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Lidar Design Study for Turbulence Sensing from Ground into the Free Atmosphere
Based on Angle-of-Arrival Fluctuation Analysis

Quantifying turbulent processes

- Exchange processes
- Gravity wave dissipation
- Clear Air Turbulence → aviation application
- Other applications: astronomy, laser comm., HEL

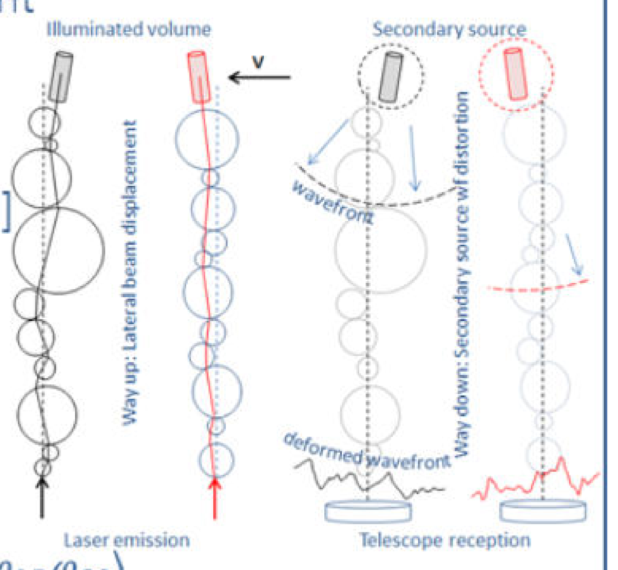
Requirements + boundary conditions:

- Parameters: ε (TKE, ε_{kin}, C_v^2), $u'/v'/w'$ or $<v'^2> = \sigma_v^2$, ε_{pot} (T', C_T^2), scales L_0
- "Free atmosphere" → free troposphere + UTLS
- Temporal + local intermittency
- Blini: high spatial resolution (< x*100m), adv. over radar
- Advection: high temporal resolution (< 1-3min)
- Availability night/day

Cn² - Structure constant

Doppler Wind Lidar insufficient
→ take C_n^2 as proxy,
use optical turbulence itself

- BSA backscatter amplif. [Banakh, Razenkov, Gurvich]
- Image jitter [Belen'kii, Gimmestad]
- Angle-of-Arrival fluctuation [Zilberman, Kopeika]

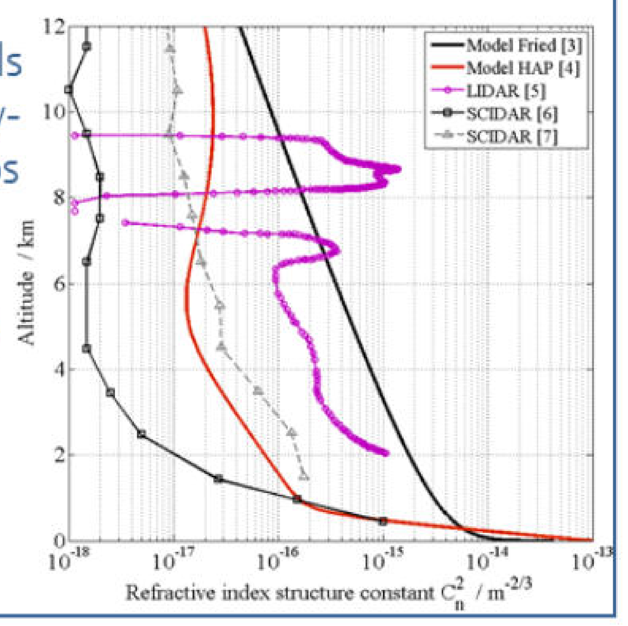


$$\langle\varphi_{AA}^2\rangle = \langle\varphi_{LB}^2\rangle + \langle\varphi_{SS}^2\rangle - 2\langle\varphi_{LB}\varphi_{SS}\rangle$$

AA = Angle of Arrival, LB = Lateral Beam centroid displacement, SS = Secondary Source, and mutual correlation

