Estimating r_0 with a Differential Image Motion Monitoring System (DIMMS)

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Outline

The Fried Parameter, r_0

- What it is a measure of
- Why it’s important for field testing of laser systems
- How to determine r_0

The Differential Image Motion Monitoring System (DIMMS)

- DIMMS field test results
- Accuracy, error bounds, and relation to r0—what is “truth?”
- Dealing with signal fades
- How “real-time” does the measurement need to be?

Conclusions

The Fried Parameter, r_0

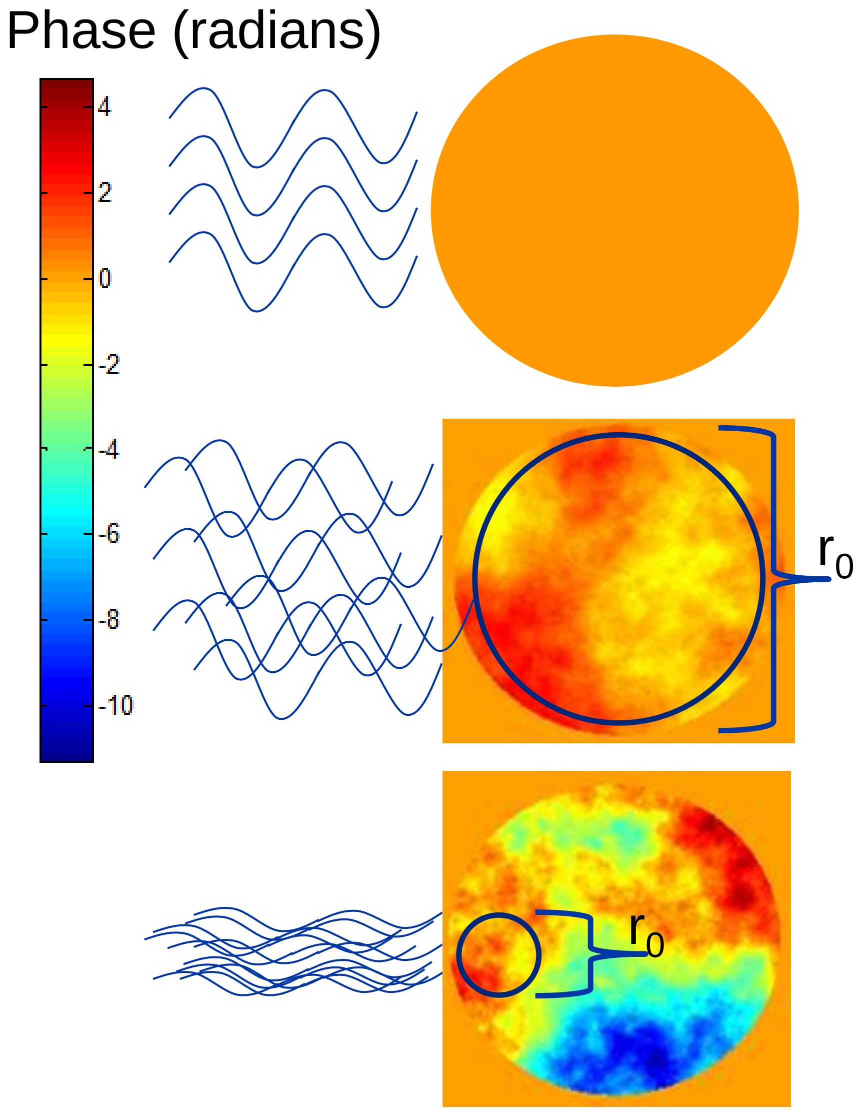
The Fried Parameter specifies “seeing conditions” for astronomical observing

Also known as the Coherence Diameter, it is a measure of the quality of optical transmission through the atmosphere as a function of random differences in the refractive index along the optical path

By definition, it is the diameter of a circular area over which the atmosphere induces a 1-radian RMS wavefront error (tilt-corrected) on a collimated beam of light at a particular wavelength, λ

r_0 is a function of wavelength. If the wavelength is not specified, it is assumed to be 500 nm. Adjusting r_0 from one wavelength to another, it varies by a $\lambda^{6/5}$ relationship

Illustration of Coherence Diameter



No distortion, zero wavefront error (Phase is the same everywhere)

Some distortion, RMS of wavefront error is 1 radian over circular area with diameter d, $r_0 = d$

More distortion, RMS of wavefront error is 1 radian over a smaller circular area with diameter d, r_0 is smaller, seeing is worse

Field Testing of Laser Systems

Highly developmental systems rely on many “moving parts”

- Poor beam quality at range can indicate problems anywhere along the optical path, including within the device under test
- Poor seeing conditions along the optical path is one potential contributor to poor beam quality

Validation of system performance and beam quality at range is possible in one of two ways

- “Range in a box” laboratory testing
- At-range field testing

Characterization of the beam path is essential for at-range field testing

- Additional parameters include Rytov number (scintillation), Tyler frequency, and Greenwood frequency
- r_0 is a valuable starting point for quantifying laser system performance

