Analysis of laser beam propagation over long-range atmospheric paths with accounting for turbulence and refractivity effects: computational fluid dynamics approach

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Analysis of Long-Range Laser Beam Propagation: Challenges

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Applications:

- Remote sensing
- Laser communication
- Time transfer for clock synchronization
- Power beaming
- Beam projection for directed energy

Challenges:

- Numerical grid limitations
- Variability of atmospheric characteristics
  - During the day
  - During the year
  - Depending on the location

Conventional models:

$C_n^2 = C_n^2(h),\ n = n(h),$

h is height above the ground.

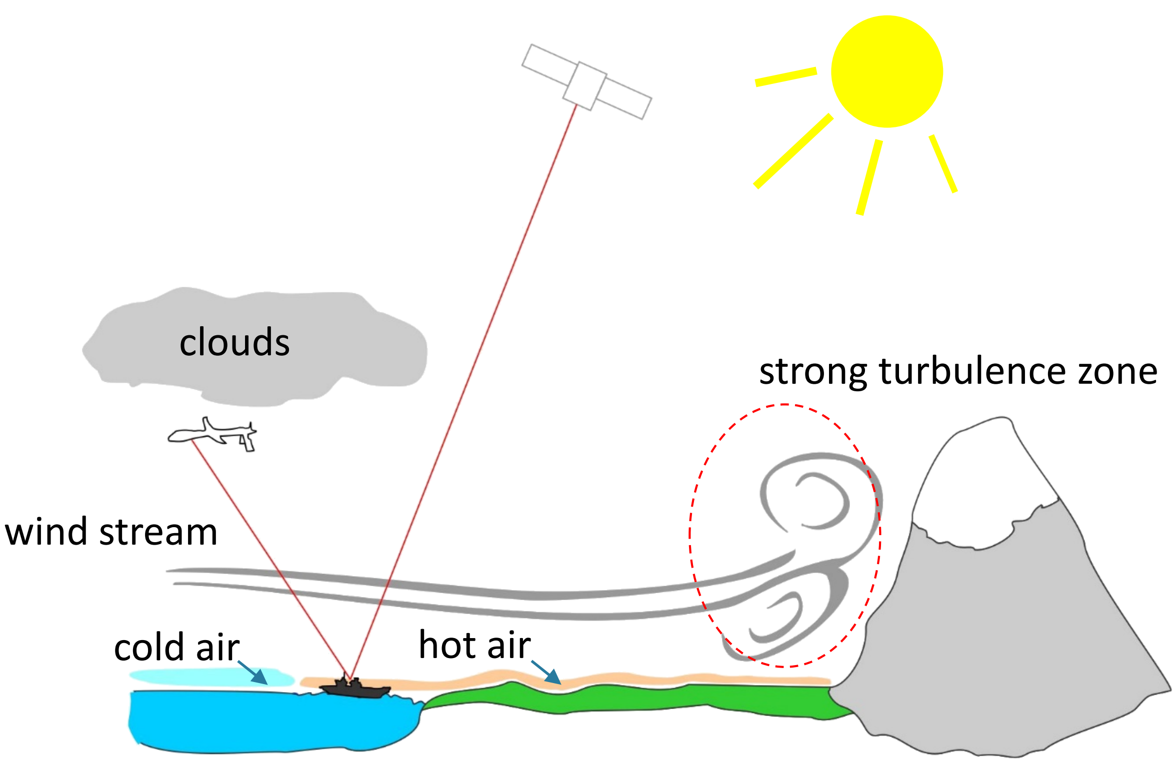
Real atmosphere:

$C_n^2 = C_n^2(\mathbf{r},t),\ \ n = n(\mathbf{r},t),\ \ \mathbf{r} = \mathbf{r}\{x,y,z\}.$

t is time.

Major factors which impact on atmospheric parameters:

- cloud cover
- sun heating
- wind speed
- landscape features
- interaction with neighborhood regions, etc.



