Atmospheric seeing studies
based on kHz millimeter SLR in Graz

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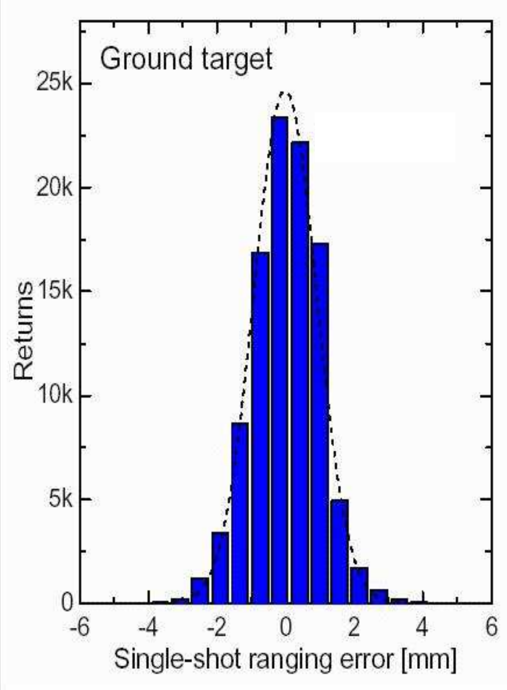
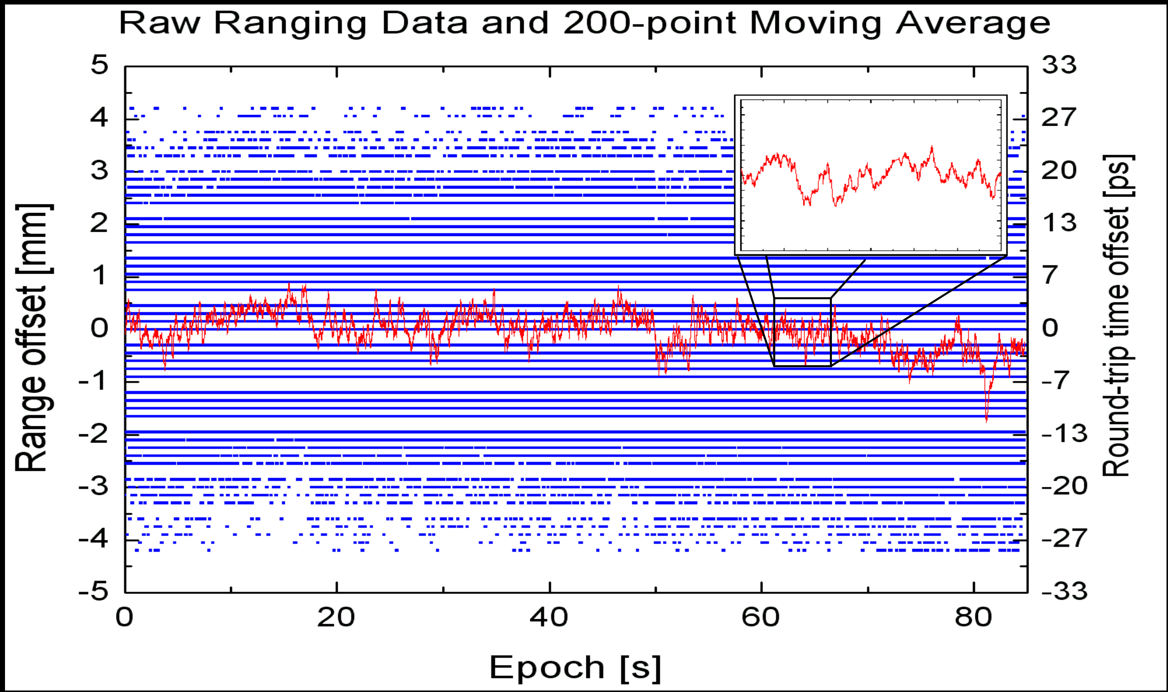
Goal & Philosophy

- Optical turbulence in the atmosphere has a measurable influence on the satellite laser ranging (SLR) data
- (sub)mm precision and 2kHz rep.rate opens new possibilities in seeing monitoring

