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Optical image reconstruction using an astigmatic lens for synthetic-aperture imaging ladar

Zhiwei Sun, Peipei Hou, Yanan Zhi, Jianfeng Sun*, Yu Zhou, Qian Xu, Liren Liu

Key Laboratory of Space Laser Information Transform and Detection Technology, Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, No. 390, Qinghe Road, Jiading District, Shanghai 201800, People's Republic of China

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ABSTRACT

An optical processor for synthetic-aperture imaging ladar (SAIL) utilizing one astigmatic lens is proposed. The processor comprises two structures of transmitting and reflecting. The imaging process is mathematically analyzed using the unified data-collection equation of side-looking and down-looking SAILs. Results show that the astigmatic lens can be replaced with a cylindrical lens on certain conditions. To verify this concept, laboratory experiment is conducted, the imaging result of data collected from one SAIL demonstrator is given.

1. Introduction

A synthetic-aperture imaging ladar (SAIL) whose principles are based on microwave synthetic aperture radar (SAR) can enable fine resolution, two-dimensional (2D) active imaging at long ranges using small-diameter optics. The one-dimensional (1D) linear and 1D quadratic phase histories are vital for image reconstruction [1–4]. A down-looking SAIL, with a transmitter of two coaxial and deflected polarization-orthogonal beams of spatial spherical or parabolic phase difference and a receiver of self-heterodyne detection, has mainly the same data form and image reconstruction process as the side-looking SAIL [3].

In the 1960s and 1970s, one of the most successful applications of coherent optical data processing involves the data generated by SAR system [5]. Nowadays, the coherent-optics technology is still attractive to researchers for processing the SAR/SAIL data because SAR/SAIL systems typically generate large amounts of data that are difficult and time consuming to digitally compress. Recently, a real-time high-resolution optical SAR processor for satellite borne SAR system was designed and tested [6,7]. Another paper has proposed a principle scheme for optical SAIL processor [8] consisting of azimuth quadratic phase compensation with cylindrical wave and 2D Fourier transform with spherical lens. However additional optical elements are needed to generate the required cylindrical wave.

In this paper, an optical SAIL processor that utilizes one astigmatic lens is proposed. Two structures of reflecting and transmission are presented. The imaging process is mathematically described using the data-collection equation of side-looking and down-looking SAILs. In this optical processor, the incident light is plane wave, no optical elements for cylindrical wave generating is required. Azimuth quadratic phase compensation and 2D Fourier transform are simultaneously realized with one astigmatic lens. Results also show that under certain circumstances, the astigmatic lens can be specialized into a cylindrical lens. Thus, this optical processor is more compact and more suitable for future on-board or satellite-borne SAIL systems. The experimental setup is constructed and the imaging results are presented.

Section 2 provides the principle scheme of the proposed optical SAIL processor, with emphasis on parameter relations, imaging resolution and compression ratios. Section 3 presents the experimental setup and the imaging results that use data obtained from the SAIL demonstrator.

2. Principles and image processing

2.1. Principle scheme of the optical processor

The schematic of the optical SAIL processor is depicted in Fig. 1 (a) and (b) represents the transmitting and reflecting structures respectively. Data collected from SAIL are uploaded on a liquid

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* Corresponding author.
E-mail address: sunjianfengs@163.com (J. Sun).

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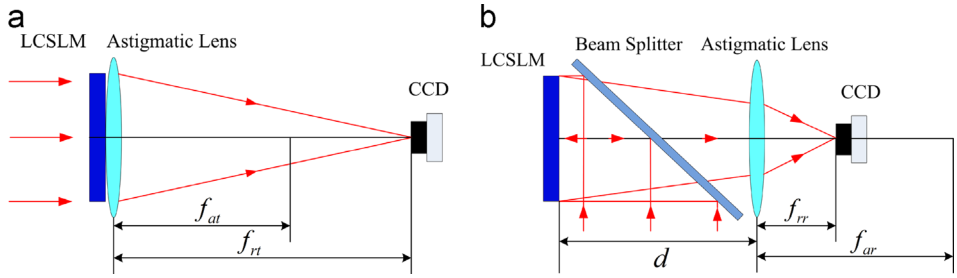

Fig. 1. Schematics of the optical SAIL processor (a) transmitting and (b) reflecting structures.

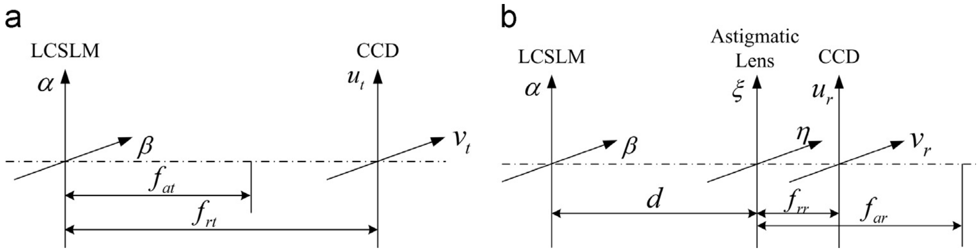

Fig. 2. Coordinate systems for (a) transmitting and (b) reflecting structures.

crystal spatial light modulator (LCSLM) to modulate the incident light. After simultaneously focusing of orthogonal direction of travel (range direction) and travel direction (azimuth direction), the intensity of imaging results are captured with a charged-coupled device (CCD). Notably, both the incident lights in the two structures are plane wave, this is different from the previously presented one [8] requires cylindrical wave for quadratic phase compensation.