There is a need for models that provide atmospheric parameters in specific location and time.

Approaches for Modeling of Atmospheric Characteristics

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Conventional approaches:	Problem:
1. Use analytical models such as • US76 for refractivity calculation based on temperature and pressure; • HV57, SLC or Greenwood models for C_n^2 height profile.	The exact distributions almost are never observed in experiments.
2. Use phenomenological models for specific places and times such us AMOS Night Model, MAUI4 etc.	Do not work well for other locations.
3. Use measured data from the meteorology stations or mobile sensors.	Only available for a few specific locations.

Suggested approach:

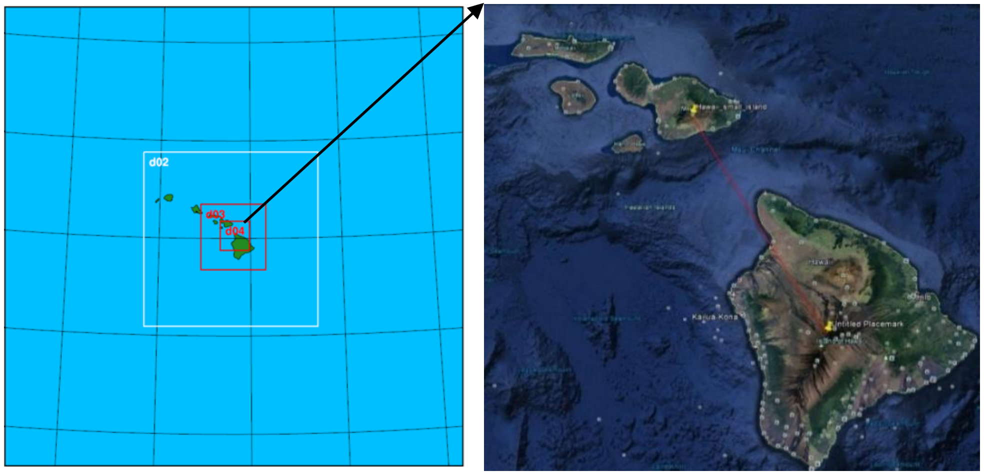
Using meteorological simulations that take into account

- Location
- Landscape
- Weather changes with time

This simulations provide 3D time-dependent fields of meteorological parameters.

Weather Research and Forecasting (WRF) model

- The WRF model enables simulations that provide mesoscale numerical weather predictions.
- Designed for both atmospheric research and operational forecasting applications.
- WRF can provide simulations based on actual atmospheric data (i.e., from observations and analyses) or idealized conditions.



Meteorological parameters, which depended on time, surface type and geographical features can be simulated in WRF. Parameters relevant for optical propagation analysis (refractive index structure constant C_n^2, refractivity) can be estimated.

Estimation of C_n^2 and Index of Refraction Based on Meteorological Parameters

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Weather Research and Forecasting Model

Input

Geographical data
Landscape
Soil type, etc.

Initial & boundary conditions: temperature, pressure etc.

Simulations

WRF

Outputs

pressure P(x,y,z,t),
temperature T(x,y,z,t),
water vapor Q(x,y,z,t),
wind components,
etc.

?

Post-processing

Refractive index **n(*x,y,z,t*)**

Refractive index structure constant $\mathbf{C_n^2(\mathit{x,y,z,t})}$

How to estimate optical parameters based on meteorological data?