Ground target laser ranging, 4 km, Graz

Atmospheric fluctuations resolving



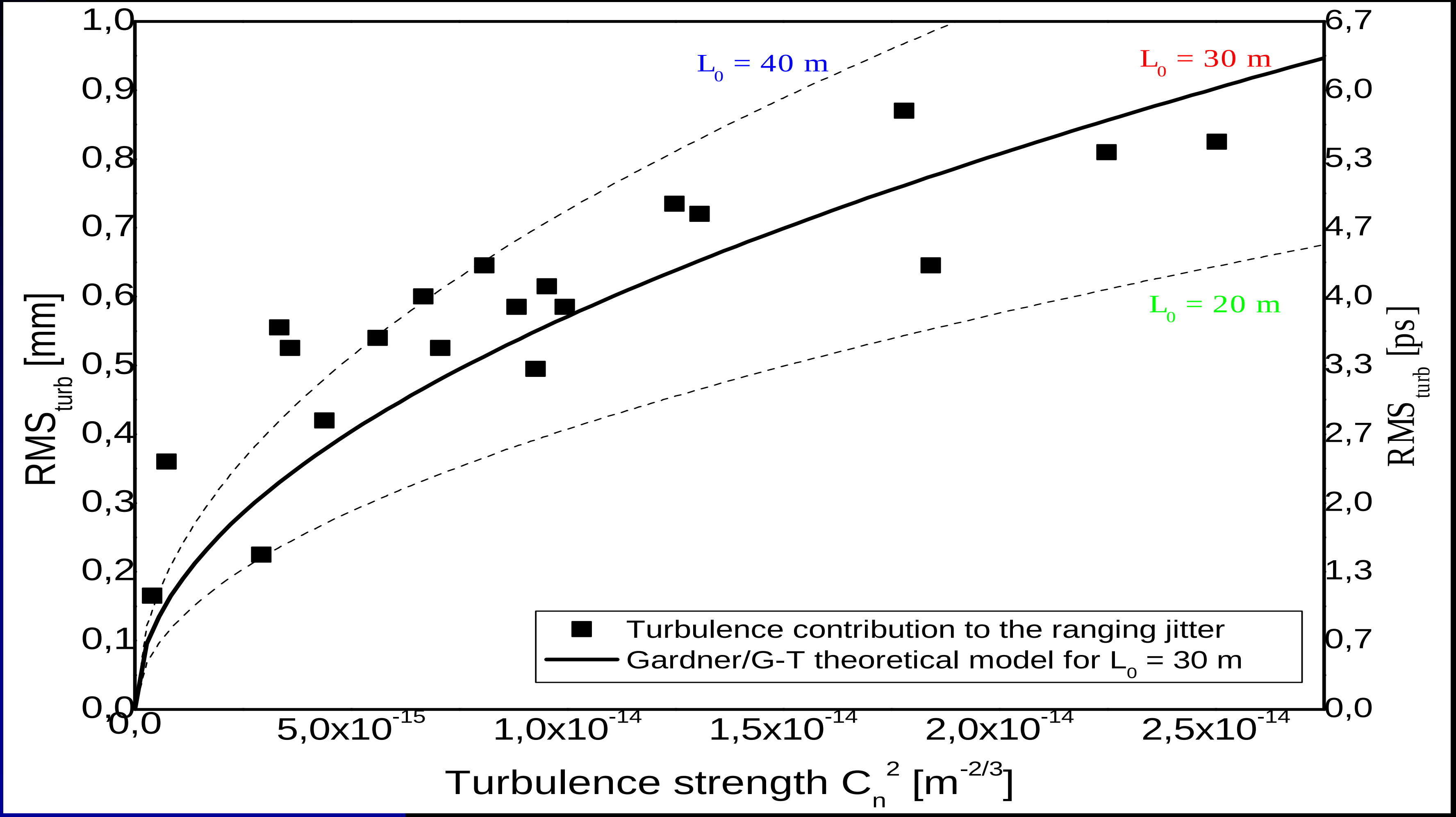


- the atmospheric turbulence-induced contribution to the overall jitter determined for the first time
- instrumental 0.9 mm rms
- atmospheric 0.6 mm rms => 1.1 mm total