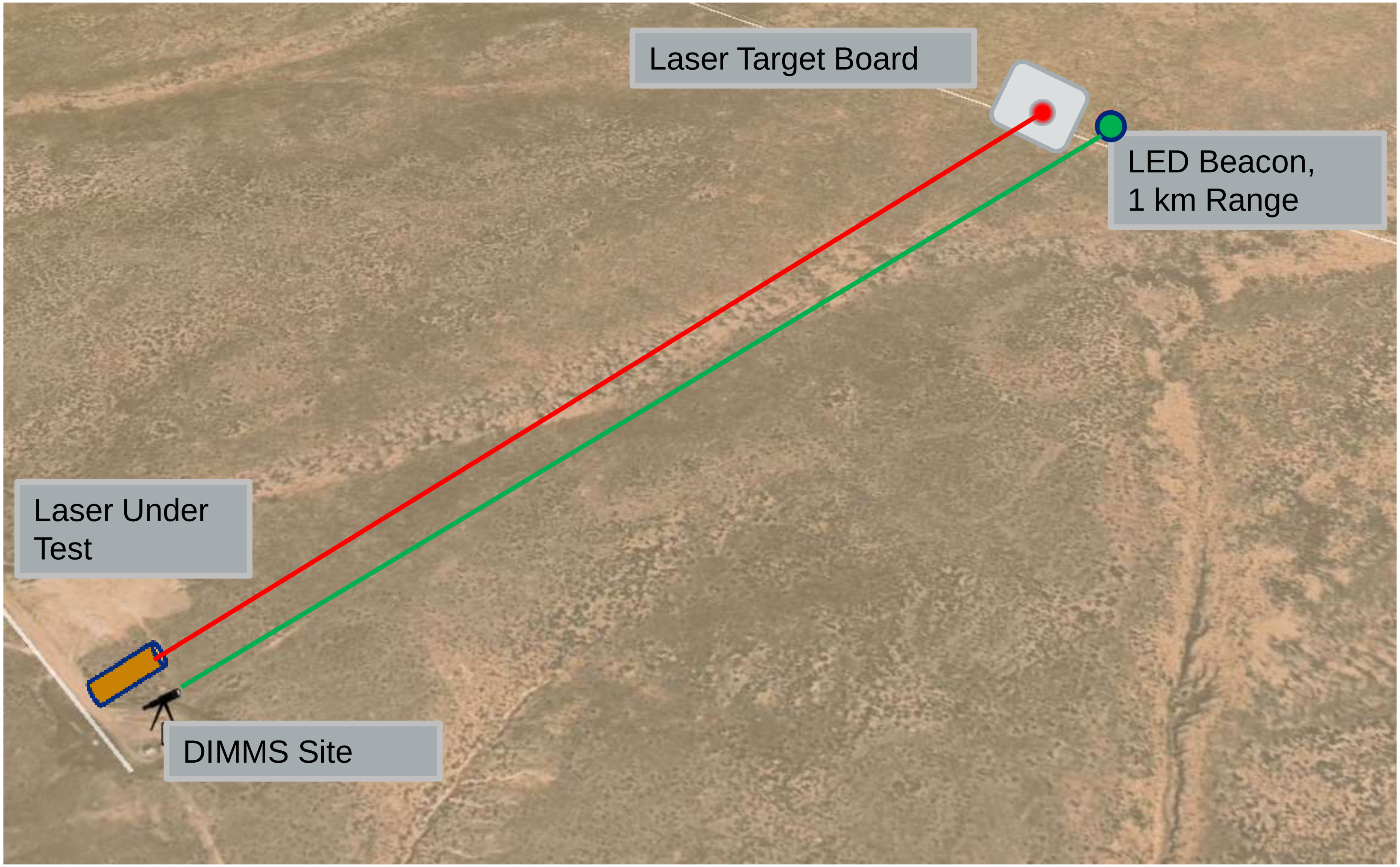
DIMMS as Tested

DIMM Beacon (529 nm)