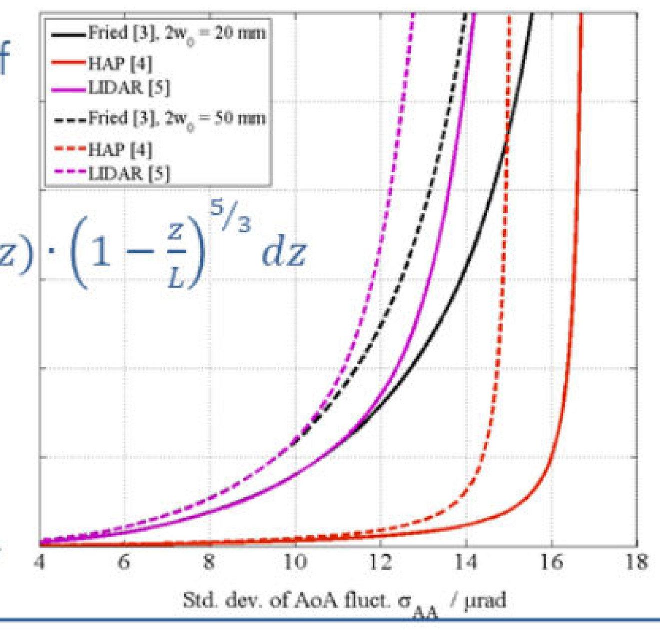
C_n^2 - magnitude: Models, measure

- Non-parametric models
  - Fried, …
- Parametric models
  - Hufnagel-Valley-Andrews-Phillips
- Measurements
  - Lidar
  - SCIDAR (astro.)

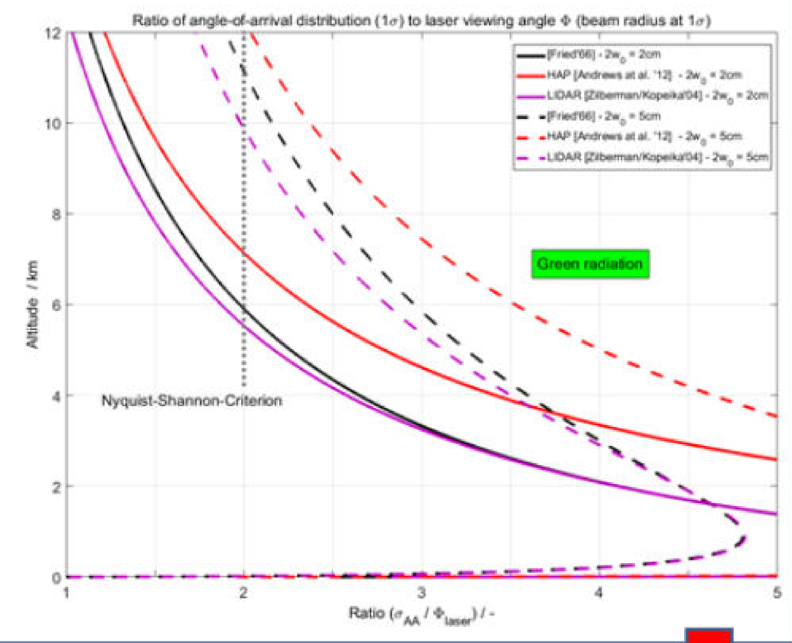


Expected AoA fluctuation $\langle\varphi_{AA}^2(h)\rangle$

- Based on [ZK'08]
  - C_n^2-profiles
  - Prefactor → optimisation / trade-off
    - w_0: Laser beam Ø
    - D: telescope Ø
  - $\langle\varphi_{AA}^2\rangle = \left(\frac{4.07}{w_0^{1/3}} + \frac{5.65}{D^{1/3}}\right) \cdot \int_0^L C_n^2(z) \cdot \left(1 - \frac{z}{L}\right)^{5/3} dz$
- Competing requirements
  - $\langle\varphi_{AA}^2\rangle$ ↑ with a_0↓
  - Diffr. divergence: $\Phi(h)$ ↑ with a_0↓
  - Turb. beam spread: $\Phi(h)$ ↓ with a_0↓



