Real Time Phase Unwrapping for Adaptive Optics Wavefront Sensors

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Abstract:

Advanced wavefront sensors (WFS) are essential for enabling new science cases for telescopes that utilize adaptive optics (AO). While complex WFS can achieve extraordinary sensitivity, comparable to the photon-noise limit, they typically measure the wrapped phase of the reconstructed wavefront, and real-time systems must be capable of unwrapping the electric field phase function within 1 μs or faster. Using simulations of atmospheric turbulence following a Kolmogorov spectrum, we profile the latency and the wavefront error RMS of eight different phase unwrapping methods. Our findings indicate that Barchers' version of the LSPV unwrapping method (RMS: 0.0774 waves, time: 5.01 μs) and the parallelized version of the fast 2D unwrapping method (RMS: 7.26e-16 waves, time: 3.77 μs) show the most promising results. These methods significantly reduce latency and error, making them viable for real-time applications. Furthermore, in addition to parallelization, these algorithms can be accelerated even further using customized, massively parallel hardware such as GPUs and FPGAs. This capability allows for faster and better unwrappers that are applicable, and promising improvement, in any complex WFS that measures a wrapped phase.

Introduction:

Phase wrapping occurs when phase values measured between -π and π are mapped back into this range, causing discontinuities or "jumps" in the data. This happens because phase measurements are inherently periodic and constrained to a single cycle of 2π, leading to values outside this range being wrapped back within it. These jumps obscure the true continuous phase information, complicating analysis and data interpretation. Phase unwrapping algorithms address this issue by identifying and correcting these 2π discontinuities, thus reconstructing the true phase. Many WFS's require phase unwrapping. Since the WFS sets how fast the AO system can operate, and the readily available unwrapping algorithms are too slow to unwrap phases accurately in real time, new methods must be developed that increase speed without sacrificing accuracy.