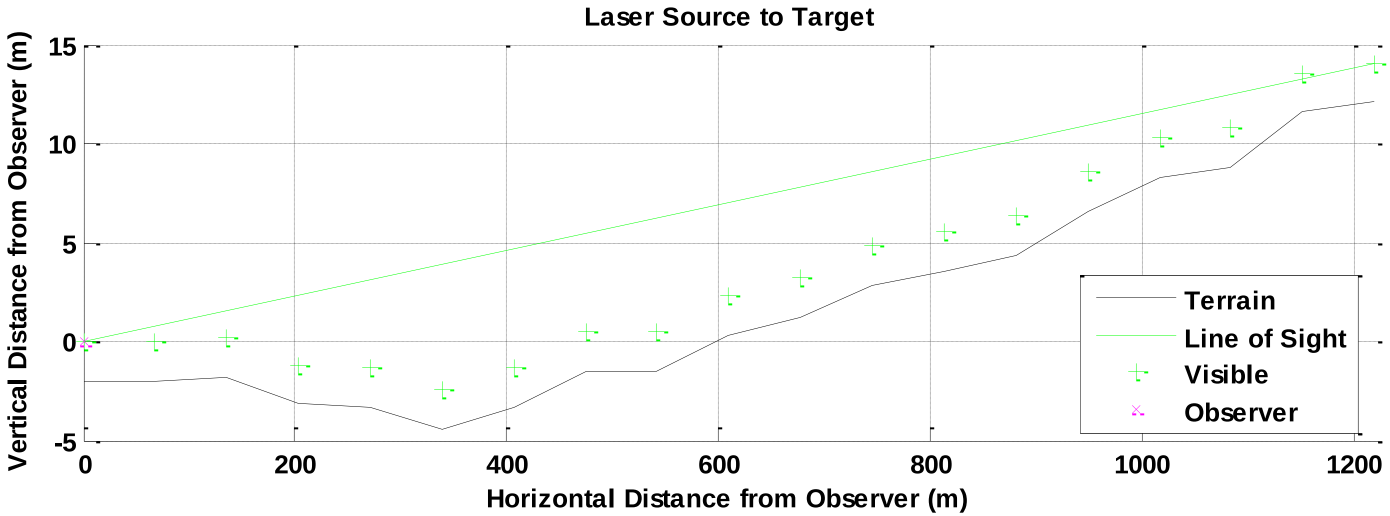
Sub-apertures

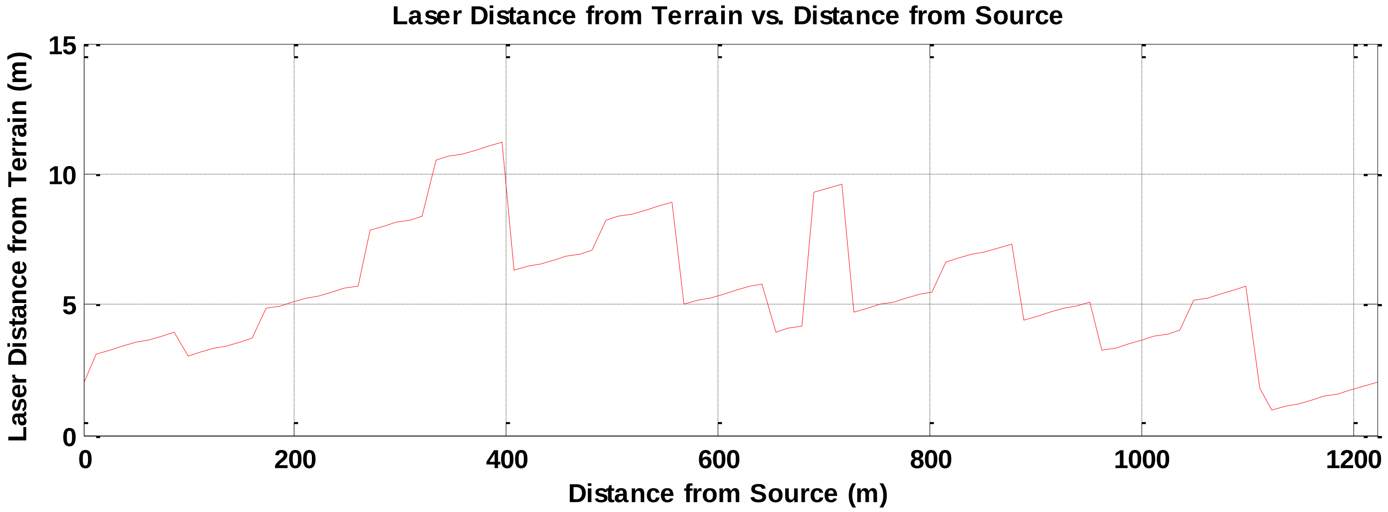
2k x 1k pixel camera

Test Setup for Characterizing r_0 in a Laser System Field Test, 1.2 km Range



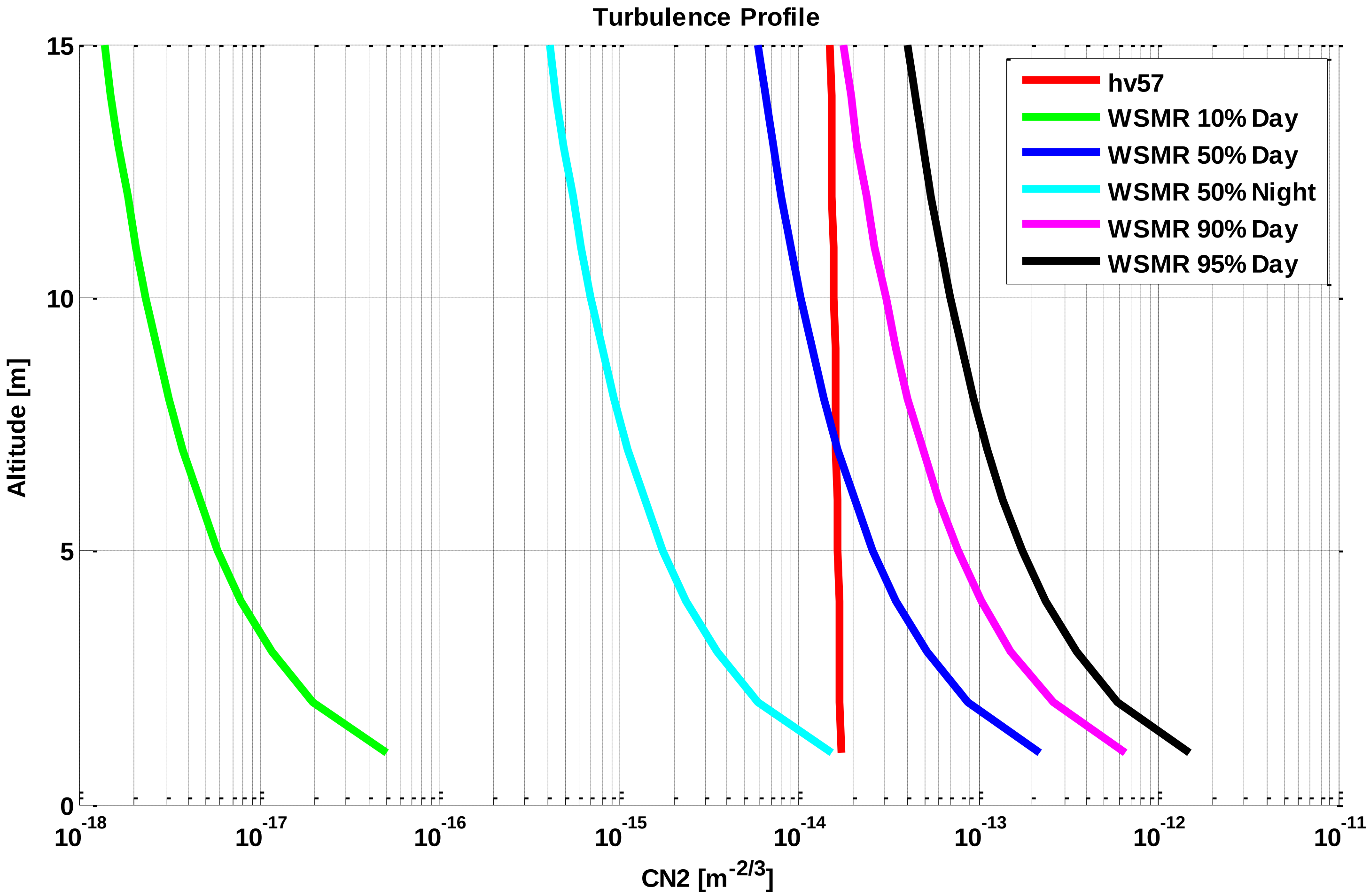
Predicting r_0 via Simulation, Step 1:
Determine Line-of-Sight Height Above Terrain





