Influence of Atmospheric Turbulence on Planetary Transceiver Laser Ranging

Abstract #3087

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We investigate the influence of atmospheric turbulence on the performance of the uplink of a planetary transceiver laser ranging system. We map the intensity variations due to turbulence to variations in the probability distribution function (PDF) of the arrival time of the 1st photon in a laser pulse, from which the range measurement error probability distribution is determined. The turbulence models are applied to assess the influence on range accuracy and precision statistics, as well as the parameter estimation quality of a Phobos Laser Ranging mission. Details on the work presented here are given by [1].

Detection Statistics

The PDF of the arrival time of the first detectable photon of a laser pulse at the receiver influences the range observation accuracy and precision, as it directly influences the reception time tag. Specifically, the number of detectable photons *N* determines the shape of this PDF (see Fig. 1).

Turbulence-induced photon time-of-flight variations are known to limit the attainable precision of SLR/LLR. However, turbulence also causes variations in the signal strength at the detector, influencing the photon detection statistics by causing stochastic variations of the number of detected photons *N*. The influence of variability of *N* on photon detection statistics is shown by the red curve in Fig. 1.

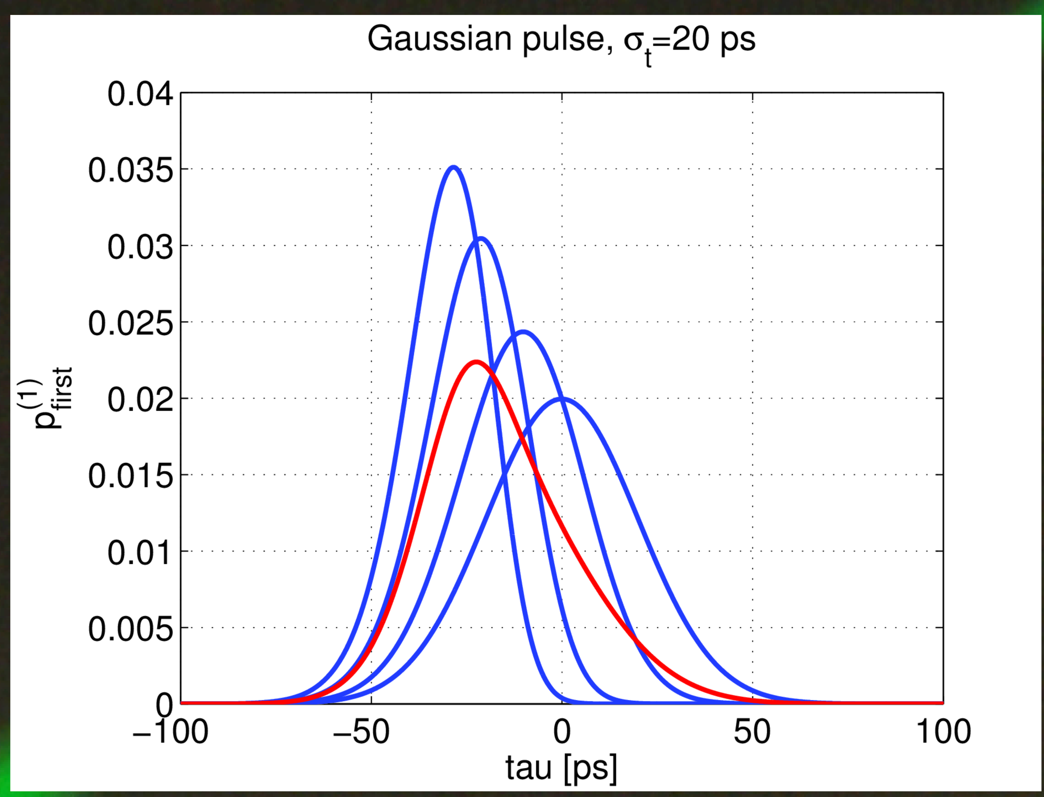

Figure 1: Examples of first photon detection time PDF, with τ=0 indicating detection of photon at the pulse center. Blue: for *N*=1,2,5,10 (peaks right to left). Red: PDF with *N* a uniformly distributed random integer in the [1,4] range.