L.Kral, I.Prochazka, Grasse, September 2007

Ranging Jitter vs. Turbulence Strength

4 km horizontal path, Graz



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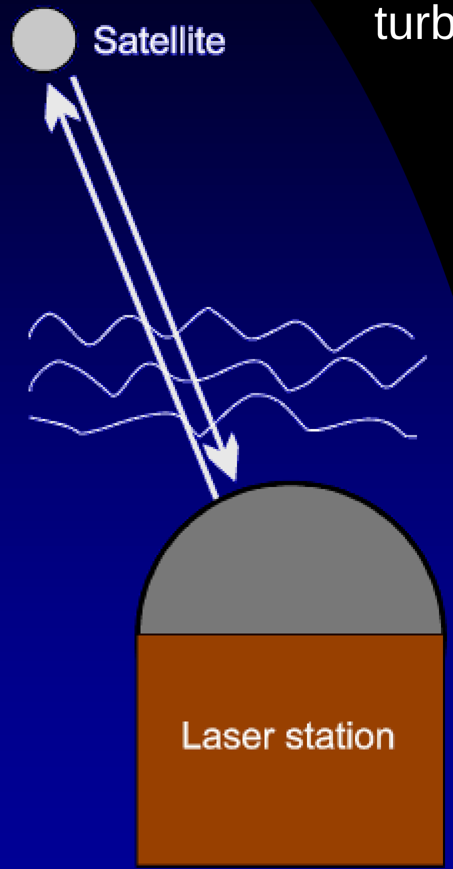
Turbulence influence on the SLR data

- Air refractive index turbulent fluctuations –> laser ranging jitter
- Gardner (1976) derived analytical formula for prediction of the turbulence-induced ranging errors RMS:



$$RMS = 5.1\, L_0^{5/6} \sqrt{\int_0^L C_n^2(\xi)\, d\xi}$$

L_o .... outer scale of turbulence (~100 m ??)
$C_n^2(\xi)$ ... turbulence strength along the beam path
L .... target distance

GARDNER, C. S. *Effects of random path fluctuations on the accuracy of laser ranging systems*. Applied Optics, 1976, vol. 15, no. 10, p. 2539–2545.