Laser spot viewing angle $\Phi(h)$

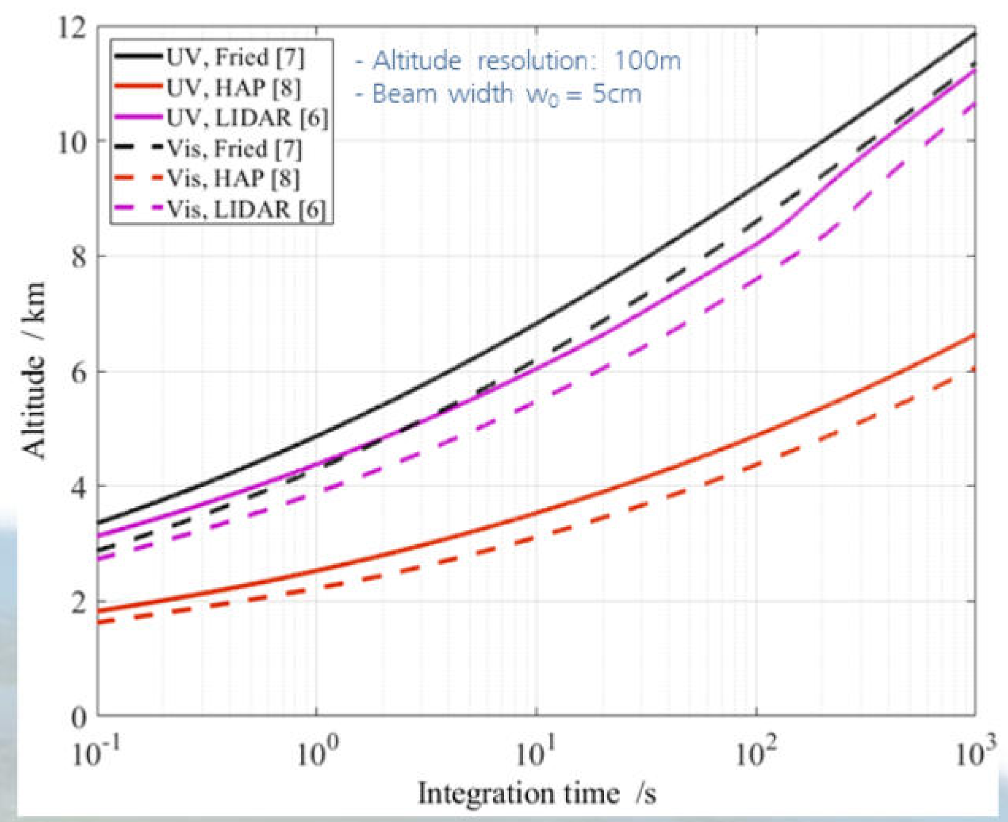


Possible performance in terms of resolution

- Averaging times with Poisson noise process $SNR_\Sigma \propto \sqrt{N_\Sigma}$

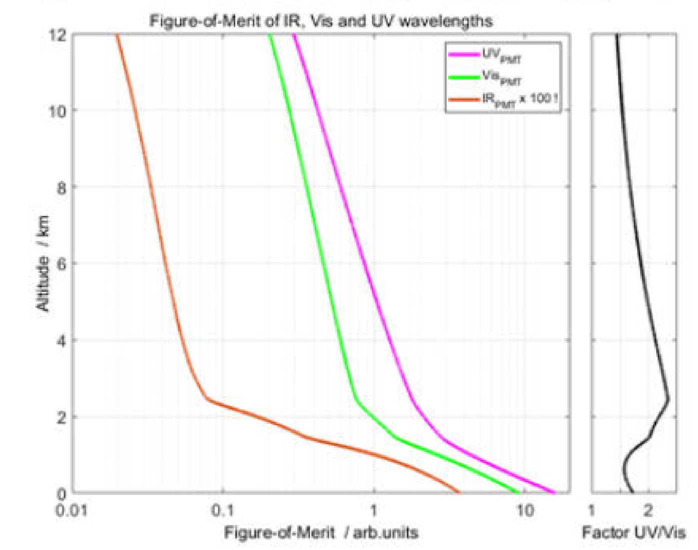
→ with Vis and UV: **spatial and temporal resolution of turbulent C_n^2 for detailed turb. structure studies**

- ! Conservative assessment (laser, signal recovery, …)
- ! Many uncertainties and assumptions, in particular w.r.t.:
  - AoA theories spread [ZK04], further approximations
  - C_n^2 models spread
  - Boundary layer depth
  - Shannon-Nyquist criterion just fulfilled
  - Laser: pointing stability measurement, …
  - Amplitude correction
  - Turbulence assumed fully frozen over measurement