Free-atmosphere C_n^2 estimation

[P. He and S. Basu, "Mesoscale modeling of optical turbulence utilizing a novel physically-based parameterization," *Proc. SPIE* **9614**, 96140K (2015)]

Surface-layer C_n^2 estimation in stable conditions (night)

[P. He and S. Basu, "Extending a surface-layer C_n^2 model for strongly stratified conditions utilizing a numerically generated turbulence dataset," *Opt. Express* **24**, 9574–9582 (2016)]

[P. He and S. Basu, "Development of similarity relationship for energy dissipation rate and temperature structure parameter in stable stratified flows: a direct numerical simulation approach," Environ. Fluid Mech., **16**, 373-399 (2015)]

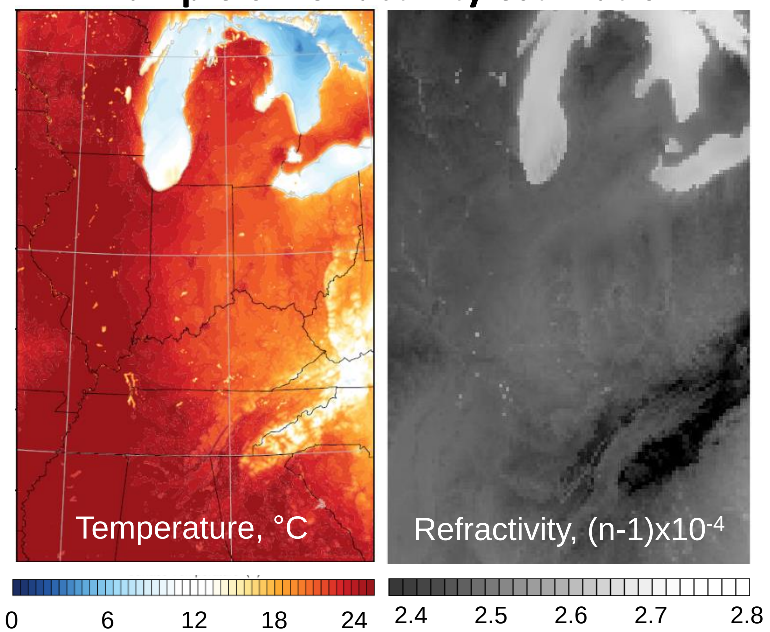
Surface-layer C_n^2 estimation in unstable conditions (day)

[J.A. Businger, J.C. Wyngaard, at el. J. Atmos. Sci., **28**, 181-189 (1971)]

Refractivity estimation

[P. E. Ciddor, "Refractive index of air: new equations for the visible and near infrared," *Appl. Opt.* **35**, 1566–1573 (1996)]

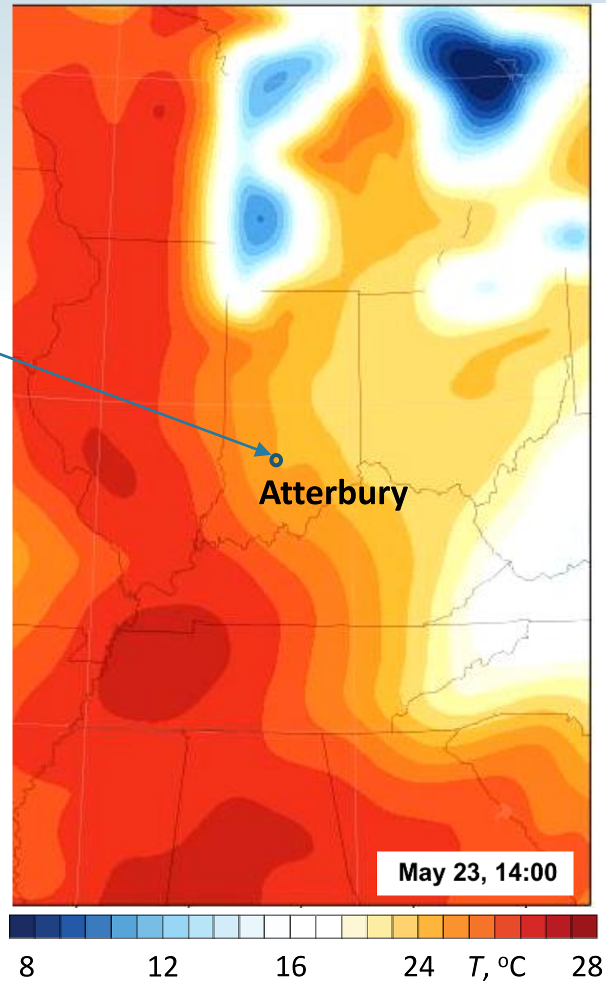
Example of refractivity estimation



The approaches for C_n^2 and refractivity estimations were developed.