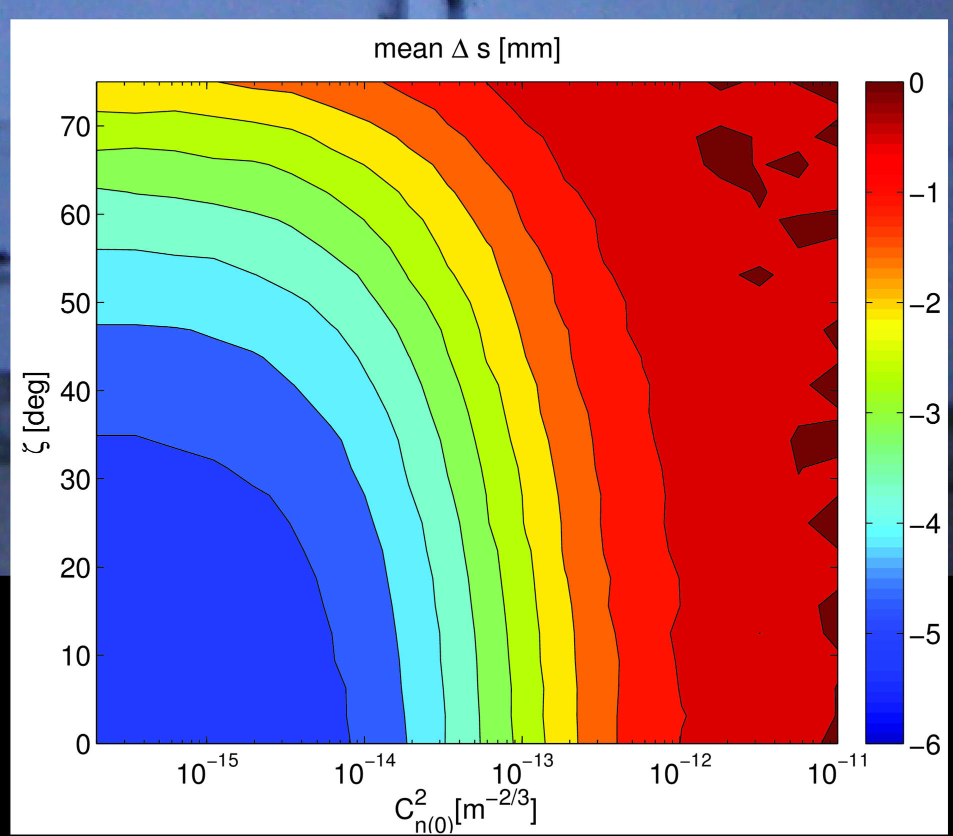

Figure 2: Variations in range accuracy with zenith angle and ground turbulence.

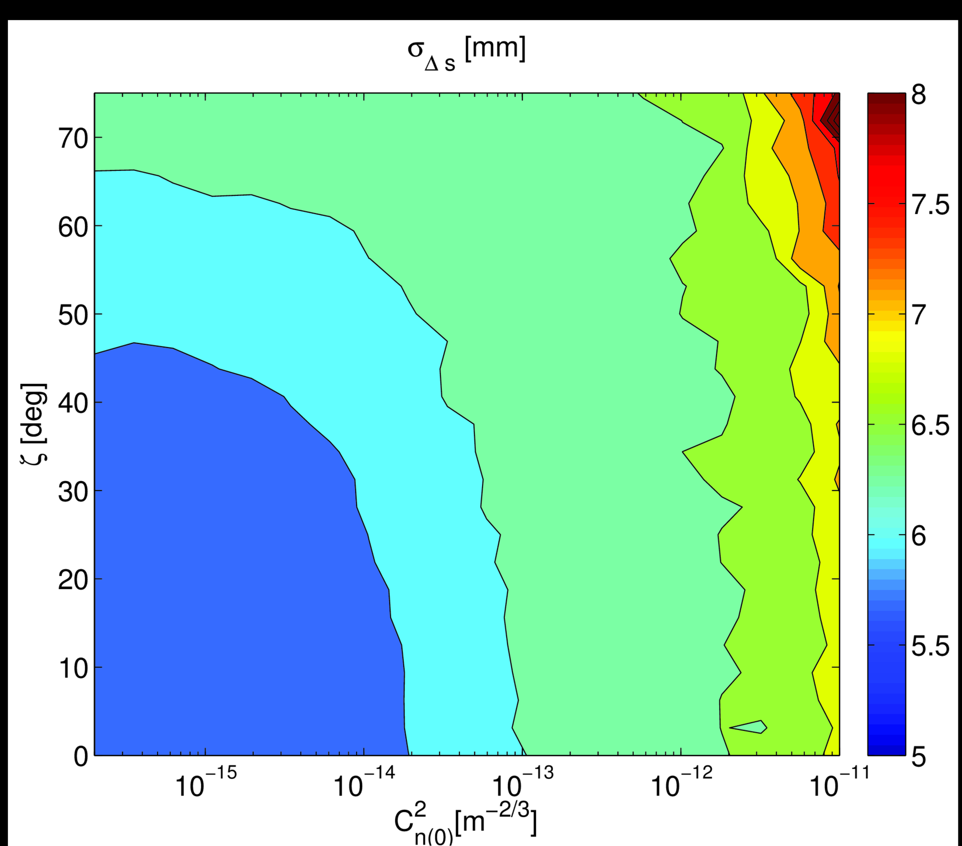

Figure 3: Variations in range precision with zenith angle and ground turbulence.

Range variations

We perform numerical simulations of the inlfuence of turbulence on laser ranging performance, combining the turbulent effects for a range of values of *w* and $C_{n(0)}^2$.

We have simulated the detection statistics for a single uplink pass of a Phobos Laser Ranging mission using a single-photon detector (turbulence-free mean $N\approx 3$). We find only marginal variability with mean wind velocity *w*. Results for variations in accuracy Δs and precision $\sigma_{\Delta s}$ as a function of $C_{n(0)}^2$ and zenith angle ζ are shown in Figs. 2 and 3.