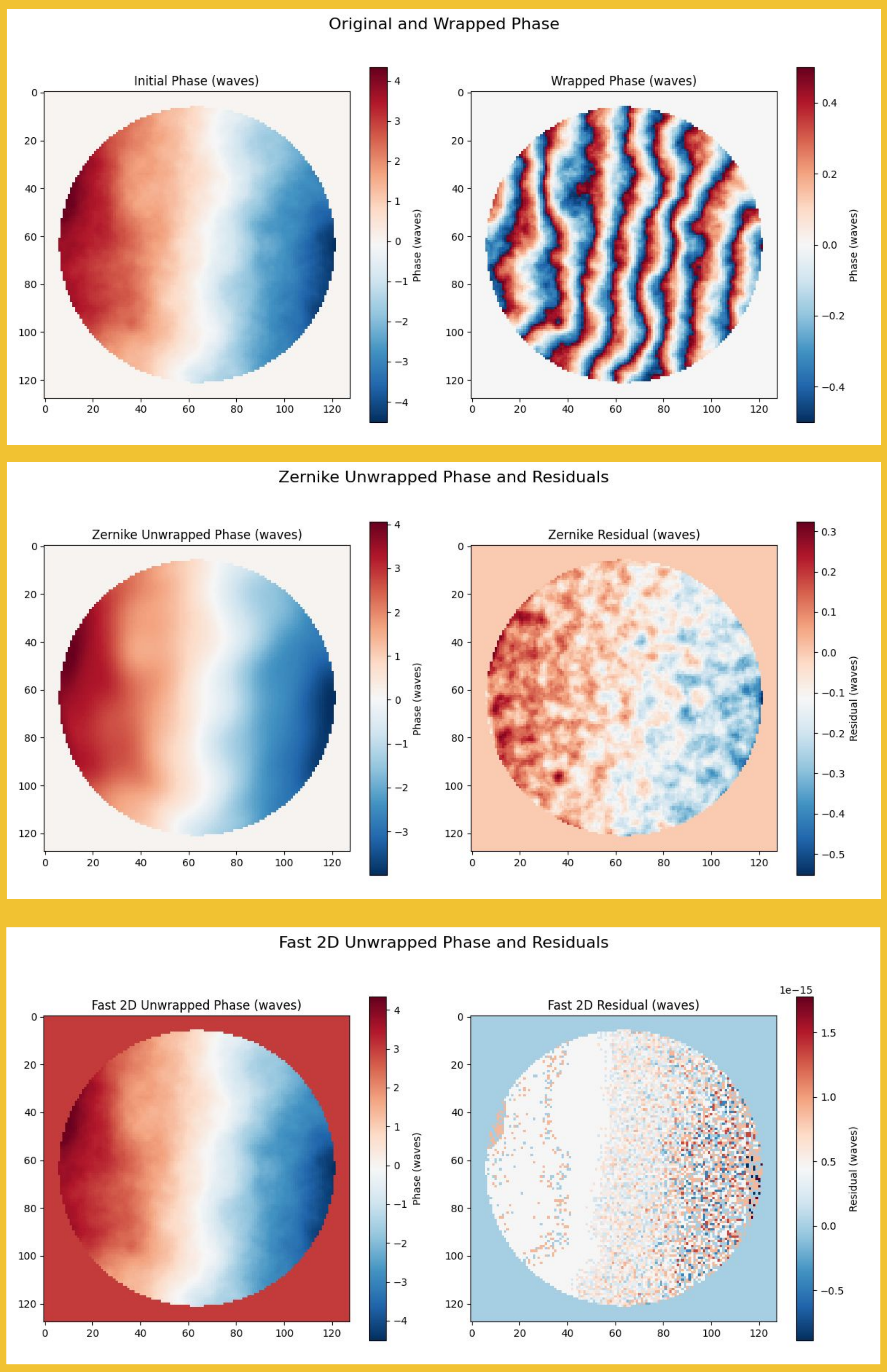

Figure 1: Simulated Kolmogorov phase before wrapping, after wrapping, and unwrapped using the Zernike and Fast 2D algorithms.

Results and Discussion:

In this study we evaluated the WFE RMS (wavefront error Root Mean Square) in waves and time in microseconds for the following phase unwrapping algorithms: Fast2D, Parallelized Fast2D, Zernike, Zernike with PyTorch, LSPV, DFT, FFT, and Barchers. The mean, median, and standard deviation of the RMS and time for each method are summarized in the table below:

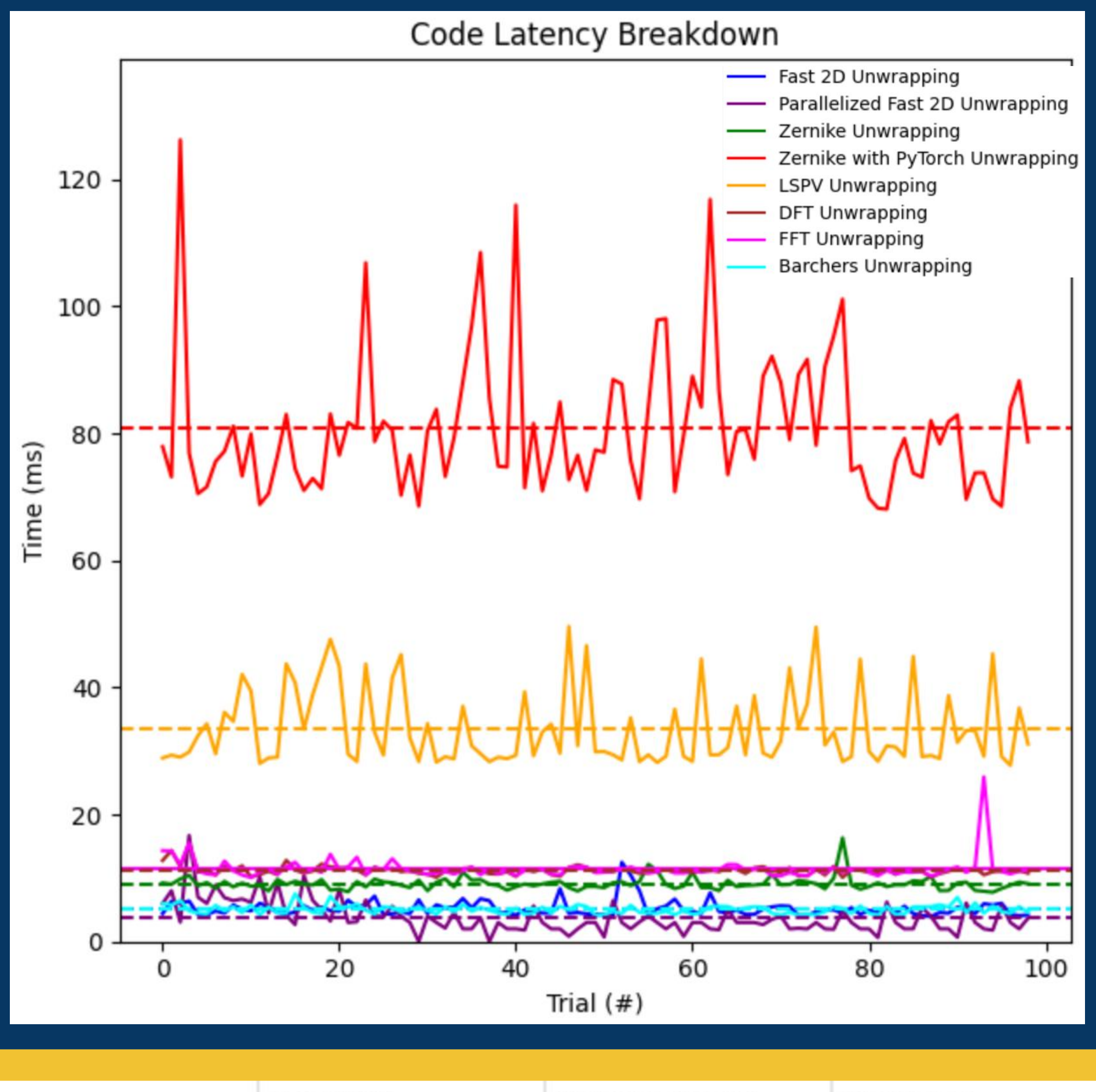

Figure 2 & Table 1:

The figure presents a comprehensive breakdown of latency times for various phase unwrapping methods used in the study. Notably, the Fast2D method demonstrates exceptional performance with an average processing time of 5.78 μs, highlighting its efficiency for real-time applications. The parallelized version of Fast2D further reduces latency to 3.77 μs on average, indicating significant speed enhancement without compromising accuracy. In contrast, methods like the Zernike with PyTorch (85.97 μs), and LSPV (31.91 μs), exhibit higher processing times, influencing their applicability in latency-sensitive systems.

	Fast2D	Parallelized	Zernike	Zernike w/Pytorch	LSPV	DFT	FFT	Barchers
Mean (μs)	5.78	3.77	9.36	85.97	31.91	11.32	11.4	5.01
Median (μs)	5.37	3	9.02	83.45	28.7	11.08	11.22	4.89
Std Dev (μs)	2.15	2.52	1.34	11.23	6.83	1.17	1.01	0.58

