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Analysis of adaptive optics-based telescope arrays in a deep-space inter-planetary optical communications link between Earth and Mars

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ABSTRACT

Earth-based telescope array receivers employing optical communications have the potential to fulfill the communication needs of technologically sophisticated, deep-space exploration missions. Atmospheric turbulence is the chief restrictive factor in an optical deep-space channel (ODSC). In this paper, investigation and design of adaptive optics (AO) subsystems are presented for the compensation of the coupled effects of optical turbulence and background noise in telescope array receivers. An end-to-end simulation platform for an ODSC between Mars and Earth is implemented, which incorporates pulse-position modulation (PPM), direct-detection receivers, and detectors with the capability of detection of single photon. The extreme conditions of atmospheric turbulence and background noise are also modeled in the analysis. AO subsystems are incorporated at individual telescopes in the array receiver to mitigate the turbulence effects. The performance of array receivers is evaluated in terms of the probability of error and communication throughput. The analysis in this research depicts that in worst-case turbulence and background noise conditions, inclusion of AO systems results in 8.5 dB performance improvement in communication data rates. The performance improvement of 5.6 dB is achievable in moderate channel conditions. Comparison of performance of array receivers with that of a large monolithic telescope shows that incorporation of AO systems is more feasible in arrays comprising telescopes with relatively smaller diameters.

1. Introduction

International space agencies (e.g., NASA and ESA) routinely send discovery missions in deep space to unravel the mysteries of planets in the solar system. These extremely sophisticated discovery missions demand massive data rates in order to transmit real time videos and hyper-spectral imagery [1,2]. Hence, a large bandwidth communications link (on the order of 100 Gbps) is required between space-crafts in deep space and control stations on Earth for telemetering large volumes of collected scientific data [2]. The current RF based technology is already touching its maximum data throughput limits. In comparison with the RF technology, optical and near-infrared communication has the benefits of smaller diameter antennas providing much higher gain, a narrower beam width, larger power density, a higher carrier frequency that can support extremely fast modulations, and a larger available unlicensed spectrum [3]. Hence, optical and near-infrared communication is a viable technology for telemetry from deep-space missions [4].

The focus of research in this article is on a deep-space optical communication link between Mars and Earth. Nevertheless, the presented results are extendable to any other deep-space link without major modifications. The initial work on the subject showed that in worst channel conditions, a large telescope is required to obtain the acceptable bit rates (in Mbps range) for a communication link between Earth and Mars [5–7]. An array of relatively smaller size telescopes is a viable alternative to a large monolithic telescope. Telescope arrays have benefits of lesser cost, better diffraction-limited performance, ease of manufacturing and maintenance, less gravitational effects, scalability, and operational redundancy [8]. It has been shown in literature that for Earth-based reception, the performance of telescope arrays is comparable to that of a large monolithic telescope with the equivalent total photon-collecting area [6,9].

Atmospheric turbulence which gives rise to optical turbulence is the chief deleterious factor in a typical deep-space optical link. Optical turbulence distorts the phase of the optical fields, resulting in the degradation of the focused field. Additionally, turbulence

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induces beam-wander and a random movement of focused spot in the focal plane and it also renders random intensity fluctuations known as scintillations [10]. The effect of beam-wander can be mitigated by an active tracking system [11]. The scintillation is insignificant for larger telescope due to aperture-averaging (i.e., having aperture diameters ≥ 1 m) [10]. Hence, only the dominant effect of random phase perturbations is considered in this paper. The turbulence-induced phase perturbations result in distorted and enlarged point spread function (PSF) in the detector plane of the receiver. Hence, comparatively, a large size detector is required for collection of the signal energy in the focal plane. In a direct-detection system, the receiver's field-of-view (FOV) is dependent on the detector size [12,13]. In a deep-space link, background light (emanating from the Sun, the sky, etc.) is received in the receiver's FOV along with the optical signal fields [14–16]. As the detector dimensions and receiver FOV are increased to capture larger PSF in the telescopic focal plane, the received background noise also increases. This results in a considerable degradation of the signal to background noise photon count ratio and performance of the optical receiver. Unfortunately, both the atmospheric turbulence and background noise are at their respective peaks during daytime and is the major challenge for optical communication systems.

Recently, many research efforts have been made for analysis and compensation of atmospheric turbulence effects for near-earth optical satellite links. For example, in a typical LEO–earth optical communication satellite link, the impact of turbulence-induced variations in atmospheric refraction and beam wander is discussed in [17] and a weighted adaptive threshold estimating method has been proposed in [18], to deal with channel fades in turbulent atmosphere. The analysis of use of telescope array receiver for Moon–Earth optical communication link in the presence of atmospheric turbulence is carried out in [19]. However compensation of turbulence in deep-space optical communication channel, such as Earth–Mars link, is much more challenging due to extremely weak received signal. This problem is analyzed and addressed in the current paper.