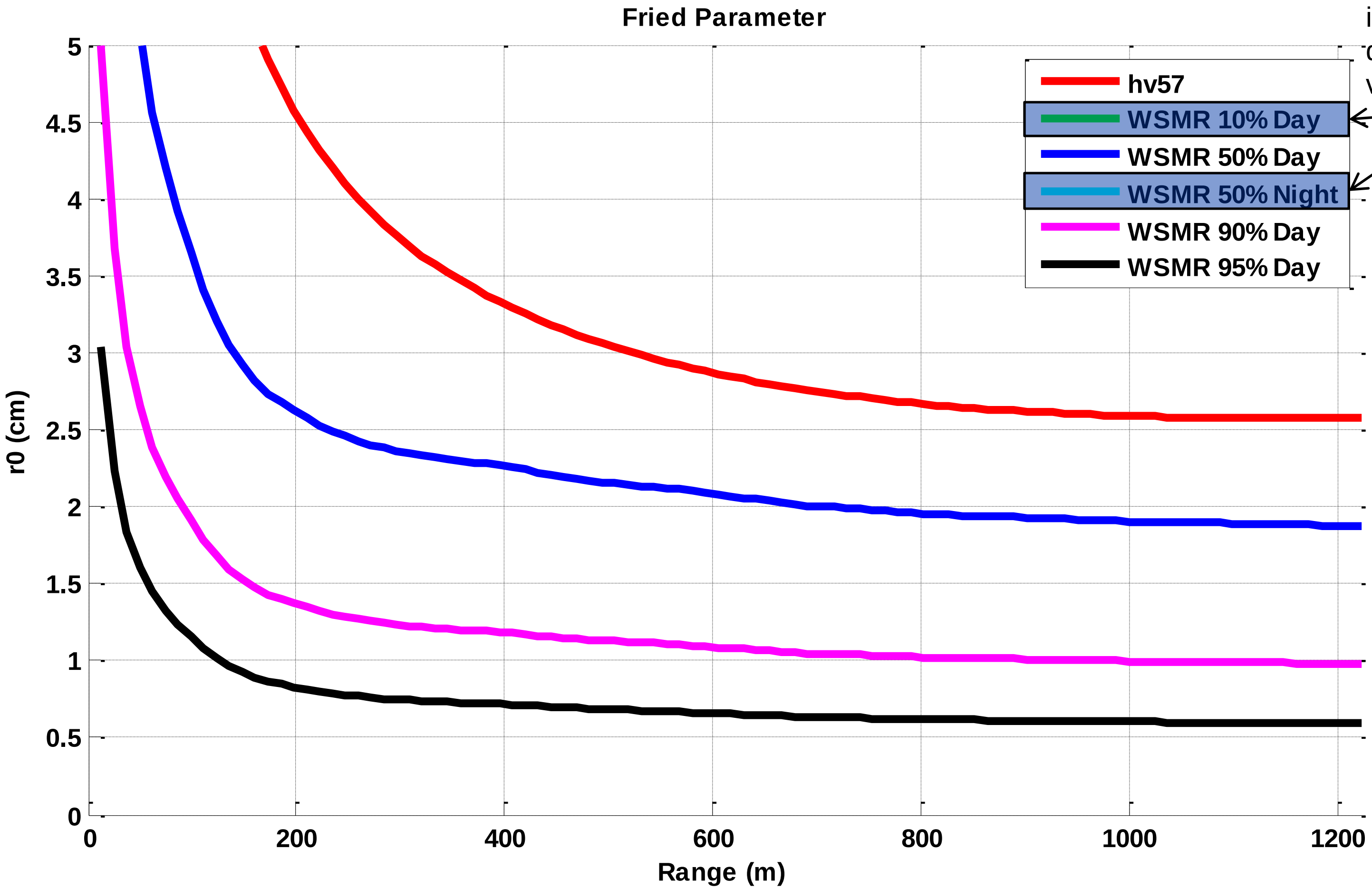
Predicting r_0 via Simulation, Step 2:

Determine Model-Based C_n^2 as a Function of Height and Time of Day



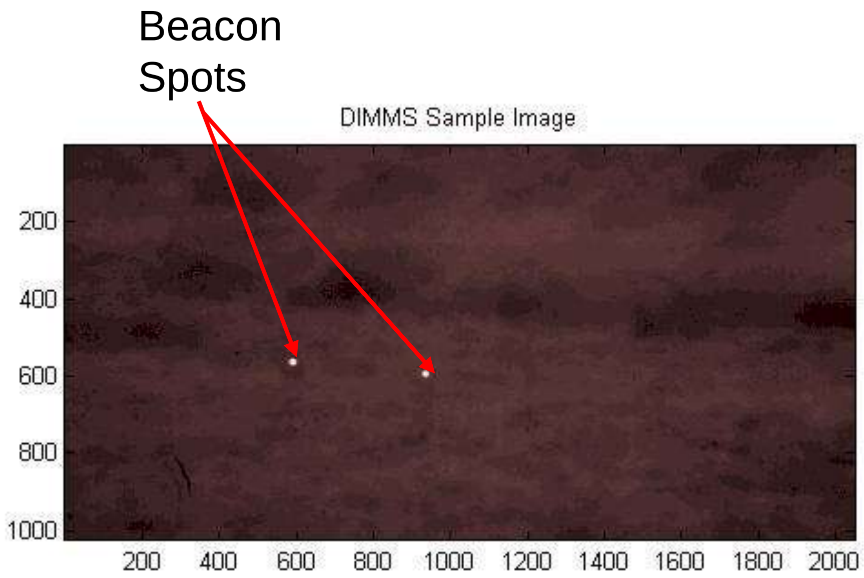
Predicting r_0 via Simulation, Step 3:

Simulate r_0 as a Function of Range Using C_n^2 Profile



Do not show up in current plot due to low C_n^2 values

How r_0 is Determined from DIMMS Measurements



- **Differential motion between the spots indicates optical path distortion, and consequently, r_0**
- **DIMMS performance is characterized for a beam in the lab to establish the noise floor of the DIMMS (motion that is present without any atmospheric distortions)**

Computing the Distance Between Spots

The beacon spot separation distance is then computed by taking the difference between the x & y centroid components

- xdiff = x1 – x2
- ydiff = y1 – y2

We then calculate beacon spot separation by:

$$d = \sqrt{xdiff^2 + ydiff^2}$$

We then compute r_0 based on d (next slide)

Computing r_0 from Differential Motion

DIMMS measures the separation distance of the imaged beacons

The separation distance measured is analyzed via:

$$r0 = \left(\frac{\sigma^2 q^2}{K \lambda^2 d^{-1/3}} \right)^{-3/5}, where$$

σ^2 = variance of the distance between the beacon spots in pixel

q = instantaneous IFOV of a pixel

d = subaperture diameter

λ = beacon wavelength

K = a tilt constant

K depends on:

- Ratio of aperture separation B to aperture diameter d (B/d)
- The direction of image motion: longitudinal (parallel) or transverse (perpendicular)
- Type of tilt considered

Types of Tilt for constant K

The type of tilt considered in earlier DIMMS versions was G-tilt, aka Centroid Tilt, and the K used for longitudinal and transverse directions were, respectively:

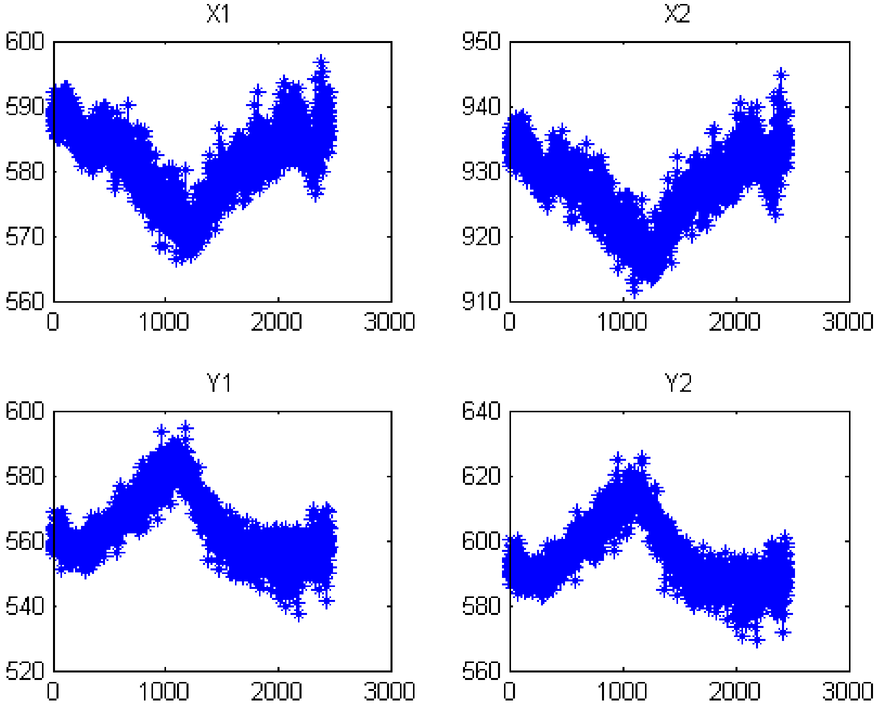
$$K_{lG} = 0.34(1 - 0.57b^{-1/3} - 0.040b^{-7/3})$$
$$K_{tG} = 0.34(1 - 0.855b^{-1/3} - 0.03b^{-7/3})$$

The DIMMS sensor measures Z-Tilt and the K constants are:

$$K_{lG} = 0.364(1 - 0.532b^{-1/3} - 0.024b^{-7/3})$$
$$K_{tG} = 0.34(1 - 0.798b^{-1/3} - 0.018b^{-7/3})$$