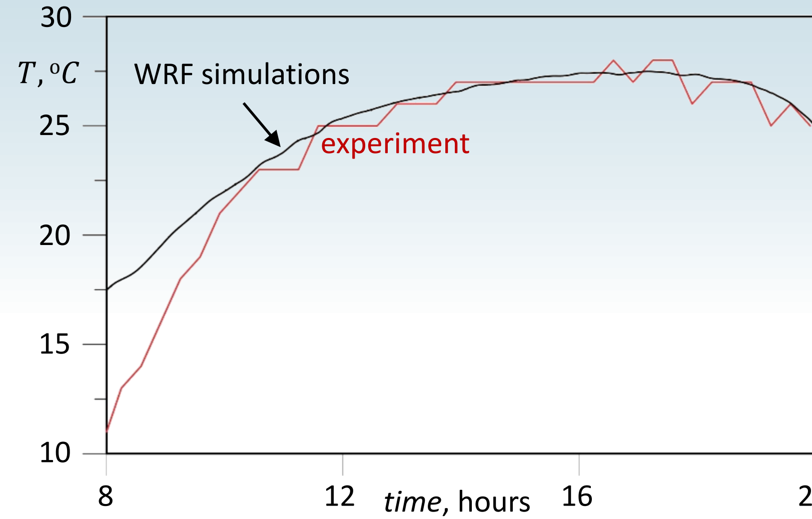
Comparison of Experimental Results with WRF Predictions

Experiment vs WRF simulations

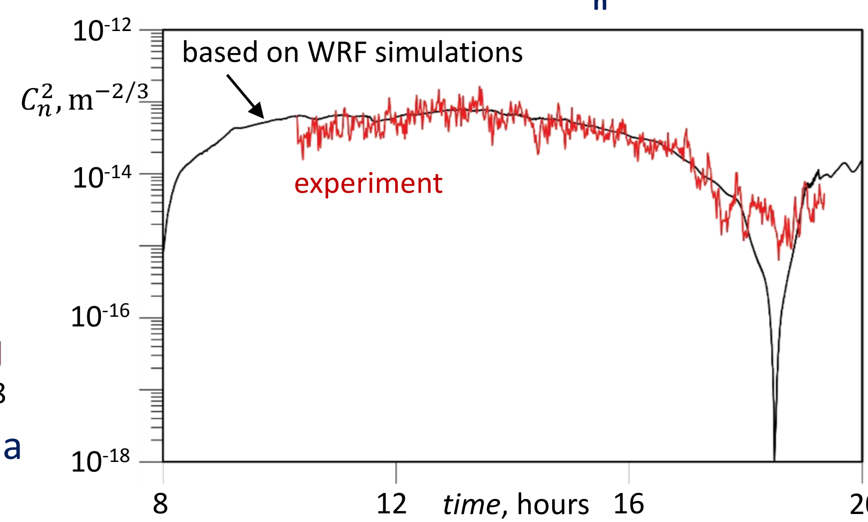


The averaged C_n^2 value along the path was measured by a Scintec BLS900 scintillometer.

Surface temperature



Surface C_n^2



The obtained C_n^2 and temperature estimations match well the experimental results.

WRF Simulations for Long Range Optical Wave Propagation

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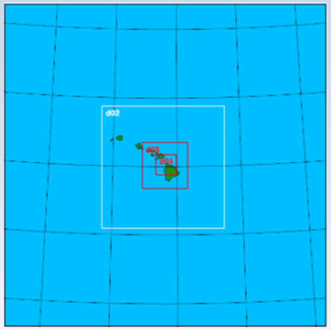
Simulation parameters




WRF simulation

Resolution:
101 vertical layers for 20-km height;
Variable vertical step:
from few meters near the ground
up to km in upper atmosphere.