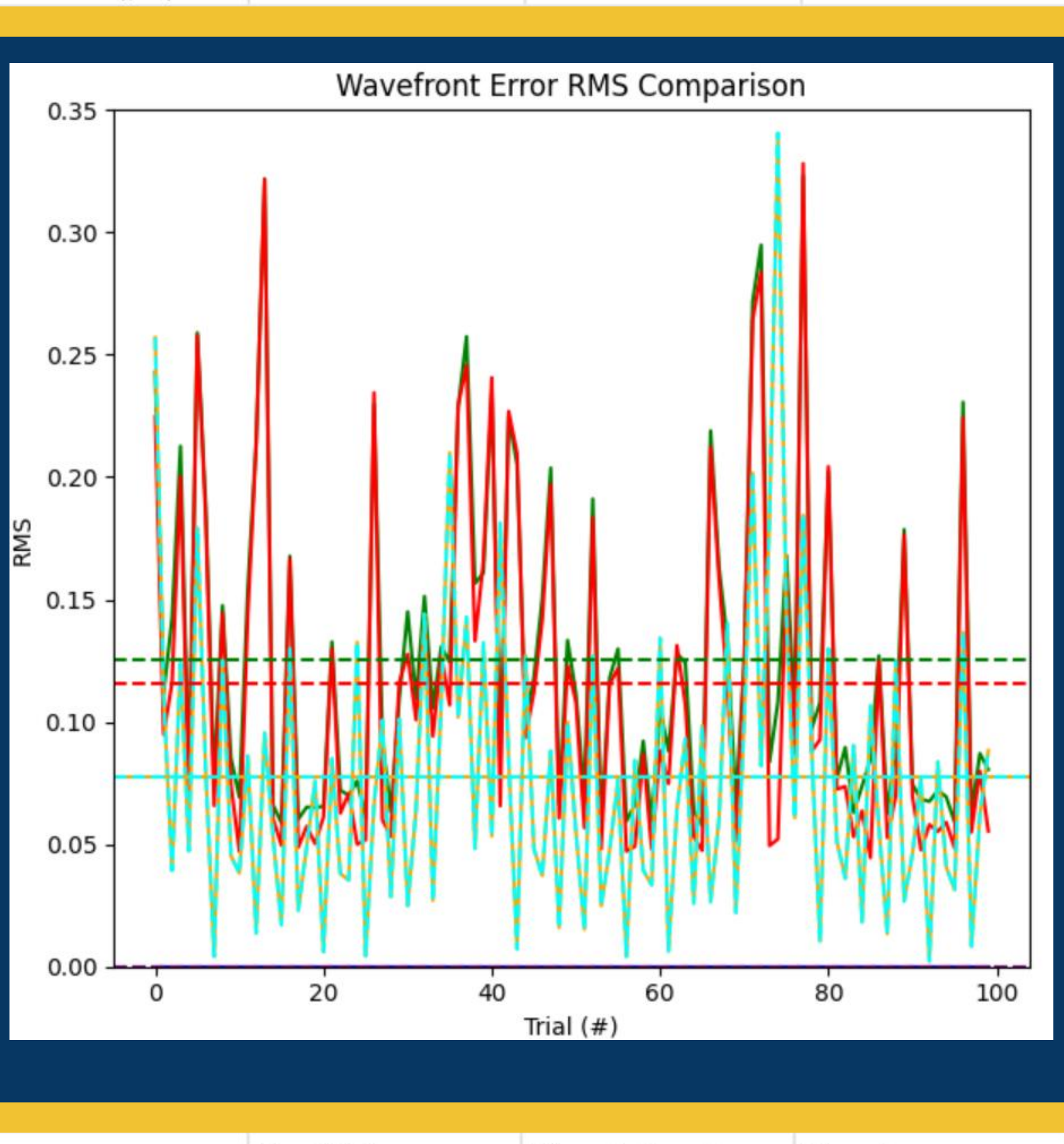

Figure 3 & Table 2:

This figure illustrates the RMS values across different phase unwrapping methods. The Fast2D method stands out with remarkably low RMS errors (mean: 7.26E-17 for standard and 7.26E-16 for parallelized), underscoring its high accuracy in phase unwrapping tasks. While the Zernike (mean RMS error: 1.26E-01) and Zernike with PyTorch (mean RMS error: 1.15E-01) unwrapping algorithms have a higher RMS, it is still within reason, therefore they should be further explored.

	Fast2D	Parallelized	Zernike	Zernike w/Pytorch	LSPV	DFT	FFT	Barchers
Mean (waves)	7.26E-17	7.26E-16	1.26E-01	1.15E-01	7.74E-02	6.12E-01	6.12E-01	7.74E-02
Median (waves)	6.24E-17	5.94E-16	1.07E-01	9.31E-02	6.42E-02	3.84E-16	3.84E-16	6.42E-02
Std Dev (waves)	4.23E-17	6.10E-16	6.60E-02	7.00E-02	5.94E-02	8.07E-01	8.07E-01	5.94E-02

Conclusion:

Overall, the Fast2D and the newly developed parallelized version of it stand out for their accuracy and speed, with the parallelized Fast2D method being particularly advantageous for real-time applications. The LSPV and Barchers methods also offer a good balance of speed and precision, making them viable for adaptive optics systems. Future work will focus on optimizing these methods for real-time implementation and exploring hardware acceleration to further reduce latency and improve performance.

References:

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