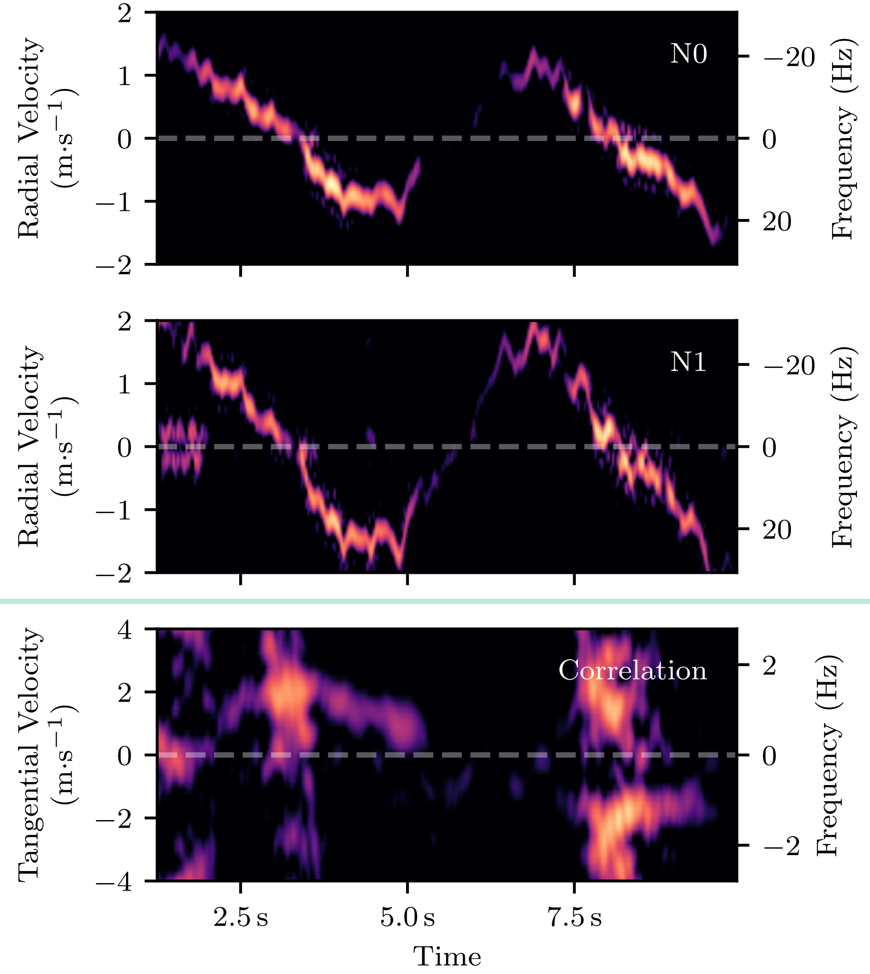
Tangential Velocity Measurements

f_c = 2.3 GHz

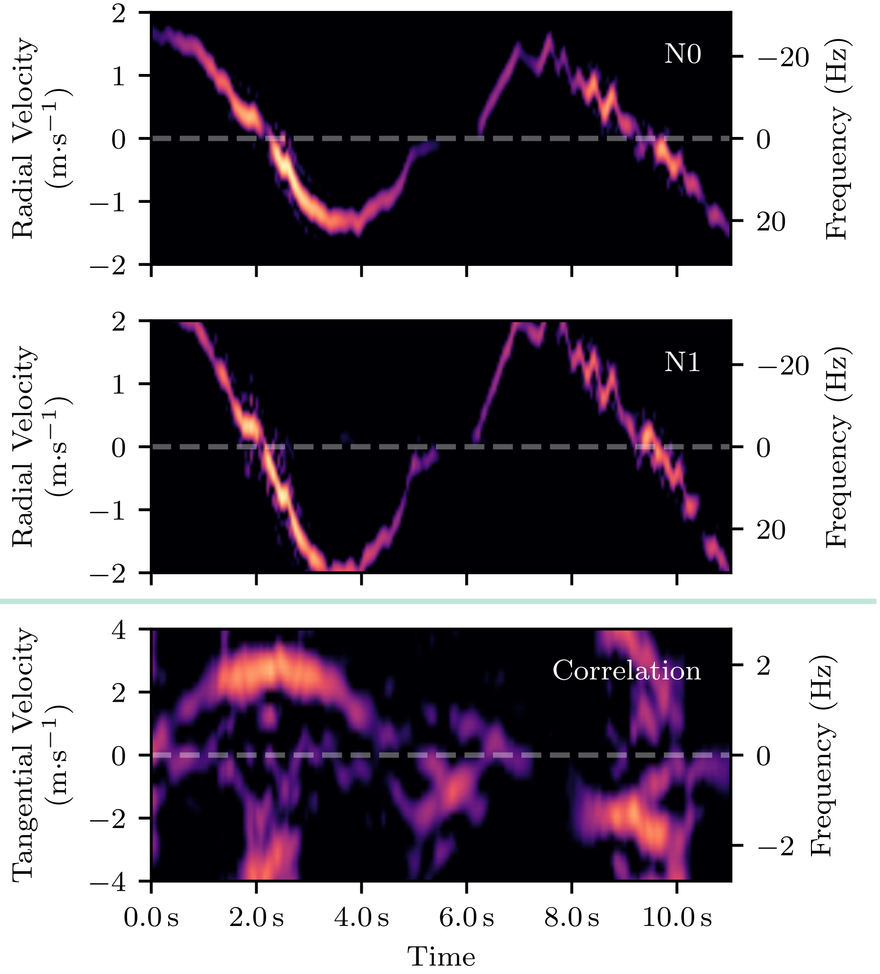
Radial Velocity

Tangential Velocity

Pass 1



Pass 2



Conclusion

- Discussed a technique for implementing wireless distributed aperture correlation interferometers
- Demonstrated a wireless distributed aperture interferometer simultaneously measuring both radial and tangential motion of a point scatterer carried by a pedestrian
- Results show a promising step towards larger distributed interferometric arrays

Questions?