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Influence of atmospheric turbulence on planetary transceiver laser ranging

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Abstract

In this paper we investigate the influence of atmospheric turbulence on the performance of the uplink of a planetary transceiver laser ranging system using a single photon detector. We numerically combine the influence of turbulence in the mean intensity profile variations, scintillation, beam-wander induced pointing errors and stochastic time-of-flight variations, using the Hufnagel–Valley turbulence profile to model the ground turbulence behavior. We map the intensity variations due to turbulence to variations in the probability distribution of the arrival time of the 1st photon in a laser pulse, which influences the range measurement error probability distribution. The turbulence models are applied to assess the influence on single-pass range accuracy and precision statistics, as well as the parameter estimation quality of a Phobos Laser Ranging (PLR) mission.

The difference in range measurement error between weak and strong turbulence is 3–4 mm in a PLR concept. This indicates that turbulence is a potentially important contributor to the error budget of interplanetary laser ranging missions, which aim at mm-level accuracy and precision. The single-shot precision is weakly influenced by turbulence, but strong turbulence is found to cause a strong decrease in detected pulse fraction, reducing normal point precision. We show that a trade-off between range accuracy and precision must be made when selecting laser system parameters, considerations for which are influenced by atmospheric turbulence effects. By consistently operating at the single-photon signal strength level, accuracy variations can be largely removed, at the expense of normal point precision, due to the reduced detection probability. We perform parameter estimation of Phobos initial state and observation biases using simulated measurements with and without turbulence, using a daily periodic turbulence strength model. We show that the parameter estimation quality is degraded significantly below that of the turbulence-free case only in the presence of strong turbulence. This shows the existence of a limit of ground turbulence strength below which its influence on parameter estimation becomes negligible.

Keywords: Planetary laser ranging; Optical turbulence; Laser pulse detection statistics

1. Introduction

The influence of atmospheric turbulence on the performance of free-space communications systems, both terrestrial and Earth-space, has been a topic of active study in recent years. Analyses of the influence of turbulence-induced scintillation and beam wander on link characteristics such as bit rate and signal fades have been performed

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by *e.g.* Andrews et al. (2000), Hemmati (2006), Farid and Hranilovic (2007) and Sandalidis (2011).

For optical ranging systems, specifically in the field of Satellite Laser Ranging (SLR), the influence of turbulence-induced stochastic time-of-flight variations has been studied by Kral et al. (2005), who verified the validity of the model derived by Gardner (1976) from measurements at the Graz SLR station.

The influence of scintillation on the performance of SLR systems has received more limited attention. The combined influence of scintillation in weak turbulence and retroreflectors on return signal intensity was modeled and measured by Bufton et al. (1977) and Bufton (1977). Attenuation of mean signal return strength due to turbulence was studied by *e.g.* Churnside (1993), Degnan (1995) and Yaoheng and Hesheng (2003). However, the statistical influence of (time-dependent) turbulence-induced signal-intensity variations on system performance has not been quantified in detail to date.

The fundamental difference between quantifying the influence of turbulence on laser ranging and optical communications is that the exact photon detection time directly influences a range measurement, whereas in optical communications a small error in photon detection time will typically have no effect on the channel performance (Hemmati, 2006). In communications systems, however, a high probability of pulse detection is required to ensure a robust communications channel. In laser ranging systems, the signal return rate may be much lower for the system to still function at a level of performance where it can meet its requirements. This is especially clear in Lunar Laser Ranging (LLR), where stations typically receive returns from very few pulses and operate in a very low signal-to-noise regime (Jefferys and Ries, 1997). Nevertheless, substantial science return is obtained from LLR measurements (Williams et al., 2006).

One- and two-way active transceiver laser ranging systems (Degnan, 2002; Birnbaum et al., 2010; Zuber et al., 2010; Chen et al., 2013) are an emerging technology that is based on existing SLR and LLR technology, modified with an active space segment to allow larger distances to be covered. These technologies have the potential to deliver mm-precise measurements over interplanetary distances, extending the technology of SLR and LLR to Interplanetary Laser Ranging (ILR). The increased range precision and accuracy that can be obtained, compared to current radiometric systems, are expected to yield order(s) of magnitude improvements in the estimation of science parameters related to, for instance, gravitational physics (Turyshev et al., 2010) and planetary interiors (Dirkx et al., 2014). Also, ILR systems could be combined with long-distance laser communications systems (Hemmati et al., 2009; Hemmati, 2011), such as the laser communications system demonstrated at lunar distances by the LADEE satellite (Boroson and Robinson, 2013).

The measurement error budget breakdown of ILR systems will be different from that of SLR and LLR. For instance, the satellite signature effect on the laser pulse (Otsubo and Appleby, 2003), which is the primary cause of changes in a pulse's temporal shape in SLR, is absent in ILR. For this reason, small intensity fluctuations (such as those caused by turbulence) could play a larger role in the detection-time statistics, uncertainties in which are no longer dominated by retroreflector signature uncertainties. Also, space segment hardware will introduce new sources of errors, such as clock inaccuracies and detector uncertainties (Prochazka et al., 2007). The role of optical turbulence in ILR has not yet been assessed. Quantification of the various error sources of ILR will be crucial in setting up system requirements during conceptual mission design, as well as for assessing the potential science return from missions using this technology. As opposed to SLR, where ranging data is freely and widely available, no such data exists for ILR, so that we are forced to rely on simulated data for performing analyses of the expected system performance.

In this paper, we investigate the influence of optical turbulence on the range precision and accuracy of the uplink of an ILR system (*i.e.* Earth-to-space). We limit ourselves to the uplink of the system for several reasons. Firstly, aperture averaging is expected to reduce the scintillation effects for the downlink (Degnan, 1995). Secondly, the far-field (as opposed to near-field) turbulence in the case of the downlink cause effects such as beam wander and beam spread to be (nearly) absent.

We simulate laser pulse propagation, including the effects of turbulence, as well as pulse detection times. We map the (turbulence-induced) variations in intensity to variations in the probability distribution of the photon detection times. From these, we statistically quantify the influence of turbulence on the achievable performance of such a system under a variety of atmospheric turbulence conditions, and assess the influence of the non-Gaussian range errors on the orbit determination process.

We use a representative planetary laser ranging system for our simulations, specifically a Phobos lander equipped with a laser transceiver system. The system uses a single photon detector and our analysis in this paper will be restricted to such systems. However, we do not consider a detector array (as is done in the PLR concept), but instead use a single detector element in our simulations. We only consider the receiver system since only the uplink is analyzed here. The feasibility of such a Phobos Laser Ranging (PLR) system was investigated by Turyshev et al. (2010), who performed a preliminary design and analyzed the capabilities of such a system to estimate gravitational-physics parameters. Subsequently, Dirkx et al. (2014) investigated the potential of such a mission to estimate physical parameters of Mars and Phobos such as moments of inertia and Love numbers. In both these studies, the noise level was quantified by a 1 mm precision averaged over a 1 min interval. Dirkx et al. (2014) additionally included systematic errors in their analysis by the use of consider-covariance analysis, distinguishing between the