UltraScatter: Ray-Based Simulation of Ultrasound Scattering

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Introduction & Motivation

- **Ultrasound simulation** is critical for designing/improving reconstruction algorithms, transducers, and training ML models.
- However, **wave-based solvers** such as k-space methods [1] are computationally intensive, and their high accuracy is not always required.
- Faster convolution-based tools such as Field II [2] or delay-based simulators like SIMUS [3] cut runtime yet still take *minutes* per B-mode frame and assume weak, single scattering.

→ **UltraScatter** replaces waves with ray fronts and leverages highly parallelized **Monte-Carlo ray tracing** to model multiple scattering, attenuation and absorption *in seconds.*

Methodology

We are interested in the received pressure P at element e over time t:

$$P(e,t) = \int_{\Omega}\int_{A} P_i(x,t,\omega_i)\; f_d(\omega_i)\, d\omega\, da,$$

Scattering in the heterogeneous media is defined by the **scattering probability** (extinction coefficient) σ_t and the **scattering amplitude** (albedo) a.

$$P_{scattered}(x,t,\omega_o) = \int_{\Omega} a(x)\; p(\omega_i,\omega_o)\; P_i(x,t,\omega_i)\, d\omega_i$$

Following the methodology of **free flight delta tracking** with null interactions (Woodcock tracking [5]):

- The distance s a ray is travelling until an interaction is triggered is sampled based on the **extinction majorant** μ (largest defined extinction value) and a randomly sampled variable $\xi \sim \mathcal{U}(0,1)$:

$$s = s_{min} - \frac{1}{\mu}\ln(1-\xi)$$

- This interaction can lead to a real or null interaction event based on the **extinction value** at the sampled position x:

$$\xi' < \frac{\sigma_t(x)}{\mu} \quad\Rightarrow\quad \text{real interaction, else null interaction}$$

- In case of a **real** interaction event the scattering amplitude defines whether the ray is absorbed or scatters

If the ray is scattered, secondary rays are cast to **all individual elements**

The phase function p defines the subsequent direction ω_o of the primary ray

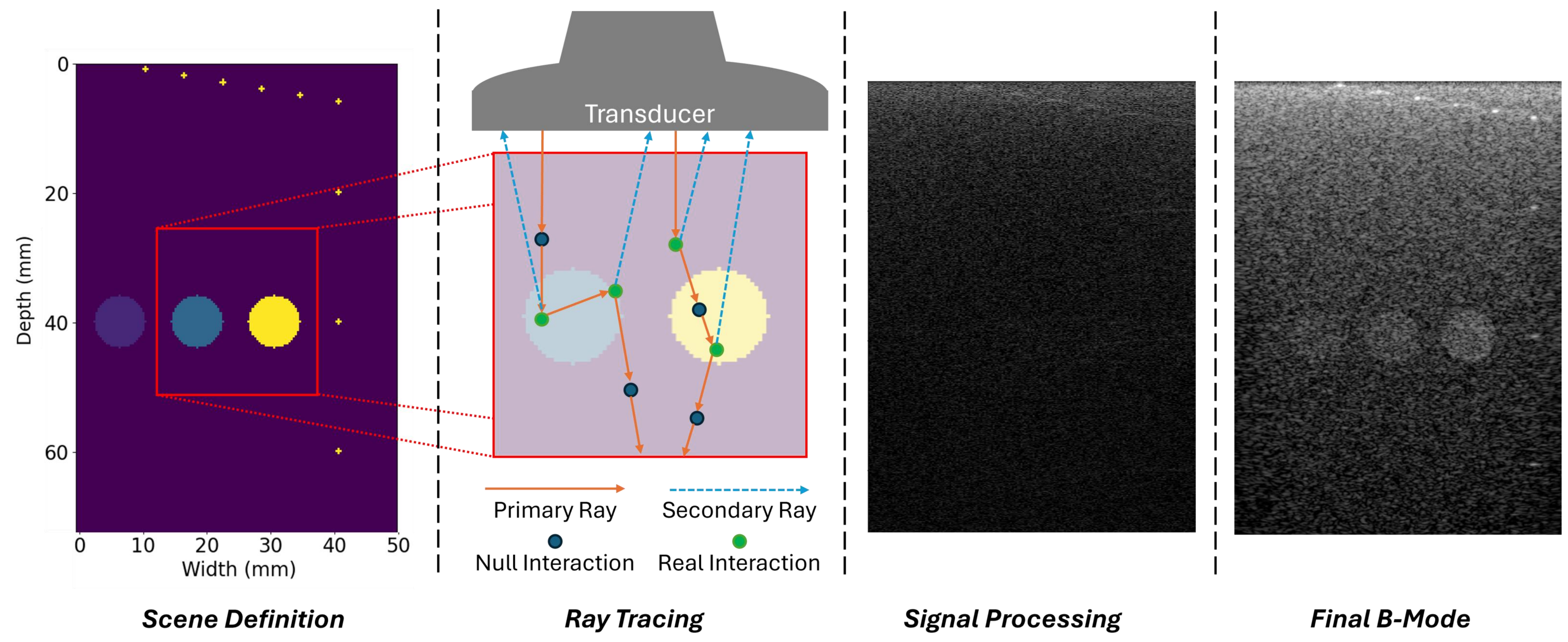
CONCLUSION

- UltraScatter approximates wave propagation using parallel ray tracing, enabling **clinical-like B-mode imaging** at a fraction of the cost of frequency-domain solvers.
- UltraScatter is **modular** and can be easily extended for elevational focusing, heterogeneous speed of sound, etc.
- **Future work**: Speckle coherence during probe translation, full 3-D transmit/receive, refraction & harmonic generation.

