Research on Military Application and Development Trend of Lidar

Gege Sun[1], Miao Tian[1], Wenbo Song[1], Xiaosi Xue[1], Zhengjun Liu[2], Hang Chen[1,*]

[1]School of Space Information, Space Engineering University, Beijing, 101416, China

[2]School of Physics, Harbin Institute of Technology, Harbin, 150001, China

*Corresponding author: hitchenhang@foxmail.com

Keywords: Lidar, Military, Applications, Development Trends

Abstract: As an important new type of active remote sensing tool, LiDAR, compared with traditional radar technology, has multiple advantages such as high measurement accuracy, high time resolution, high spatial resolution and long detection distance, which makes up for the shortcomings of the performance of optical, radar and other traditional payloads, and has a broad application prospect in the military field. Firstly, the concept of LiDAR is introduced, and the domestic and international research status and existing technology level of five kinds of LiDAR in military applications, such as reconnaissance imaging, homing guidance, underwater detection, atmospheric prediction and obstacle avoidance, are introduced in detail. Finally, the military advantages and development trends of LiDAR are summarised, and the author's suggestions are put forward.

1. Introduction

LiDAR (Light Detection and Ranging) integrates traditional radar and modern laser technology, representing a novel active optical remote sensing approach. The system primarily consists of a laser emitter, a photodetector, and signal-processing circuitry. LiDAR utilizes laser beams as information carriers, detecting data through amplitude, phase, frequency, and polarization variations, among other parameters[1]. Compared to traditional remote sensing technologies, LiDAR offers several advantages, including high precision, all-weather capability, non-contact measurement, and extensive mapping range. Compared to conventional optical sensors, LiDAR is characterized by its smaller size and lighter weight, enhancing its practical utility in military operations. Furthermore, LiDAR exhibits superior performance in areas such as a wide velocity measurement range, high-velocity resolution[2], excellent angular and distance resolution, and remarkable resistance to interference. These attributes address the shortcomings of traditional optical measurement systems in military applications, such as insufficient imaging reconnaissance precision, the inability to detect target bodies obscured by exhaust plumes, and the complexity of data processing.

In modern military applications, LiDAR is pivotal in monitoring individual soldier operations and battlefield environments. LiDAR has been successfully applied across various combat domains, including imaging reconnaissance, weapon guidance, obstacle avoidance, and chemical warfare agent detection[3-4]. Additionally, due to its compact size, lightweight design, low power consumption, and resilience to atmospheric attenuation and scattering in space, LiDAR holds significant potential for aerospace applications. LiDAR is currently employed in spacecraft docking, close-range imaging of aerial vehicles, and other space-related fields.

This paper begins by briefly outlining the operational principles and main classifications of LiDAR. It then delves into an in-depth examination of the current state of research and technological development in five key military applications: reconnaissance imaging, seeker guidance, underwater detection, atmospheric prediction, and obstacle avoidance. Finally, the paper provides an overview of the advantages of LiDAR in military contexts and offers some recommendations for its future development.

  DOI: 10.25236/icmmct.2025.023

2. Related Concepts of LiDAR

2.1 The Principle of LiDAR

LiDAR (Light Detection and Ranging) is an optical remote sensing technology that leverages the properties of scattered light to acquire target information from long distances. It encompasses several core areas of physics and is considered one of the most advanced applications in the field. The LiDAR system consists of components such as the laser source, photodetector, and signal detection apparatus, with the laser source positioned at the front end and the detector at the rear end of the optical system. As illustrated in Figure 1, the typical wavelength range for LiDAR spans from 250 nm to 11 μm, primarily covering the near-infrared, visible, and ultraviolet spectral ranges. In contrast to microwave radar, the radiation frequency of LiDAR is at least two to four orders of magnitude higher[5]. The narrow beam, high energy concentration, and excellent coherence of the laser endow LiDAR with exceptionally high angular, velocity, and distance resolution. These attributes enable it to detect small-scale targets, such as aerosols, and generate reliable echo signals. The detection principle of LiDAR is depicted in Figure 2, while the resulting imaging is shown in Figure 3.