Variations in range accuracy are at **3-4 mm** level between weak and strong turbulence at a given zenith angle, similar to variations with zenith angle at $C_{n(0)}^2$. This indicates that these stochastic variations may limit the performance of laser ranging systems, which aim at consistent mm-level accuracy. We find the primary contributor to turbulence-induced accuracy and detected pulse fraction variations to be the turbulence-induced pointing error.

Table 1: Summary of results (in mm) for Phobos orbit determination. Shown are st. dev. σ and mean (overbar) error in x- and y- initial position components for no/nominal/strong turbulence.

	Formal		True			
Simulation case	σ_x	σ_y	σ_x	σ_y	$\bar{x}$	$\bar{y}$
No turbulence	4.9	0.5	87.8	11.9	21.6	-6.4
Nominal turbulence	6.2	0.7	86.1	12.0	21.1	-6.9
Strong turbulence	9.5	1.0	114.3	16.1	14.3	-9.7

Parameter estimation influence

We have simulated one month of data for the PLR mission from 8 ground stations using both nominal ($10^{-15}<C_{n(0)}^2<10^{-13}$) and strong ($10^{-15}<C_{n(0)}^2<10^{-12}$) turbulence variations. This data was used to estimate the orbit of Phobos, as well as a constant bias value (per ground station). Results are shown in Table 1, where the true values were obtained from 250 simulations.

The error budget is significantly influenced only in the case of strong turbulence. For nominal turbulence, inherent signal strength variations due to varying zenith angle, atmospheric transmission, *etc.* are of stronger influence.

Turbulent Effects

We model a number of turbulent effects in addition to the time-of-flight variation [2]:

- Scintillation causes temporal variations of signal strength.
- Long-term beam spread flattens the time-averaged pulse intensity profile.
- Beam wander causes stochastic pointing errors

For planetary laser ranging systems, where the retroreflector-induced range variations are absent. These effects will be more prominent in the photon detection statistics.

We use the Huffnagel-Valley ground turbulence model, defining its influence on pulse propagation by the mean wind velocity *w* and ground turbulence strength $C_{n(0)}^2$.

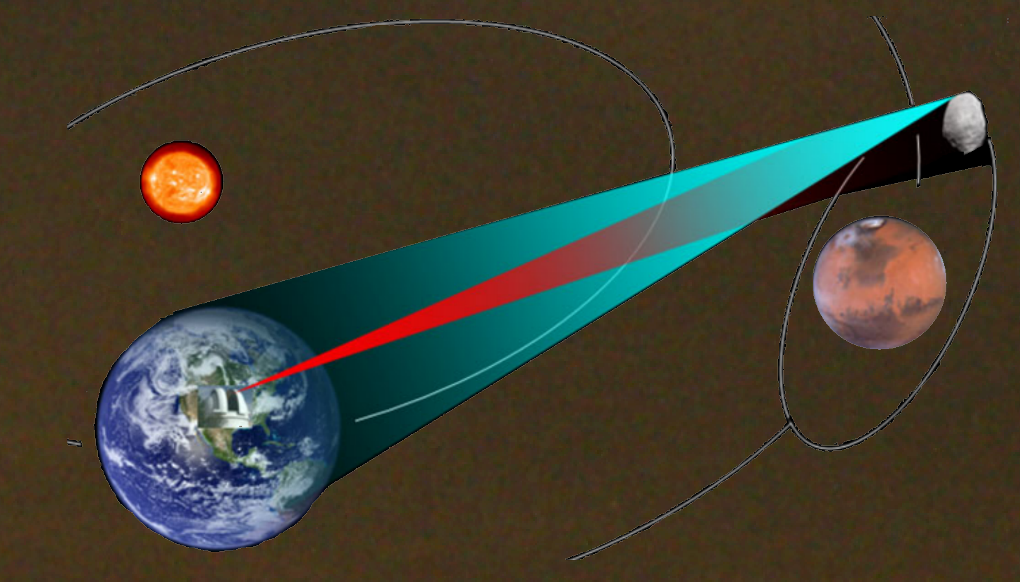

Figure 4: Schematic representation of Phobos Laser ranging mission

Mitigation strategies

By ensuring single photon detection for (nearly) all pulses, the turbulence-induced accuracy degradation can be largely mitigated. Options for this are:

- Operating at kHz frequencies. Each pulse has a very low energy and associated very low probability of multi-photon detection.
- Use of a detector system with a multi-array system; the probability of multiple photon detections by a single detector element is substantially reduced.

Additionally, the influence of turbulence induced pointing errors may be partially mitigated by using a wider beam.

Conclusion

We have simulated the influence of various turbulence effects on laser range uplink statistics. Although several mm variations in single pass accuracy and precision are observed, we find that the effects of turbulence are only of substantial influence on estimation quality for strong ground turbulence.

[1]: Dirkx, D. et al. (2014), Advances in Space Research (in press)
[2]: Andrews, L. and Philips R.,Laser Beam Propagation through Random Media, 2nd edition, SPIE
[3]: Turyshev et al. (2010), Exp. Ast., 27(1-2), 27-60, 2011

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