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Atmospheric turbulence induced synthetic aperture lidar phase error compensation

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ABSTRACT

The resolution of a conventional optical imaging radar system is constrained by the diffraction limit of the telescope's aperture. The combination of lidar and synthetic aperture processing techniques can overcome the diffraction limit and provide a higher resolution air borne remote sensor. Atmospheric turbulence is an important factor affecting lidar imaging, and the phase screen simulation method is an effective method to simulate the degradation of laser signal propagating through turbulent atmosphere. By using Monte-Carlo random factor, the randomness of phase screens can be improved. The lidar imaging with different turbulence intensity is also calculated in this paper, then the improved rank one phase estimation autofocus method is used to compensate the imaging phase errors. The results show that the method of generating phase screen is consistent with the statistics of atmospheric turbulence, which can well simulate the effect of atmospheric turbulence on synthetic aperture lidar, and the influence on synthetic aperture lidar azimuth resolution is greater when atmospheric turbulence is stronger. Improved rank one phase estimation algorithm has good autofocus effect, which can effectively compensate the phase errors and enhance the image quality degraded by turbulence.

1. Introduction

Synthetic aperture imaging is a well-known high-resolution method which improves the imaging capabilities of various ground and satellite telescopes [1–4]. Synthetic aperture imaging extends the resolution capabilities of an imaging system beyond the diffraction limit dictated by the system's real aperture [5]. Using this technique, Synthetic Aperture Radar (SAR) image processing has become a rapidly developing field in the past decade [6]. SAR is a mature remote sensor that was developed to construct microwave images of high resolution by use of antennas of reasonable size. As an active sensor, SAR is widely used in airborne and spaceborne remote sensing [7]. A large number of SAR images that cover most of the Earth's surface have recently been collected by satellites [8].

Compared with SAR, A Synthetic Aperture Lidar(SAL)can provide great improvements in resolution and time to process an image. When the observation range is more than 100 km, the only method can offer centimeter-class resolution with reasonable real aperture size is SAL [9]. SAL techniques, in comparison to those of other optical systems, provide image resolution beyond the diffraction limit of the real optical aperture, allow imaging at night/low-light-level situations, and require relatively low resources [10]. Recent SAL work in the literature includes tabletop-scale laboratory demonstrations [11–13] and aerial-platform demonstrations [14].

One of the main practical issues with SAL is the need to correct turbulence-induced phase errors for proper SAL image formation. With the wide application of laser beams in the atmosphere, such as optical communications, the propagation of high-power laser beams, and laser ranging, the propagation of laser beams in turbulent atmosphere has been studied for many years. When a low-power laser beam propagates through the atmosphere, it can be affected by various phenomena, of which absorption, scattering, and turbulence are the most important [15–19]. An effective method in the research of atmospheric turbulence is the numerical simulation technique, which is based on a multi-phase screen transmission model [20–22]. This method sets up a bridge between theoretical and experimental research and is increasingly being used. The multi-phase screen transmission model was first applied to the acoustic transmission analysis by Tappert and Hardin, and then it was introduced to the free space optical communication field by Fleck et al. in 1976 [23]. The key point of this multi-phase screen transmission model is to use idealized random phase screens to simulate real long-distance atmospheric turbulence. Thus, it is quite important and necessary to develop high-precision and high-efficiency phase screen generation