In this paper, we present a solution to this problem by incorporating adaptive optics (AO) subsystems in an optical array receiver for mitigation of optical turbulence and background noise effects. The use of AO systems is common in astronomical applications [20] and numerous advanced telescopes employ AO systems for compensation of turbulence effects [21–23]. The AO systems have also been proposed for terrestrial, free-space optical (FSO) communication systems for compensation of atmospheric turbulence [24]. Nevertheless, deep-space communication applications are different from the astronomical and terrestrial FSO applications. Astronomical systems mostly operate during the nighttime, whereas deep-space optical communication systems would operate also during peak turbulence conditions in daytime. Moreover, short-range FSO systems are different in that scintillations are the dominant effect, background noise is not that strong and communications distances are small. Hence, analysis of the use of AO system in array receivers for deep-space optical communications is a new field addressed in this paper.

In this article, performance of AO-based telescope array receivers is evaluated. A Poisson probability model is used to calculate the signal and background photons [13]. The performance is examined in terms of probability of error and achievable data rates. The analysis presented in this paper shows that the use of AO systems significantly improves the performance of direct-detection array receivers in the worst-case optical channel conditions. Specifically it is shown that the incorporation of AO systems results in 8.5 dB performance improvement for an array receiver consisting of 100 1 m telescopes, in extreme background and turbulence conditions. During moderate background conditions, the performance improvement is 5.6 dB. It is further shown that the use of high-performance AO systems is more feasible in an optical array consisting of relatively smaller-sized telescopes.

This paper is organized as follows. The origin and impact of atmospheric turbulence are discussed in Section 2. The conceptual design of an array-based receiver is given in Section 3. Details of the design of AO subsystems are given in Section 5. The performance evaluation of array-based communication systems is presented in Section 6. Discussion of the results is given in Section 7, and finally conclusions are presented in Section 7.

2. Impact of optical turbulence

Atmospheric turbulence is generated due to the temperature and pressure gradients in atmosphere. This creates random fluctuations in the refractive index of the atmosphere, known as *optical turbulence*. When a laser beam propagates through optical turbulence, its spatial coherence is lost [10]. The disturbance in spatial coherence limits the extent of focusing capabilities of the collecting aperture. As a result, the point spread function (PSF) in the focal plane of collecting aperture distorts and deviates from the diffraction-limited performance. In the diffraction-limited case the incoming plane waves from a far-off point source are focused into a spot size, which is dependent upon the operating wavelength and size of the collecting-aperture D, i.e., $\cong (2.44\lambda f/D)$ [6,13], where f is the focal length of the telescope. In this case, the background noise collected by the aperture is not dependent upon the size of the aperture itself [13]. Hence, aperture diameter can be increased to increase the signal energy. Whereas, in turbulent conditions, focused spot size is dependent on the atmospheric Fried parameter r_o (which typically varies from 20 cm to 4 cm with the strength of optical turbulence), i.e., $(\cong 2.44\lambda f/r_o)$ [6,13]. For deep-space applications, typically $D \gg r_o$, hence, the turbulence-limited spot size is much larger than the diffraction-limited case. Hence, a larger detector is needed to encompass the widespread signal energy. On a downside, an increase in detector size results in increased received background noise, which degrades the performance of the receiver.

The optical turbulence can be described by employing Stochastic Theory. For optical waves, power spectral density for refractive index fluctuations can be described by the Kolmogorov spectrum given as [10]

$$\Phi_n(\kappa) = 0.033 C_n^2(\kappa)^{-11/3}, \quad \text{where} \, 1/L_o \ll \kappa \ll 1/l_o, \tag{1}$$

where κ is the spatial frequency in the collecting aperture plane, L_o is the outer-scale and l_o is the inner-scale of turbulence. In this paper, turbulence effects are simulated by generating a phase screen on the telescope aperture by using the methods described in [25]. The aperture-plane signal distribution is Fourier transformed to get the focal-plane intensity distribution of the received signal. Simulated turbulence effects for a telescope with $D = 1$ m and $r_o = 4$ cm are illustrated in Fig. 1. The aperture-plane phase distribution in Fig. 1(a) deviates from an ideal plane wave. Fig. 1(b) shows the focal-plane distribution (normalized with respect to the diffraction-limited spot size), which deviates from the ideal Airy pattern. It is evident from Fig. 1(b) that the PSF is about $\cong D/r_o$ times that of the diffraction-limited Airy disc.

3. Telescope array-based optical communication receiver

A telescope acts as an antenna in an optical receiver, which collects and focuses the transmitted optical fields onto photodetectors in the focal plane. The photodetectors perform optical to electrical signal conversion followed by communication decoding electronics. A telescope array receiver is an aggregation of a