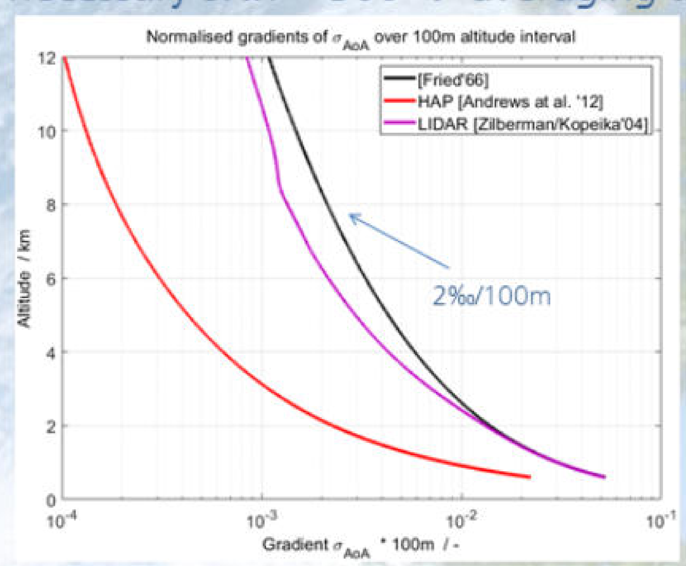
Backscatter and detection

- No further req.'s on spectrum, purity
- Not sensitive on scattering process
  →molecular + aerosol backscatter
- Figure-of-merit = $\beta_\Sigma \cdot T_{Atm} \cdot \eta_{c_V} \cdot Q.E.$



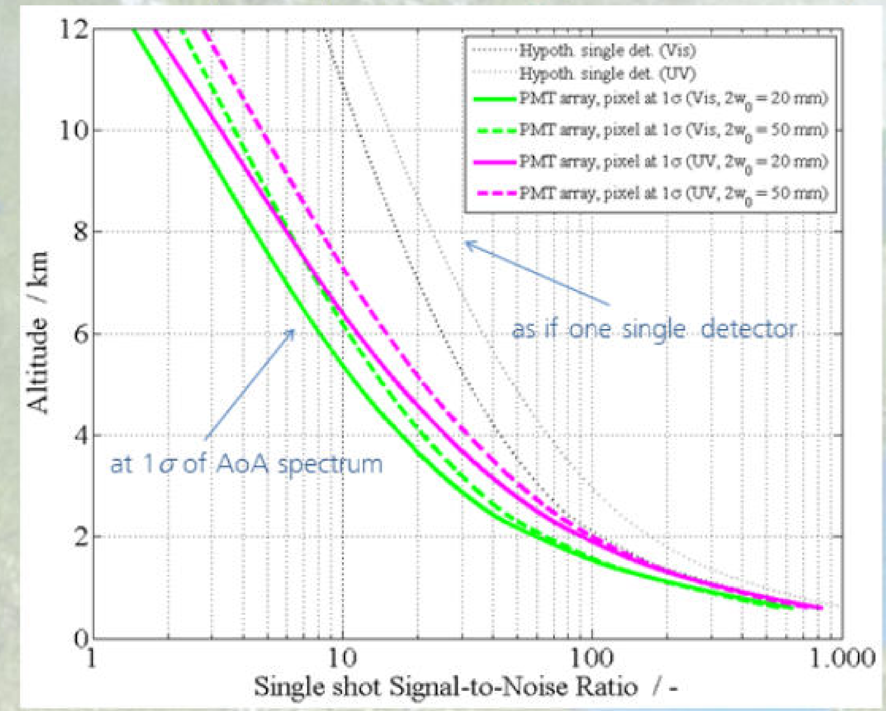
Measurement and retrieval

- Measurement is altitude-integrated AoA fluctuation spectrum width
- Recover C_n^2 features with inversion
- Resolve gradients, e.g.: 2‰/100m → necessary SNR = 500 → averaging times



SNR – per pulse

- Determine single-shot SNR with lidar equation
- Flatter slope (h ↑) due to σ_Φ↑ from 1 to >7 µrad

