Northwestern/SLAC Simulation Update

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On behalf of NU team (Yiping Wang, Arthur Perce, Zilin Chen, Jonah Glick, Tim Kovachy) and SLAC team (Sean Gasiorowski, Michael Kagan, Ariel Schwartzman, Sanha Cheong, Murtaza Safdari, Maxime Vandegar, Omer Rochman)

MAGIS-100 Science and Simulation Meeting
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Overview

- Northwestern creating AI simulators (semiclassical, quantum, adding LMT/finite pulse effects to each)
- Also have beam propagation simulator for generating realistic aberrated beam profiles
- SLAC augmenting simulations – making them differentiable to be able to fit input parameters
- SLAC also considering how to speed things up with ML

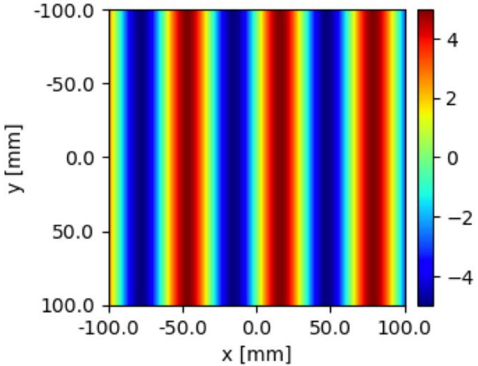
Point source interferometry

- PSI used to measure laser wavefront aberrations *in situ*
- Semiclassical approximation is sufficient because PSI uses "hot" atom cloud
- Current work toward using 3D reconstructed image to fit initial beam aberrations
  - Parameterization of beam aberrations using Zernike polynomials and spatial frequencies

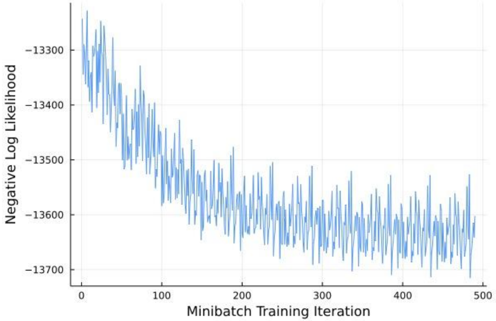
Slide from Sean Gasiorowski

Laser wavefront fitting

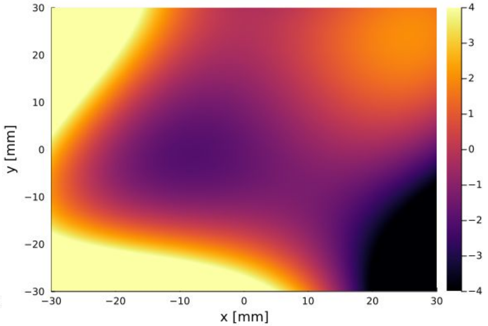
- Update at beginning of August
- Fitting wavefront via gradient descent with differentiable version of point-source interferometry simulator
  - "Northwestern builds simulator, SLAC augments it + does ML"
- Current focus: expand to more complicated wavefronts
  - Zernike polynomial parametrization:
    - Fit up to ~40-50 parameters!
  - If need more flexibility: maybe neural network
- Other projects: incorporate a camera system, reduce fitting time



Sinusoid wavefront (last time)



Loss for 10 parameter fit.
"Noise" due to batched training



Example Zernike wavefront

MAGIS science simulation

- Want to capture quantum corrections, semiclassical limit might not be sufficient
- Standard SE solver is the “split-step” method
  - Separates linear and nonlinear parts of equation (applying Baker–Campbell–Hausdorff formula)
  - Error from solving each separately is order dt^2 — small step sizes
  - Computationally expensive

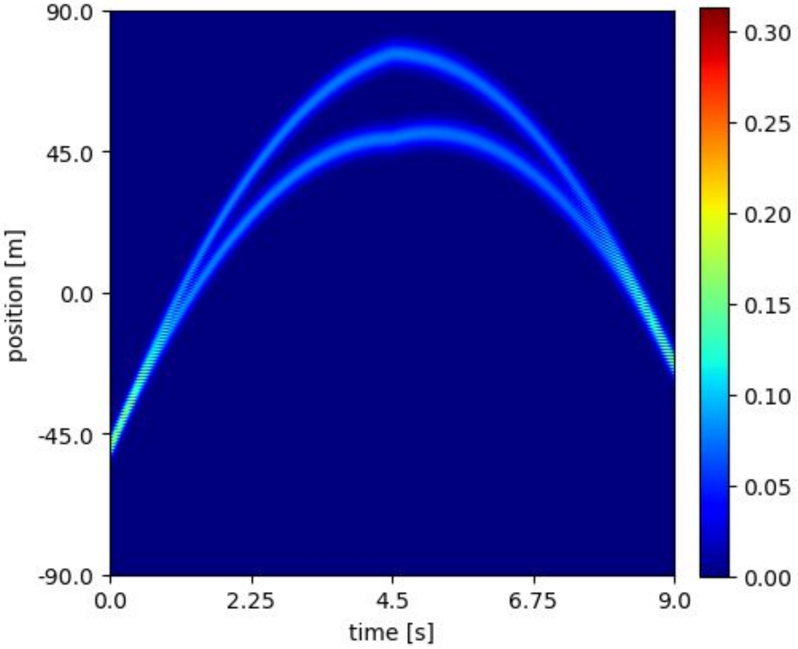
MAGIS science simulation *with ML*

- Can make the numerical SE solver differentiable to fit input gravity gradient terms
- If numerical solver is too slow, can generate a large amount of data once to train ML model to solve faster with new inputs
  - PINNs (physics-informed neural networks)
  - Other ML approaches use CNN/RNN architecture to solve PDEs directly

Current numerical SE solver progress

- Quantify agreement of 1D version with analytical result

- Next steps:
  - 3D version
  - Check clock mode
  - Evaluate speed/step size needed when using physical parameters (currently $\hbar$=1, etc.)
  - Determine best scheme for pulsing (separate pulse evolution or integrated into split-step)
  - Add finite pulses / LMT



Illustrative example of split step result in Bragg mode

Next steps

- Incorporate finite pulse and LMT to PSI differentiable simulation
- Generalize split-step solver to 3D
- Add finite pulse and LMT to split-step
- Benchmark split-step simulation
  - Is the numerical solver too computationally expensive to use for simulating a large amount of data?

Other open questions

- Will ML methods meet precision requirements for full MAGIS-100 simulation?
- Generally, what are our requirements as far as speed for both the PSI simulation and MAGIS science run simulation?
- What functionality is desired from the simulators?
  - Add predefined time-dependent gravity gradient signal
  - What else??