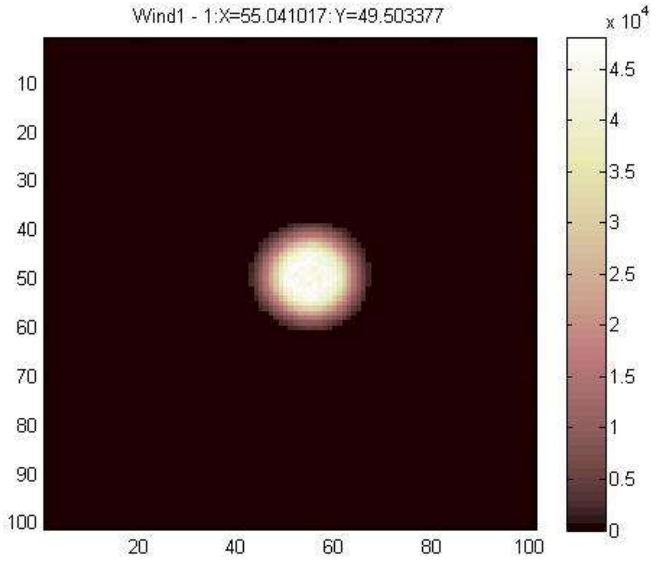
We used the Z-Tilt formula for the DIMMS as tested, but need to review this choice—G-tilt is likely the correct formula (Ref: Safanov, *Experimental Examination of the Type of Tilt Measured by DIMM*, © 2011, Instituto de Astronomía, UNAM - Astronomical Site Testing Data in Chile)

Data Set 1



Centroids of both Spots

- Data taken on 12/14/2013
- Data set starts at 9:00 AM
- Data approx 40 minutes long
- Data taken at ~1Hz
- No image frames are missing
- Minimal aberrations on the spots
- Spots are well defined



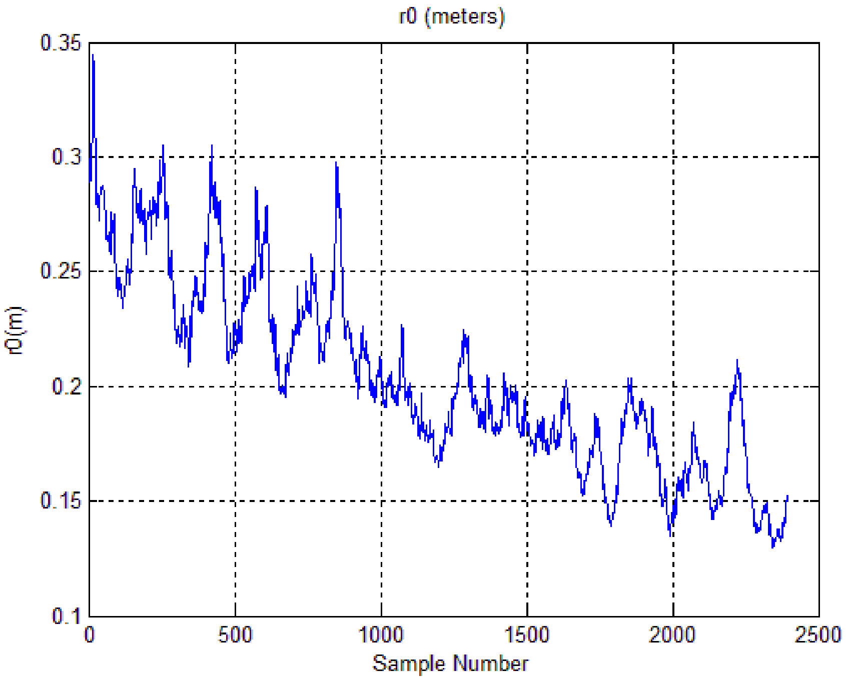
Variance of Separation Distance

We implemented the variance estimate using two different methods:

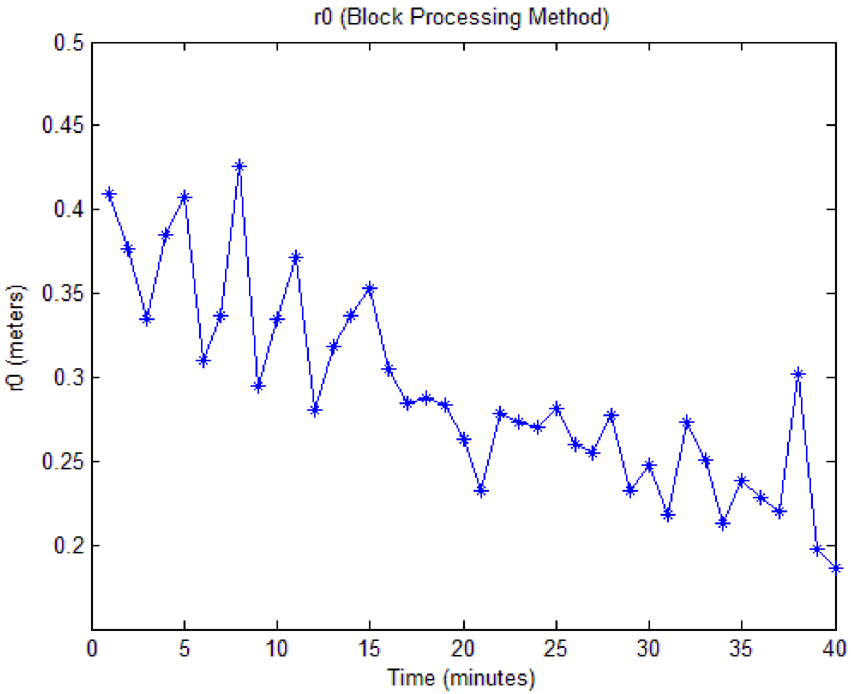
- The first method employs a circular buffer of 60 measurements from which the variance is computed
- The second method computes the variance using a block of measurements. The size of each block is equivalent to a one minute sample period