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0030-4018/

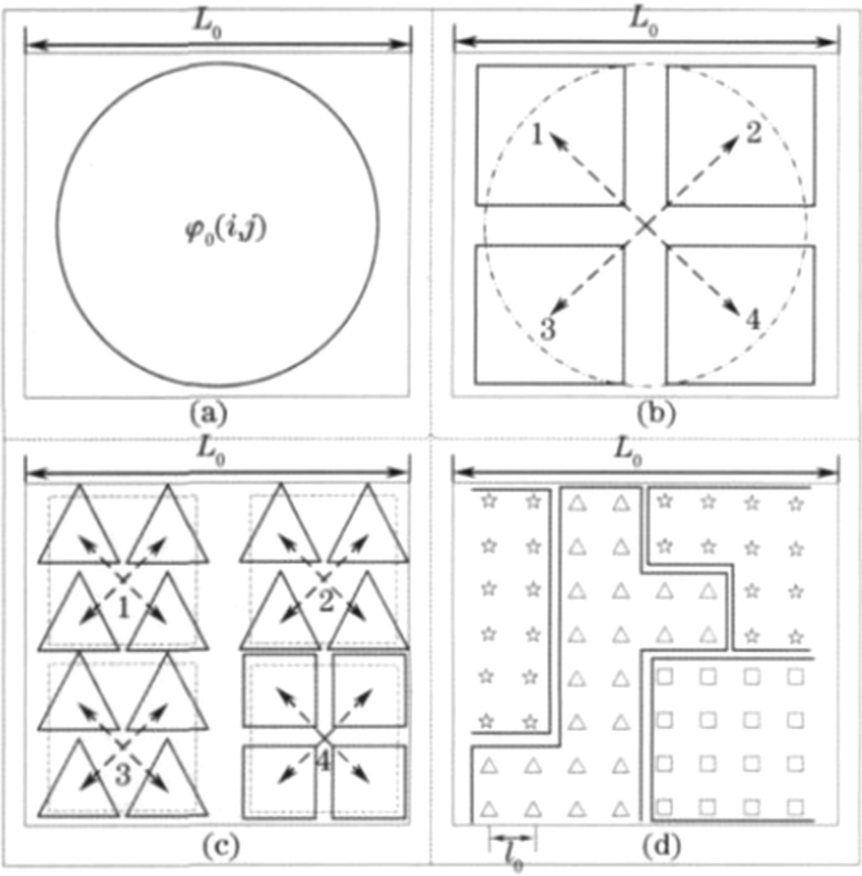

Fig. 1. Process of random unit expansion.(a)Initial phase $\varphi_0(x_0, y_0)$; (b) 2 × 2 grid by 1st expansion;(c) 4 × 4 grid by 2nd expansion;(d) 8 × 8grid by 3rd expansion.

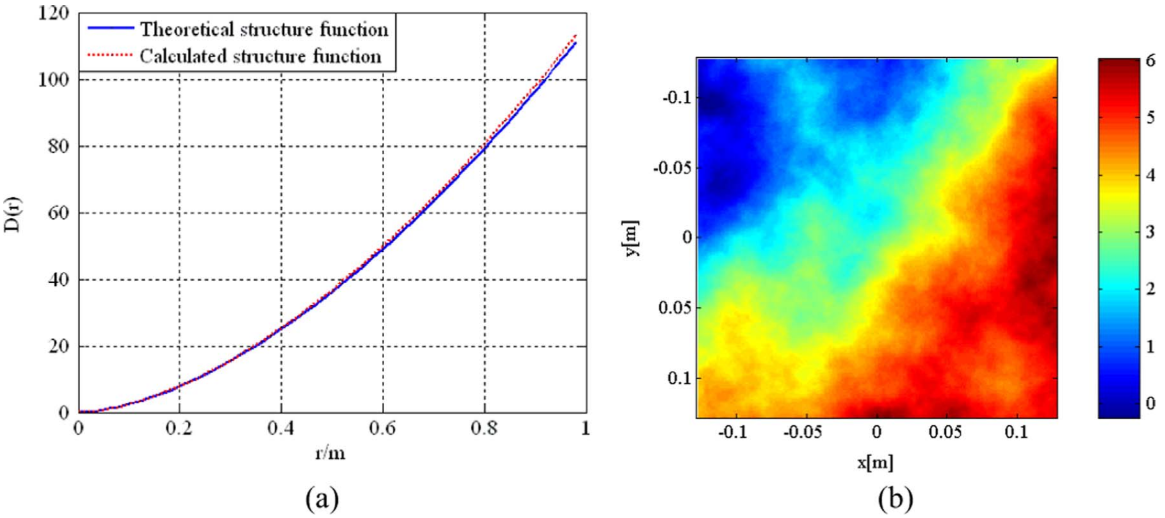

Fig. 2. (a) Structure function calculation results; (b) example of a phase screen.

Table 1
The generation time of a phase screen (unit: second).

Grid number	128 × 128	256 × 256	512 × 512	1024 × 1024
Monte – Carlo	1.356	2.638	7.576	28.644
Spectral inversion	0.344	0.578	1.844	6.593
Spectral inversion with sub–harmonics	3.879	5.938	21.97	78.36

algorithms. At present, the most widely used phase screen generation algorithm is the spectral inversion algorithm [24,25]. Lane et al. introduced two new methods for modeling Kolmogorov phase fluctuations over a finite aperture. The first method relies on the incorporation of subharmonics in order to model accurately the low frequencies of the Kolmogorov spectrum. The second method provides a much faster method for simulating the Kolmogorov spectrum by using a midpoint displacement algorithm