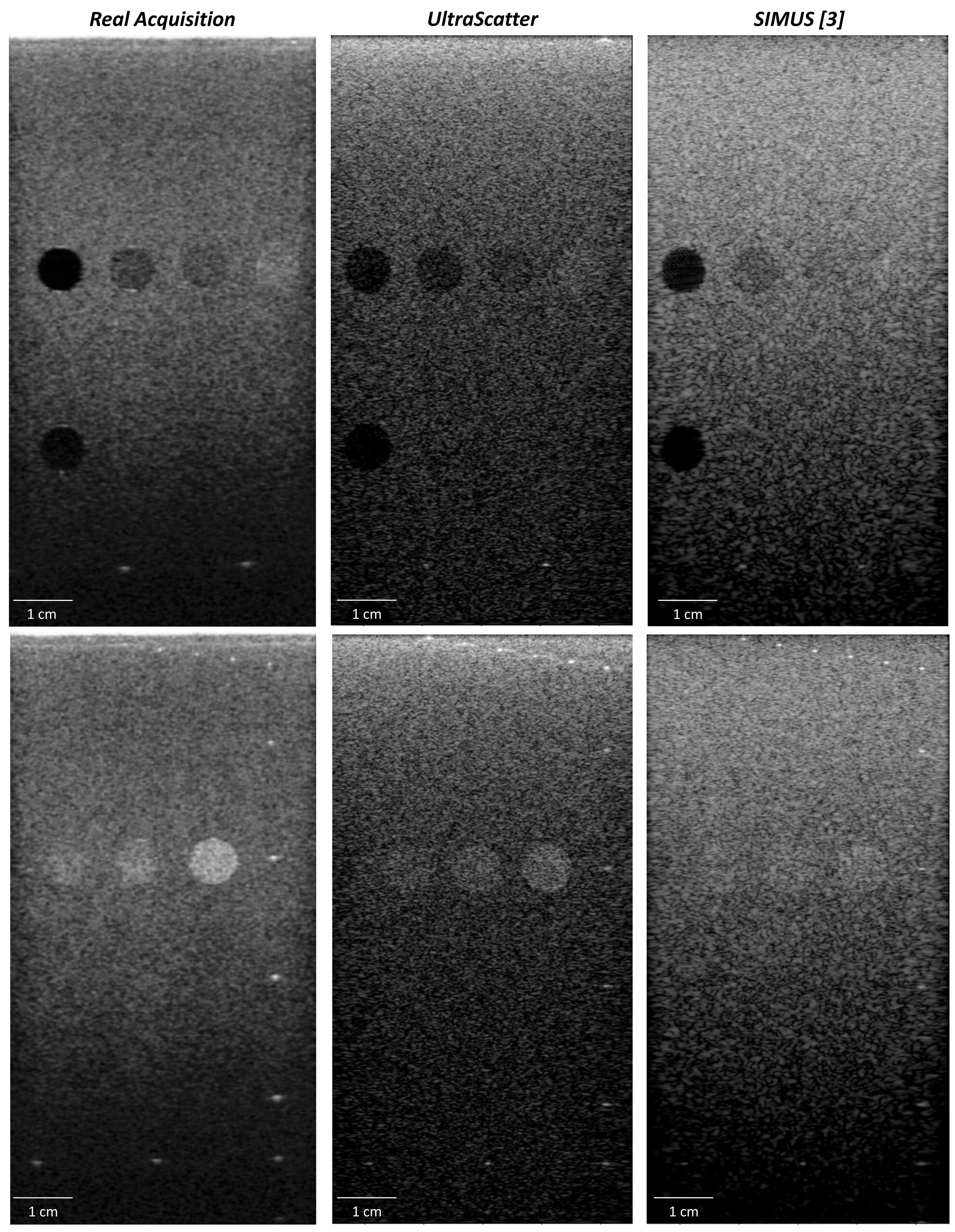
Idea & Implementation

- Physics-Based Rendering (PBR) has achieved remarkable image fidelity and advanced simulators (such as Mitsuba 3 [4]) facilitate synthetic image generation
- By using a **Monte-Carlo** ray tracing approach multiple nested integrals can be solved computationally efficiently
- We are building on top of **Mitsuba 3 [4]** – a modular framework that allows us to add modules (e.g. transducer) but also customize and adapt existing software (e.g. integrator)

Pipeline



Results



REFERENCES

[1] B. E. Treeby and B. T. Cox, "k-wave: Matlab toolbox for the simulationand reconstruction of photoacoustic wave fields," Journal of biomedicaloptics, vol. 15, no. 2, pp. 021 314–021 314, 2010.
[2] J. A. Jensen, "A model for the propagation and scattering of ultrasoundin tissue," The Journal of the Acoustical Society of America, vol. 89,no. 1, pp. 182–190, 1991.
[3] D. Garcia, "Simus: An open-source simulator for medical ultrasoundimaging. part i: Theory & examples," Computer Methods and Programsin Biomedicine, vol. 218, p. 106726, 2022.
[4] W. Jakob, S. Speierer, N. Roussel, M. Nimier-David, D. Vicini, T. Zelt-ner, B. Nicolet, M. Crespo, V. Leroy, and Z. Zhang, "Mitsuba 3renderer," 2022, https://mitsuba-renderer.org.
[5] E. Woodcock, T. Murphy, P. Hemmings, and S. Longworth, "Techniquesused in the gem code for monte carlo neutronics calculations in reactorsand other systems of complex geometry," in Proc. Conf. Applicationsof Computing Methods to Reactor Problems, vol. 557, no. 2. ArgonneNational Laboratory, 1965.