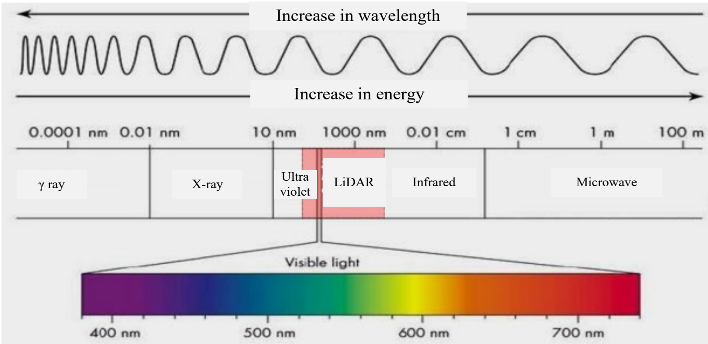

Figure 1 Common Wavelength Ranges of LiDAR

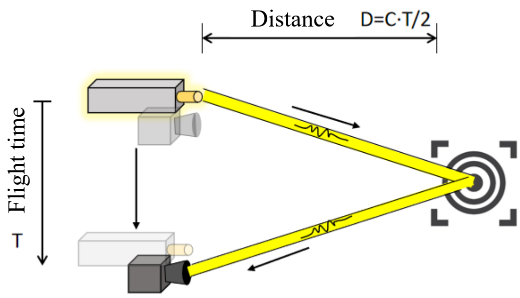

Figure 2 Schematic of LiDAR Detection Principle

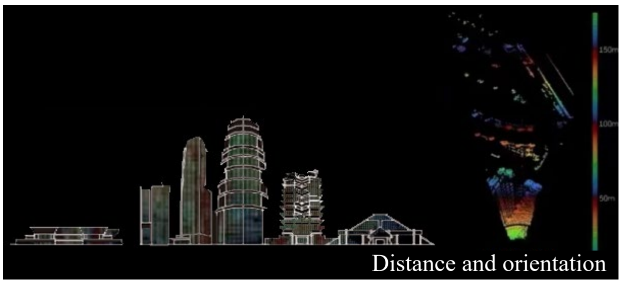

Figure 3 Illustration of LiDAR Detection and Imaging Results

2.2 Classification of LiDAR

In the military domain, LiDAR applications are diverse. They can be classified based on their functionality into categories such as laser ranging radar, optical velocity radar, laser angle tracking radar, laser imaging radar, atmospheric sensing LiDAR, and biological LiDAR, each tailored to different operational scenarios and requirements. For instance, atmospheric sensing LiDAR can monitor wind field dynamics in real-time within operational areas, thereby supporting missile launches and aircraft take-offs.

LiDAR systems can also be categorized based on the platform they are mounted on, including portable, ground-based, vehicle-mounted, shipborne, airborne, spaceborne, and missile-borne systems. Several Western military-industrial companies, including Canada's Optech, France's Top Sys, and the United States' Leica, have developed commercialized airborne LiDAR systems. However, these systems are limited by factors such as the divergence angle of the laser, scanning field of view, and flight range, which hinder their ability to cover the entire globe[6]. In contrast, spaceborne LiDAR systems offer distinct advantages, such as higher orbits and wider fields of view, enabling global coverage and the provision of three-dimensional control points and Digital Elevation Models (DEM) for regions beyond national borders. Additionally, spaceborne LiDAR is used in U.S. lunar and Mars exploration missions to create comprehensive three-dimensional topographic maps. These systems also play a crucial role in monitoring vertical vegetation distribution, sea surface height, cloud and aerosol distribution, and special climate events[7].

3. Military Applications of LiDAR

3.1 Imaging Reconnaissance

In modern military operations, obstacles such as camouflage nets and tree canopies have significantly increased the difficulty of identifying military targets. Consequently, rapid and accurate survey of camouflaged military targets has become critical. With advancements in laser technology and electro-optical detection systems, Synthetic Aperture Laser Radar (SAL) has found widespread application in military reconnaissance.

Under the Defense Advanced Research Projects Agency (DARPA) support, Raytheon Company in the United States has conducted imaging research on Inverse Synthetic Aperture Laser Radar (ISAL) for satellite detection and camouflaged satellite identification. However, no public imaging results have been disclosed as of yet. The operational principle of ISAL is illustrated in Figure 4. Additionally, the Massachusetts Institute of Technology (MIT) has proposed a novel LiDAR imaging modality known as the "rebound flash LiDAR," which enables strategic localization of light sources and can also be used to estimate the shape of concealed objects and obscured surfaces.