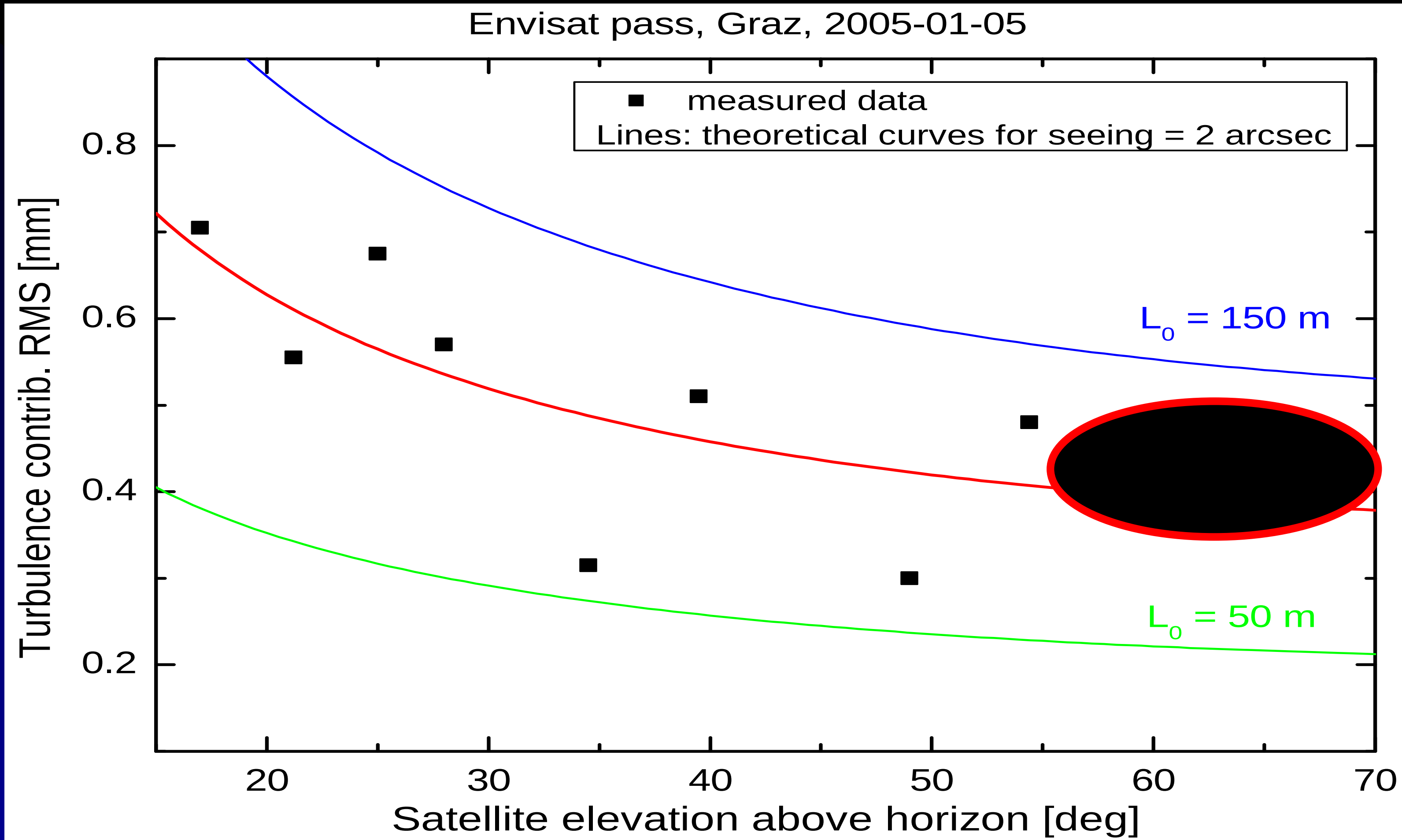
Outer Scale Estimation from SLR Data

- Gardner –> relation between:
  - Turbulence-induced laser ranging jitter RMS (σ)
  - Turbulence outer scale (L_0)
  - Turbulence strength (seeing at zenith … ε)
  - Wavelength of seeing observation (λ)
  - Elevation above horizon (α)

$$\sigma = 1.28 L_0^{5/6} \lambda^{1/6} \varepsilon^{5/6} (\sin\alpha)^{-1/2}$$ (for slant path to space)

- The outer scale L_0 is key to measure, and still not well understood
- By measurement of seeing ε (by a telescope) together with determination of the laser ranging jitter σ from ordinary SLR data, **<u>the outer scale L_0 can be determined</u>**
- High-repetition, high precision laser system required (2 kHz, 1 mm RMS)