Comparison of Results Using Two Variance Computation Methods

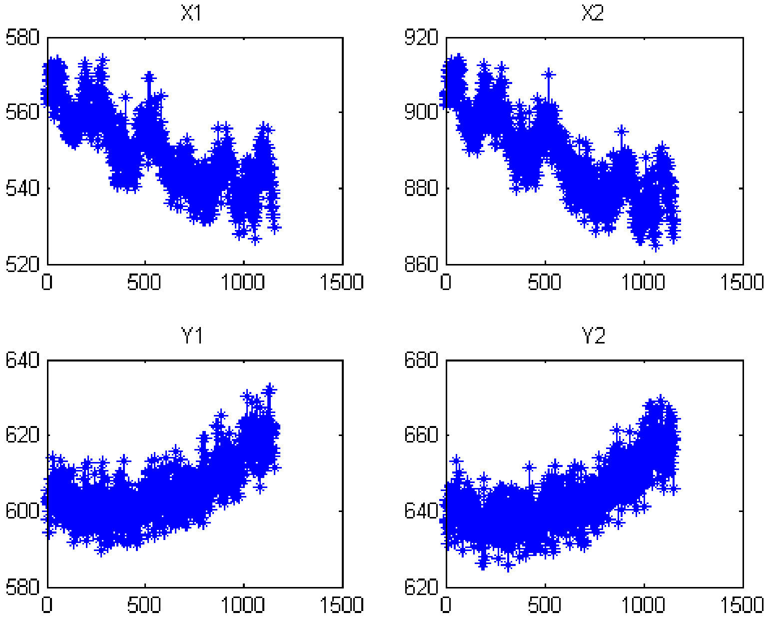
- Centroid variance computed using a circular buffer
- Buffer length set to 60 samples, 1 minute
- Results were higher than predicted by simulation



- Centroid variance computed in 1-minute non-overlapping blocks
- Results appear to follow the circular variance method but at a low sample rate

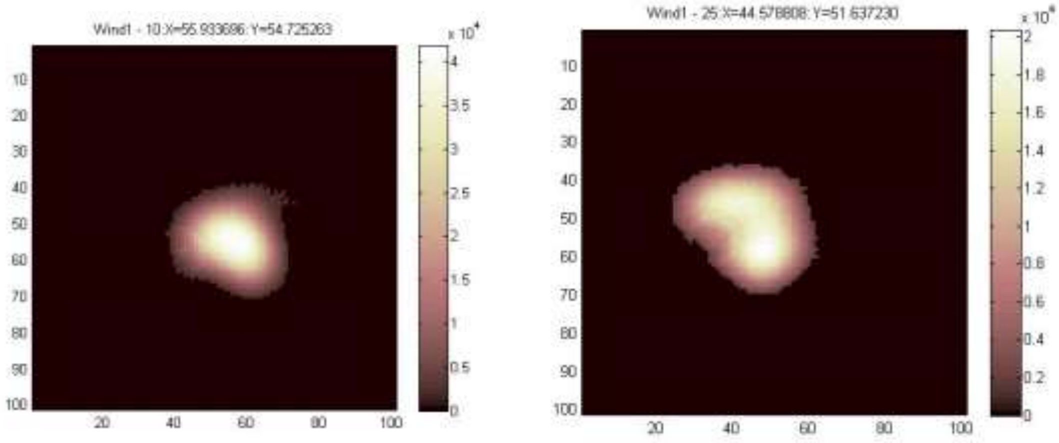


Data Set 2



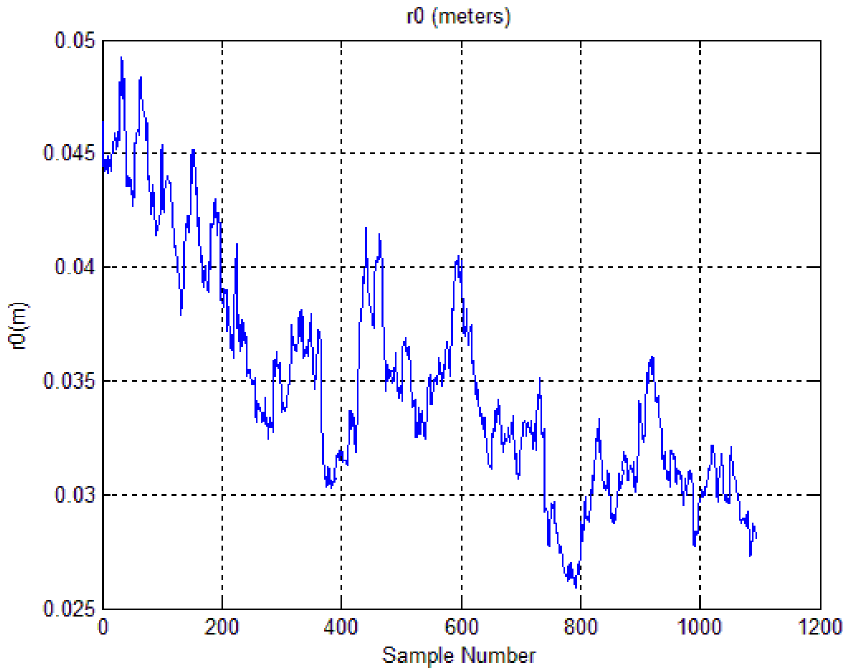
- Data taken on 12/14/2013
- Data set starts at 11:15 AM
- Data approx 20 minutes long
- Data Taken at ~1Hz
- 80 Image frames are missing
- Interpolated with preceding data to fill missing points
- Spots vary in shape across images