Domain 1: 2560x2560 km, step 32 km
Domain 2: 968x968 km, step 8 km
Domain 3: 362x362 km, step 2 km
Domain 4: 161x161 km, step 1 km

Local time (36-h interval):
02.12.10 14:00
02.14.10 02:00

Optical path

Length ~149 km
Height profile known from Google Earth.

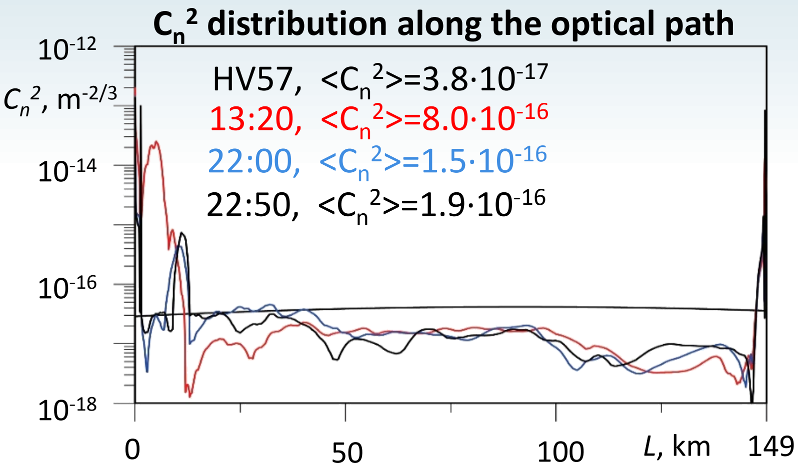
Laser beam

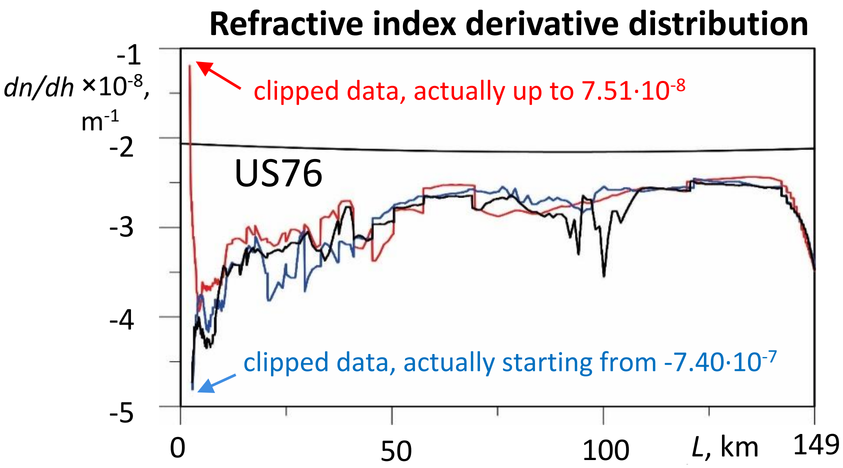
Radius: $a_0 = 1.5$ cm
Wavelength: $\lambda = 532$ nm.

Results: atmospheric optical characteristics

WRF simulations were used for estimation of 4D fields of refractive index and structure function of refractive index:

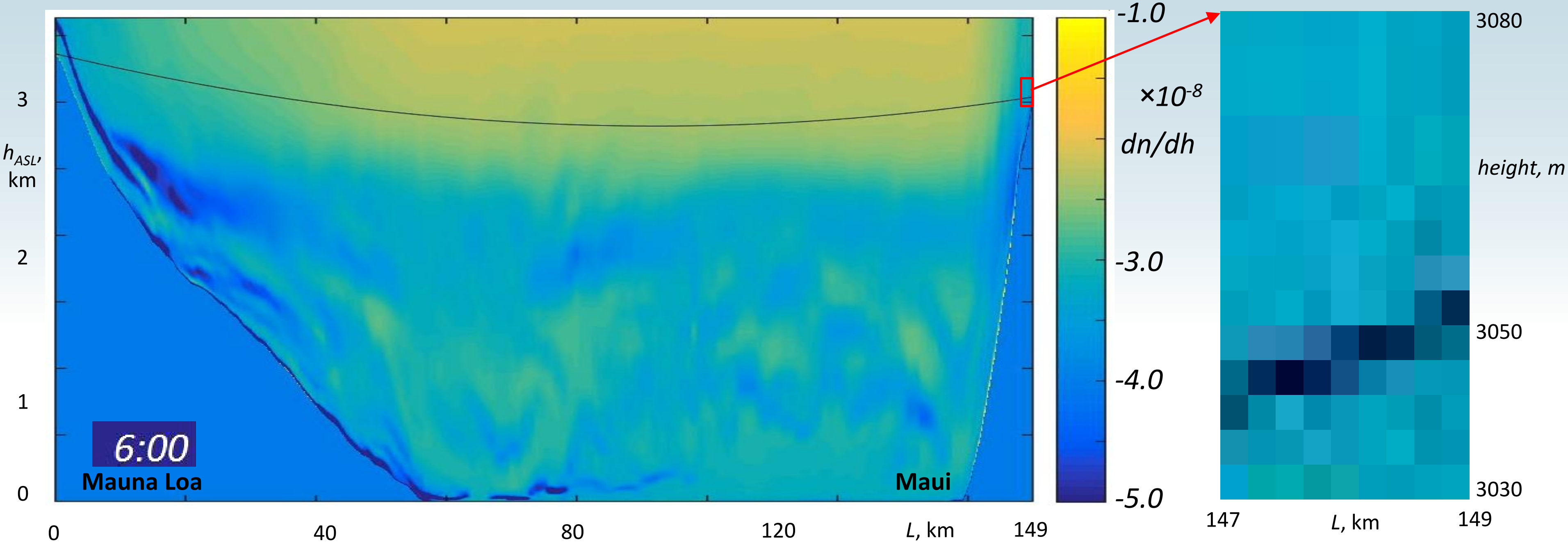
$$n = n(\mathbf{r}, \lambda, t),\ C_n^2 = C_n^2(\mathbf{r}, t),\ \mathbf{r} = \{x, y, z\}.$$



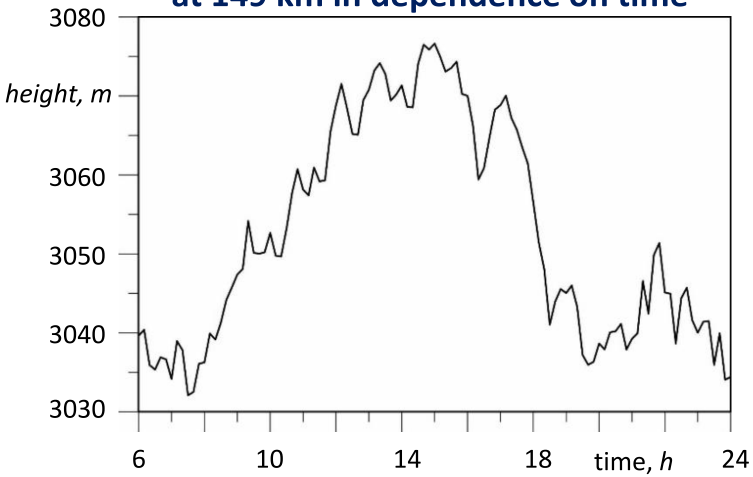


Optical characteristics vary significantly for different regions such as ocean and coastal zone.