Determination of Outer Scale Parameter L_0 from SLR Data



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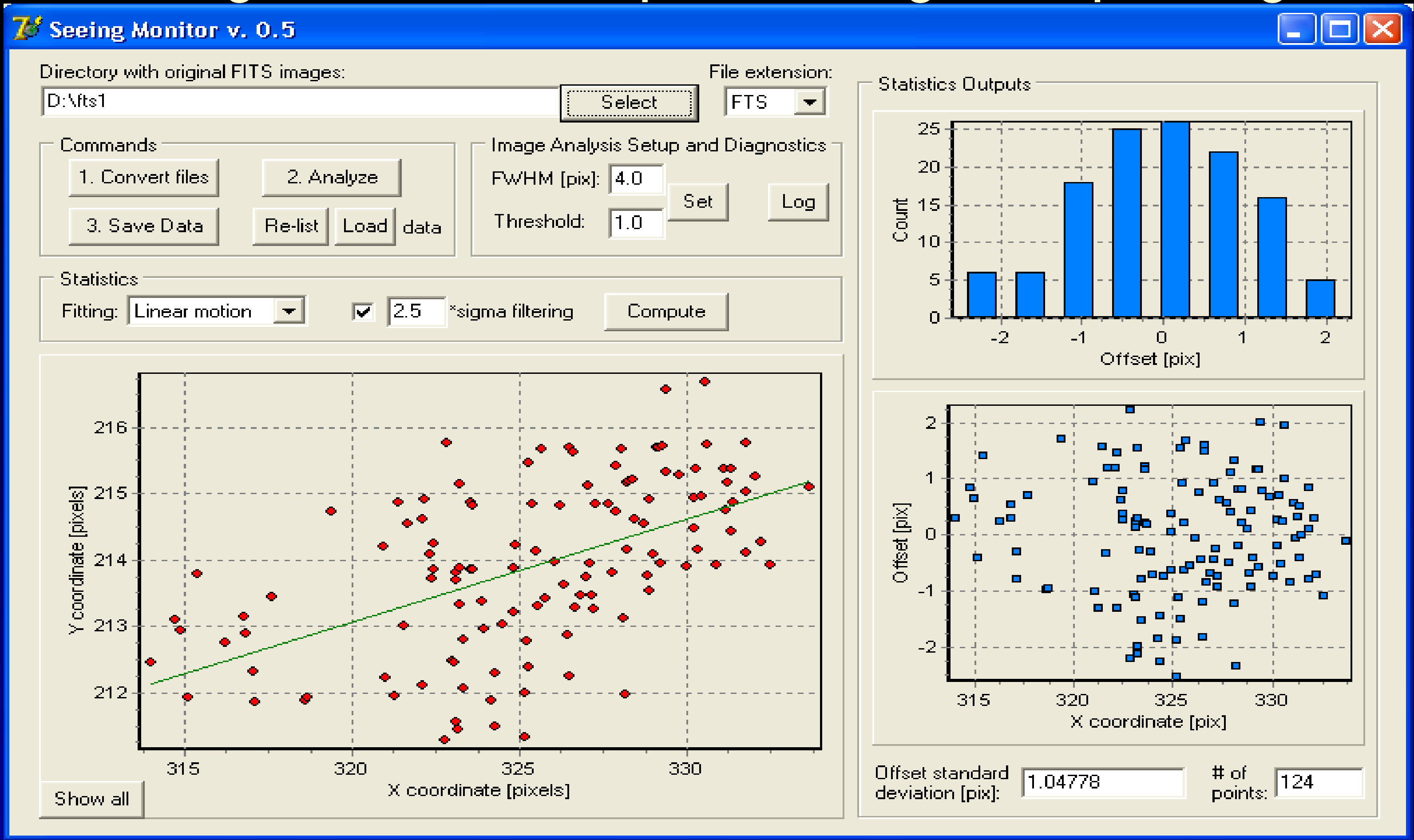
Compact Seeing Monitor

- Small telescope (D = 70 mm, f = 350 mm) low cost CCD sensor (200+100 USD)
- Stellar image motion amplitude is measured from short exposures (< 10 ms)
- Telescope must be perfectly stable
- Result: integral turbulence strength on
  - Slant path to space (star) – nighttime only
  - Horizontal path (lamp) – nighttime/daytime

Seeing Monitor data processing SW package



- Polar star image position fluctuations, no tracking
- Seeing 4 arc sec Polaris
- 7 arc sec horizontal

Results - Summary

- Atmospheric turbulence – seeing is a factor limiting the SLR
  - precision on the (sub) millimeter level
  - energy budget link for arc second pointing
- Seeing measurement together with high repetition SLR data analysis is capable
  to determine the turbulence outer scale (L_0)
- Seeing (turbulence strength) can be monitored even with low-cost telescopes and image sensors

Conclusion

- the new fundamental phenomenon has been identified :
  “image” seeing versus “signal” seeing
  < 1 µm > 100 µm
  phase velocity group velocity

- different seeing models are required for those two

- critical consequences in
  - free space optical communication
  - astronomy / coherent, interference…/
  - others ..?

- => 2kHz millimeter SLR is a powerfull tool to accomplish, among others, a lot of optical science

- => GO FOR kHz SLR