Deep-Turbulence Simulation in a Scaled-Laboratory Environment Using Five Phase-Only Spatial Light Modulators

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Diagram credit: Jason Schmidt at MZA

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Why is beam control difficult? BLUF: Extended, non-cooperative targets

Things to consider:
Low SNRs — lack of photons
SWaP — size, weight, and power
Latency — can you keep up?

We need to address all aspects of the problem
The branch-point problem is a three part problem in beam-control applications.

**Branch-point problem:**

- Actual phase
- Least squares reconstructed phase
- Hidden phase

Ref: AFIT thesis work of Venema, Pellizzari, Spencer, and Steinbock

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**Part 1:** First we need to sense the “Hidden” phase

- Laser
- Receiver
- Local Oscillator
- FPA

**Part 2:** Then we need to compensate for the associated branch cuts

- Continuous face-sheet DM

**Part 3:** Then we need to separate the branch points induced by atmospheric scintillation from those induced by target speckle
The anisoplanatization problem requires that we develop a volumetric solution.

A volumetric solution requires that we sense the complex optical field – Digital Holography.
To address the deep-turbulence problem, AFRL/RD proposed the following scaled-laboratory research:

**Such research has utility to all the services:** Army, Navy, and the AF
AFRL/RD teamed with Guidestar Optical Systems to develop their scaled-laboratory approach

LcSLM Turbulence Module

The developed atmospheric turbulence simulator (ATS) uses five modules in series to simulate deep turbulence
The ATS was delivered in late October (FY 15) with a digital holography WFS
The completed GUI for the ATS and digital holography WFS – open-loop demo

SLM 5 commanded to “flat”

LS estimated wave-front
The completed GUI for the ATS and digital holography WFS – closed-loop demo

SLM 5 commanded to phase conjugate

LS estimated wave-front
Scaled-laboratory validation for $D/r_0 = 10$

Experimental structure functions behave as expected.
Moving forward, ARFL/RD will compare three different WFS architectures in scaled time in FY 16.

Shack Hartmann Vs. Self-referencing interferometer Vs. Digital holography

With cooperative-point and non-cooperative-extended beacons & traditional-least-squares and branch-point-tolerant reconstructors

Simulated pupil plane Rytov 0.8:

Irradiance

Wrapped Phase

Atmospheric Turbulence Simulator (ATS)
AFIT has developed a branch point tolerant reconstructor that will be tested with the ATS. Estimate the complex optical field using SRI. Perform metric-based optimization. Compensate with a continuous face-sheet DM. Hidden phase with different phase shifts, $h$. Ref: MS Thesis of Pellizzari.
NPS has developed a branch point tolerant reconstructor that will also be tested with the ATS.

Estimate the wave-front slopes

Perform metric-based optimization...

\[ J = - \sum_{i=1}^{m} \sum_{j=1}^{m} \left[ a_{(i,j)} \cos \left( 2s_{x(i,j)} h - \Delta \phi_{x(i,j)} \right) + a_{(i,j)} \cos \left( 2s_{y(i,j)} h - \Delta \phi_{y(i,j)} \right) \right] \]

...through gradient decent of cost function

\[ \hat{\phi}_{(i,j)}(k + 1) = \hat{\phi}_{(i,j)}(k) - \alpha \nabla J_{(i,j)}(k) \]

Compensate with a continuous face-sheet DM

POC: Prof Jae Jun Kim
In FY 17, AFRL/RD will test the winning WFS architecture from FY 16 in real time.

Things to consider:
- Radiometry — throughput of ATS
- Polarization — BILL/SHEL isolation
- Wavelengths — chromatic aberrations
- Power thresholds — pulsed operation
- Repeatability — anomalies in the results
- Cost — needs to be affordable

Goal: Enable TRL 5 field demos in FY18

Simulated pupil plane
Rytov 0.8:

Transmissive phase screens are less traceable to system-level demos

AFRL/RD needs to build an all-reflective, real-time ATS for TRL 4 laboratory demos in deep turbulence
Nominal layout for the Phasor Laboratory:

- Modules 1-5 provide ~50' propagation path

- Scaled-time computer space
  - Laser, speckle cell, and scoring camera
  - SH WFS
  - tSRI and DH WFS

- Real-time computer space
  - Real-time ATS
  - Laser, speckle cell, and scoring camera

- Reflective phase plates
  - SH WFS
  - tSRI and DH WFS
In summary, AFRL/RD will use the Phasor Laboratory for deep-turbulence experiments

In FY 16, AFRL/RDLTS will implement a real-time ATS into the Phasor Laboratory

Enables deep-turbulence technology development

Original slide developed by Jason Schmidt at MZA