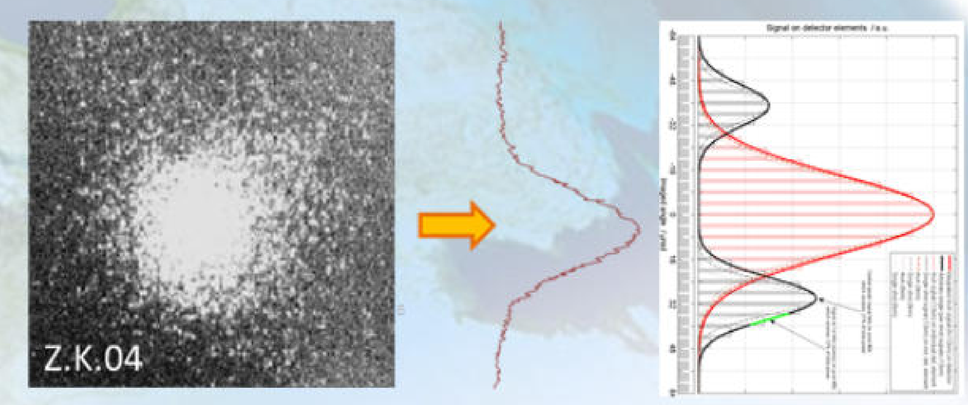


SNR – detector and laser considerations

- AoA-fluctuation 2D „spectrum" → compress to 1D
  - e.g. PMT line detector H7260
  - demonstrated sub-pixel resolution 2.5 mPix

- size AoA spectrum on detector: $[3\sigma_{AoA} + 3\sigma_F]$ x 2

- COTS Nd:YAG P_{Vis} = 110mJ, P_{UV} = 60mJ
- Beam width $2w_0$ = 20 + 50mm, Tel-Ø = 50cm, O.R.



References

- Andrews, L. C., & Phillips, R. L. Laser beam propagation through random media (2nd ed). SPIE Press, 2005.
- Andrews, L. C., Phillips, R. L., Wayne, D., Sauer, P., Leclerc, T., & Crabbs, R. Creating a C_n^2 profile as a function of altitude using scintillation measurements along a slant path. Proc. SPIE 8238, High Energy/Average Power Lasers and Intense Beam Applications VI; Atmospheric and Oceanic Propagation of Electromagnetic Waves VI (p. 82380f), 2012. https://doi.org/10.1117/12.913756
- Fried, D. L., & Cloud, J. D. Propagation of an Infinite Plane Wave in a Randomly Inhomogeneous Medium. JOSA, 56(12), 1667–1676, 1966. https://doi.org/10.1364/JOSA.56.001667
- Liu, L., Yao, Y., Vernin, J., Wang, H., Chadid, M., Wang, Y., Giordano, C., Yin, J., & Qian, X. Optical turbulence profiling with single star SCIDAR technique. Chinese Science Bulletin, 58(36), 4566–4570, 2013. https://doi.org/10.1007/s11434-013-6083-9
- Sathe, A., & Mann, J. A review of turbulence measurements using ground-based wind lidars. Atmospheric Measurement Techniques, 6(11), 3147–3167, 2013. https://doi.org/10.5194/amt-6-3147-2013
- Vaughan, J. M., Geddes, N. J., Flamant, P. H., & Flesia, C. Establishment of a backscatter coefficient and atmospheric database. ESA-CR12510, 22, 1998.
- Vernin, J., Chadid, M., Aristidi, E., Agabi, A., Trinquet, H., & Van der Swaelmen, M. First single star scidar measurements at Dome C, Antarctica. Astronomy & Astrophysics, 500(3), 1271–1276, 2009. https://doi.org/10.1051/0004-6361/200811119
- Vrancken, P., & Herbst, J. Development and Test of a Fringe-Imaging Direct-Detection Doppler Wind Lidar for Aeronautics. EPJ Web of Conferences. 29th International Laser Radar Conference, Hefei, People's Republic of China, 2019. https://elib.dlr.de/123605/
- Zilberman, A., & Kopeika, N. S. Laser beam wander in the atmosphere: Implications for optical turbulence vertical profile sensing with imaging LIDAR. Journal of Applied Remote Sensing, 2(1), 023540, 2008. https://doi.org/10.1117/1.3008058
- Zilberman, A., & Kopeika, N. S. LIDAR measurements of atmospheric turbulence vertical profiles. Free-Space Laser Communication Technologies XVI, 5338, 288–298, 2004. https://doi.org/10.1117/12.532386