Centroids of both Spots

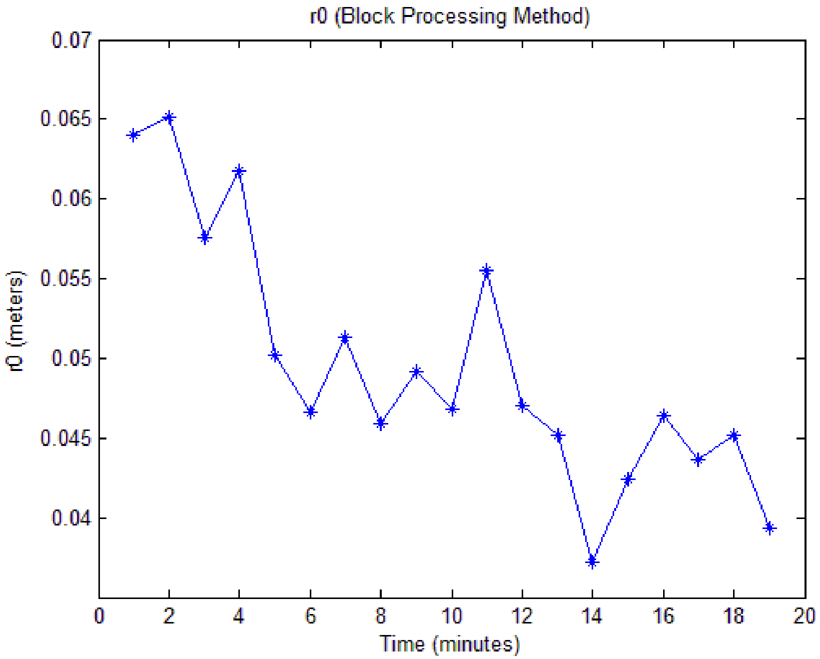


Data Set 2 r_0 Results

- Centroid variance computed using a circular buffer
- Buffer length set to 60 samples or 1 minute
- Results were higher than predicted by simulation, but within reason
- Spots are not as well defined as in Data Set 1



- Centroid variance computed in 1 minute non-overlapping blocks
- Results appear to follow the circular variance method but at a lower sample rate



How to Validate DIMMS Results (General Observations and Guidelines)

What constitutes "truth" along a given optical path?

DIMM instruments can be calibrated in several ways

- Comparison of results to simulation output
- Hardware simulation of an optical path with known r_0 (for example, phase wheels)
- Side-by-side comparison of results using additional DIMM instruments
- Air temperature measurements along the optical path
  - Requires expensive instrumentation
  - Analysis yields r_0 estimation based on air temperature variations

Comparison to Simulation Results

Advantages

- Simulation runs are relatively inexpensive
- Multiple runs can be executed fairly quickly
- Multiple parameters can be adjusted and repeated easily, enabling efficient sensitivity analyses and simulation of “outlier” conditions

Disadvantages

- Multiple-parameter conditions are difficult to validate (parameter space grows exponentially)
- Traceability to real-world conditions can be expensive (A demo is worth a thousand simulations)

Hardware Simulation of Atmosphere

Advantages

- Real hardware-in-the-loop results add credibility to system performance
- Atmospheric parameters can be adjusted and simulation runs can easily be repeated

Disadvantages

- Simulations are typically limited to real-time—running faster than real-time can introduce errors that must be quantified
- Hardware that simulates the atmosphere has to be validated, can be time consuming and expensive
- Outlier conditions and special cases are usually difficult to generate

Side-by-side Comparison with Other DIMM Instruments

Advantages

- Real-world results
- If the comparison is with a validated system, confidence is high that the results are accurate

Disadvantages

- Validating a “truth” system is expensive and subject to risk
- Multiple systems can yield widely varying results (Ref: Bradley, et al, *Characterization of Meteorological and Seeing Conditions at Haleakala,* © 2006, Publications of the Astronomical Society of the Pacific)
- Test conditions are limited to location and time

Air Temperature Measurements Along the Optical Path

Advantages

- Real-world results
- Well-established and repeatable relationship between air temperature and air density

Disadvantages

- Instrumentation for a dense temperature field is expensive
- Airborne instrumentation is expensive (balloons and/or aircraft) and impractical to simultaneously measure many points in a dense temperature field
- Accuracy is subject to the validity of assuming the temperature is the same across the air volume near the temperature measurement
- Other mechanisms that affect seeing conditions (particulates, density and humidity changes) are not accounted for

Signal Fades

- In the event of a signal fade, the signal-to-noise ratio (SNR) of the centroid of each spot falls below a pre-determined threshold
- When the SNR falls below a threshold, the data are no longer valid
- Currently, the algorithm “consumes” all signal fades, introducing errors and discounting runs that include fades
- Upgraded algorithms must truncate runs bounded by periods where the SNR drops below threshold (in-work)

Real-time Requirements

How quickly does a particular laser test need to know the seeing conditions?

In cases where limited availability drives test schedule, r_0 needs to be characterized quickly enough to provide high confidence that the seeing will stay as good as or better than a required level during a subsequent laser shot

- This can be seconds to minutes, depending on the time of day and the rate at which seeing conditions are changing
- In some cases, a target will get destroyed or degraded during the test, and repeating the shot may not be affordable

When repeating tests is relatively inexpensive and easy, post-processing of collected data is acceptable

Conclusions

- DIMM is a widely recognized and mature means of determining r_0 along an optical path
- Anchoring DIMMS results to truth data presents particular challenges
- The ability to process data and measure r_0 in the presence of signal fades increases measurement availability and reduces test schedule risk
- Real-time capability is a must for many laser tests, while post-processing capability is sometimes adequate