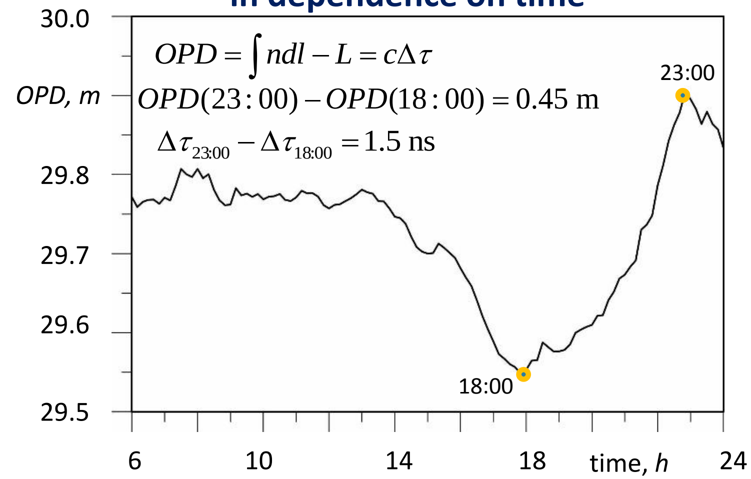
Impact of Refractive Index Daytime Changes



Height of the laser beam at 149 km in dependence on time



Optical path difference (OPD) in dependence on time



Daytime refractive index variations significantly change both beam final height and optical path length.

WRF Simulations for Long Range Laser Beam Propagation

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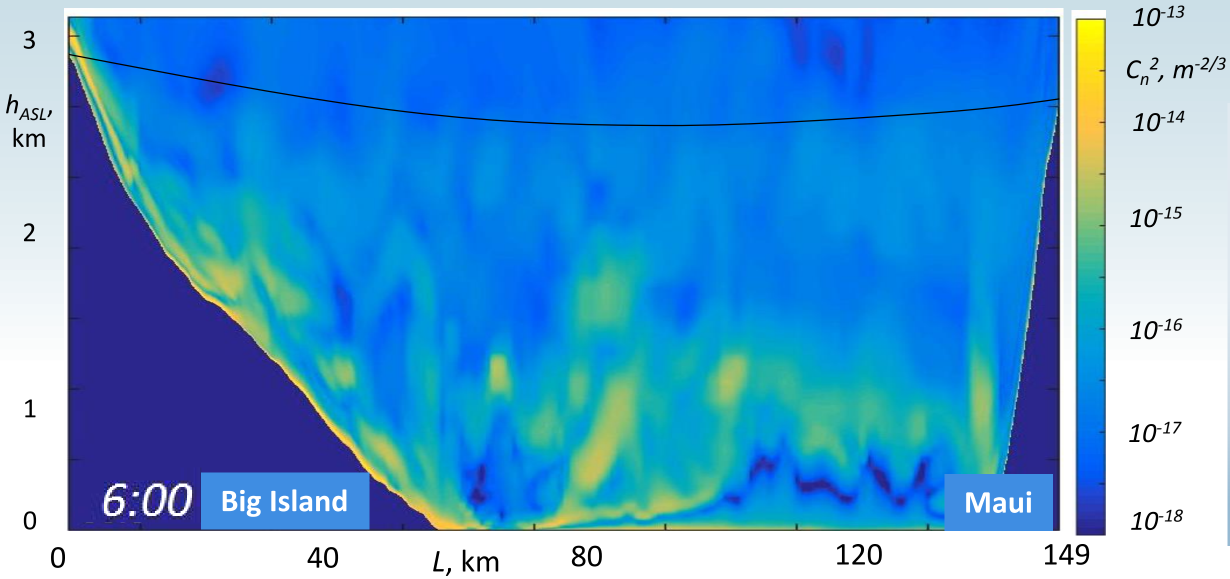
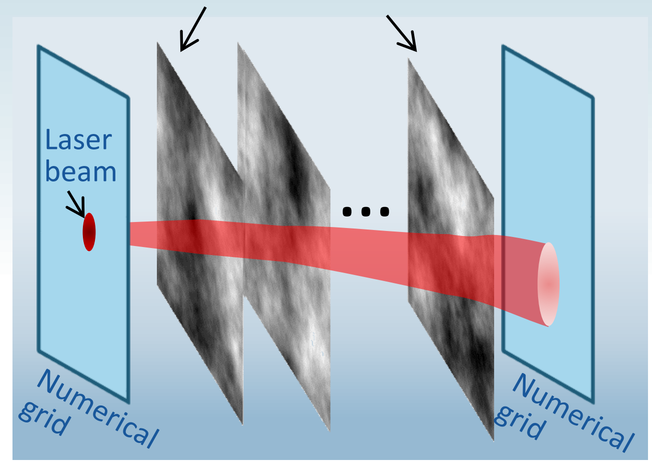


