Anisoplanatic Wavefront Error Estimation using Coherent Imaging

Rick Kendrick¹, Joe Marron², Bob Benson¹

¹Lockheed Martin Advanced Technology Center
Palo Alto, California

²Lockheed Martin Coherent Technologies
Louisville, Colorado

15th Coherent Laser Radar Conference
June 2009
Previous CLRC Papers

14th Coherent Laser Radar Conference

Experiments with Multi-Aperture Three-Dimensional Coherent Imaging

J.E. Mason, K.A. Anderson, R.L. Kendrick, T.S. Kubo, J.C. Marron*, T. Zhao
Lockheed Martin Advanced Technology Center
3251 Hanover St.
Palo Alto, CA 94304

Novel Multi-Aperture 3D Imaging Systems

J.C. Marron, R.L. Kendrick*, T. A. Höft, and N. Seldomridge
Lockheed Martin Coherent Technologies
135 South Taylor Ave.
Louisville, CO 80027
Anisoplanatism

Local Oscillator
Agenda

- Bar Target Imaging Experiment
- Data Analysis Process
- Anisoplanatism
- Point Source Array Experiment
- Comparison to closed form calculation
- Depth of focus demonstration
- Summary
Table Mountain Test Range

100 meters

1.2 meter beam height
Sensor Arrangement

Scintec Scintillometer

Active Imager
Typical Scintillometer Reading

Sunny, Cloudless day with Little wind

$Cn^2 = 6.5e^{-13}$
$L = 100$ m
Data analysis steps

16 pupil images

Fringes from LO interference

FFT

Complex Object Information

Calculate Sharpness

\[ \Sigma (\text{Intensity}^2) \]

FFFT

Maximize Sharpness by adding phase estimate (48 Zernikes)

FFT

Final Image

Complex Pupil Function

© 2009 Lockheed Martin Corporation. All Rights Reserved
Set: 1244
\( C_n^2 = 5.11 \times 10^{-13} \)
\( r_0 = 0.0083 \)
Iso patch = 0.0046

Set: 1451
\( C_n^2 = 5.51 \times 10^{-14} \)
\( r_0 = 0.0317 \)
Iso patch = 0.0176

Set: 1544
\( C_n^2 = 6.0 \times 10^{-15} \)
\( r_0 = 0.120 \)
Iso patch = 0.0666

D = 50 mm
Wavelength = 532 nm
16 speckle realizations
Target moved for each realization
**Anisoplanatism**

Set: 1244

\[ C_n^2 = 5.11 \times 10^{-13} \]

\[ r_0 = 0.0083 \]

Iso patch = 0.0046

MTF = 0.26

MTF = 0.43

MTF = 0.61

Region over which the sharpness metric is maximized
Point Source Array

- **Retro Array is on 20 mm centers**
  - 12.7 mm diameter
Point Source Array

Raw Data

Sharpened for one field point

© 2009 Lockheed Martin Corporation. All Rights Reserved
Phase Versus Seeing

• Cosine of the (phase difference )^2

(14:46) 
\[ r_o = 5.6 \text{ mm} \]

(15:28) 
\[ r_o = 51 \text{ mm} \]
Anisoplanatism Versus Seeing

- Time  \( C_n^2 \)  \( r_o \)
- 1446    9.85 E-13    5.6 mm
- 1502    2.20 E-13    13.8 mm
- 1528    2.49 E-14    51.0 mm
- 1540    5.83 E-15    122.0 mm

1446 sharpened over entire image  Phase Map

1540 sharpened over entire image  Phase Map
Predicted phase error as a function of field angle

The phase difference structure function, \( S(r, \theta) \), derived by Fried,* is evaluated in these calculations for a horizontal path (constant \( C_{n}^{2} \)). The separation of two points in the aperture is denoted by \( r \), and \( \theta \) is the angular separation between point sources. Denoting by \( \Delta \Phi \) the difference in phase between the two sources after the mean value is removed, the aperture-average square of the phase difference, ensemble-averaged, is given by

\[
\langle \delta \Phi^2 \rangle = \frac{1}{\pi} \int_{0}^{1} x S(x, \theta) MTF(x) \, dx 
\]

[1]

\[ MTF(x) = \left( \frac{2}{\pi} \right) \left[ \cos^{-1}(x) - x \sqrt{1 - x^2} \right], \quad 0 \leq x \leq 1 \]

[2]

In using eq. [1] we have neglected a weak dependence of \( S \) on azimuth within the aperture. When \( D/r_{o} \) is not large, eq.[1] predicts mean-square phase differences that can be significantly smaller than the simple expression \((\theta/\theta_{iso})^{5/3}\) which is appropriate for very large \( D/r_{o} \).

**Anisoplanatism Experiment vs. Theory**

Aperture-average of the phase difference at points in the aperture for varying seeing conditions.

The error bars indicate the one sigma variability in the data. Note that the variability is much larger for large values of $C_n^2$ as expected.
Depth of Focus Demonstration

-3 Waves of Focus

-2

-1 Best Focus at ~700 meters

0

1

2

3

Corrected image

3 waves corresponds to about a 600 meter range shift

The Jeep is ~ 700 meters
The stand is ~ 100 meters
The beam went through the stand about where the bar target is shown
Summary

• Reasonable agreement between experiment and theory.
• This work continues at longer ranges and with more severe atmospheric turbulence.
THANK YOU