In the transmitting structure, the LCSLM is close to the astigmatic lens whose focal length in the orthogonal direction of travel and travel direction are f_{rt} and f_{at} respectively. The CCD is on the focal plane of the astigmatic lens along the orthogonal direction of travel. As to the reflecting structure, the beam splitter is utilized to reflect the light beam. The distance between the LCSLM and the astigmatic length is d, and f_{rr} and f_{ar} are the focal length of the astigmatic lens in the orthogonal direction of travel and travel direction respectively. The CCD is located on the focal plane of the astigmatic lens along the orthogonal direction of travel.

The coordinate systems adopted here for mathematical analysis of the two structures are depicted in Fig. 2. The vertical axis and horizontal axis represent the orthogonal direction of travel and travel direction, respectively.

The amplitude of incident light is assumed to constantly be 1, and the modulating function of the LCSLM is $t(\alpha)t(\beta)$, which is orthogonal in the two directions for simplicity. The 2D imaging result is obtained by Fourier transform in the orthogonal direction of travel and Fresnel transform in the travel direction. For the transmitting structure, the complex amplitude of the imaging result is given by

$$e_t(u_t,v_t)=\frac{\exp(j2\pi f_{rt}/\lambda_i+j\pi)}{\lambda_i^2 f_{rt}^2}\exp\left[j\frac{\pi}{\lambda_i f_{rt}}(u_t^2+v_t^2)\right]\mathcal{F}_{\alpha\to u_t/\lambda_i f_{rt}}\{t(\alpha)\}$$
$$\times\int_{-\infty}^{+\infty}t(\beta)\exp\left[j\frac{\pi}{\lambda_i}\left(\frac{1}{f_{rt}}-\frac{1}{f_{at}}\right)\beta^2\right]\exp\left(-j\frac{2\pi}{\lambda_i f_{rt}}v_t\beta\right)d\beta \tag{1}$$

where $\mathcal{F}$ denotes Fourier transform, and λ_i is the wavelength of incident light. For the reflecting structure, the complex amplitude of the imaging result is derived as follows:

$$e_r(u_r,v_r)=\frac{j\exp[j2\pi(d+f_{rr})/\lambda_i]}{\lambda_i^3 f_{rr}^2 d}\exp\left\{j\frac{\pi}{\lambda_i f_{rr}}\left[v_r^2+\left(1-\frac{d}{f_{rr}}\right)u_r^2\right]\right\}$$
$$\mathcal{F}_{\alpha\to u_r/\lambda_i f_{rr}}\{t(\alpha)\}\int_{-\infty}^{+\infty}\exp\left[j\frac{\pi}{\lambda_i}\left(\frac{1}{f_{rr}}+\frac{1}{d}-\frac{1}{f_{ar}}\right)\eta^2\right]\int_{-\infty}^{+\infty}t(\beta)\exp\left(j\frac{\pi}{\lambda_i d}\beta^2\right)$$
$$\exp\left(-j\frac{2\pi}{\lambda_i d}\eta\beta\right)d\beta\exp\left(-j\frac{2\pi}{\lambda_i f_{rr}}v_r\eta\right)d\eta \tag{2}$$

Thus, the imaging intensity captured by the CCD in the two structures have thus the form: $|e_t(u_t,v_t)|^2$ and $|e_r(u_r,v_r)|^2$.

2.2. Image reconstruction

SAIL data are discretely collected in the temporal domain both at the travel direction and orthogonal direction of travel of the side-looking and down-looking SAILs. For concise analysis of the imaging process, consecutive temporal variables are adopted. For the side-looking SAIL with a chirped laser and the down-looking SAIL with two coaxial and deflected polarization-orthogonal beams, the unified data-collection equation [3] for a target point (x_k,y_k) is given by

$$i_k(t_s,t_f:x_k,y_k)=A(x_k,y_k)\,S\,(x_k,y_k-v_yt_s)\,W\,(t_f)$$
$$\exp[j2\pi f_{eq}(x_k)t_f]\exp\left[j\frac{\pi}{\lambda F}(y_k-v_yt_s)^2\right] \tag{3}$$

where x_k and y_k represent the location in travel direction and orthogonal direction of travel, respectively, of the target point. The variable t_s is the slow time in the travel direction and t_f is the fast time in the orthogonal direction of travel. $A(x_k,y_k)$ is the receiving factor of the optical field related with SAIL construction, system arrangement and target reflecting characteristic. $S(x_k,y_k-v_yt_s)$ is the optical footprint function determined by the common regime of the illuminated area and the detectable area at the target plane. v_y is the SAIL speed of along the travel direction. $W(t_f)$ is the sampling window function in the orthogonal direction of travel. $f_{eq}(x_k)$ is the equivalent beat frequency in the orthogonal direction of travel. F is the curvature radius of the optical footprint on the target plane.