Phase screens were generated based on C_n^2 values along the optical path



Wave optics simulation parameters

Turbulence:

Kolmogorov theory

- 8 equidistant phase screens for first 2 km
- 147 equidistant phase screens for next 147 km

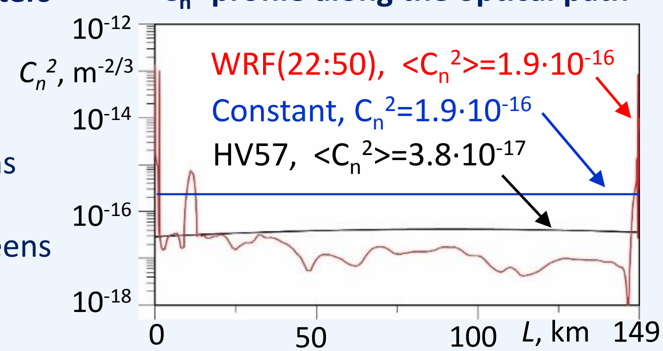
Numerical grid parameters:

4096x4096 points (8.182m x 8.182m) for HV57 model

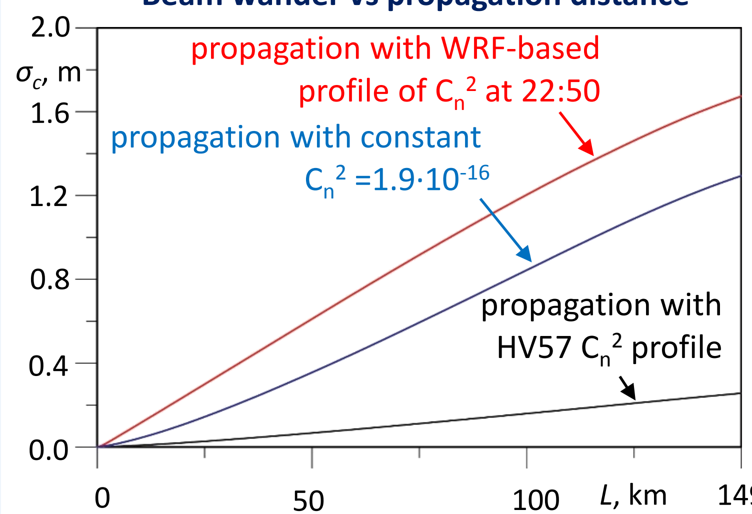
7500x7500 points (22.5m x 22.5m) for WRF C_n^2 profile

Atmospheric averaging over 2000 realizations

C_n^2 profile along the optical path



Beam wander vs propagation distance



Laser beam characteristics obtained based on WRF-based simulations significantly differ from standard model prediction.

Summary

- An approach for estimation of the refractive index structure parameter and the index of refraction based on meteorological information using WRF simulations was developed
- Simulated data obtained with this approach matched experimental data
- Daytime refractive index variations significantly change both
    - the beam centroid trajectory
    - pulse time delay (impact on time delivery and laser ranging)
- Laser beam characteristics obtained from WRF-based distributions significantly differ from standard model predictions