In China, research on SAL began relatively early, and despite a later start in experimental investigations, significant progress has been achieved in recent years. A Chinese Academy of Sciences research team proposed a laser synthetic aperture radar technology system that greatly expands the imaging field of view. Experimental results have shown that the imaging resolution exceeds 3 cm × 1 cm. Furthermore, a successful demonstration of a large-aperture synthetic aperture laser imaging radar was conducted by the Shanghai Institute of Optics and Fine Mechanics (SIOM). The experiment demonstrated that the prototype system could perform dynamic two-dimensional SAL imaging at a transmission distance of 14 meters, with an imaging resolution superior to 1.4 mm × 1.2 mm. These advancements provide novel technological solutions for military imaging reconnaissance and offer vital support in addressing the challenges of identifying camouflaged military targets[8].

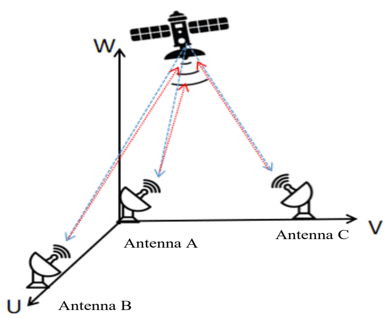

Figure 4 Operational Principle of Inverse Synthetic Aperture Laser Radar (ISAL)

3.2 Seeker Guidance

With the advancement of infrared jamming technologies, traditional infrared-guided weapons have faced significant challenges, leading to the emergence of laser-guided technology. Laser guidance systems employ lasers to precisely direct missiles or bombs to their targets, offering advantages such as high accuracy and strong resistance to interference. Common methods of laser guidance include laser beam-rider guidance and laser semi-active seeker guidance.

Laser-guided weapons have demonstrated significant advantages in combat, which have garnered the attention of military forces worldwide. The U.S. military initiated the Joint Common Missile (JCM) project and successfully conducted JAGM-MR-guided flight tests, significantly improving strike accuracy. The Copperhead laser-guided artillery shells, for example, can continuously track and engage targets, allowing for mid-flight corrections to the projectile's trajectory. Russia has introduced the "Hermes" multipurpose tactical missile system, which can carry different types of seekers, including semi-active laser homing, to meet varying operational needs. Additionally, countries such as Israel, South Africa, and Iran have actively developed and deployed laser-guided weaponry[9].

Research into laser-guided weapons in China began in the late 1970s, gradually evolving into a primary means for precision strikes. The fourth-generation laser-guided bombs GB-1000 and GB-100, developed by Harbin Engineering Group, are characterized by their high precision, extended range, ease of maintenance, and cost-effectiveness. The "Cloud Arrow 1000," a heavy laser-guided bomb developed by China's Ordnance Group, can penetrate reinforced concrete structures up to 6 meters thick, providing substantial operational capability against traditional underground fortifications[10].

3.3 Underwater Detection

In the study and exploration of oceans, technological limitations have traditionally constrained the detection of underwater environments. While acoustic detection has been widely utilized, the total internal reflection at the air/water interface has significantly hindered the broader application of acoustic technologies. Recently, oceanographic LiDAR has rapidly developed into a key technology for detecting the air-water interface and shallow marine environments. Ocean LiDAR systems employ laser beams to measure various oceanographic parameters rapidly, offering advantages such as high repetition rates, fast detection speeds, and long-range remote sensing capabilities. These systems can be mounted on various underwater, shipborne, airborne, and spaceborne systems, for various applications, such as ocean temperature measurement, depth sounding, oil spill detection, and water quality monitoring[11-12].

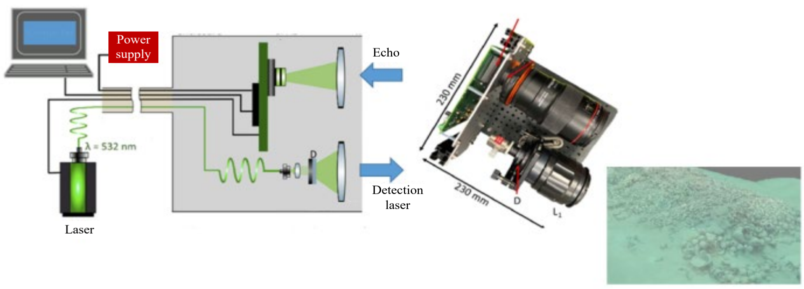

Figure 5 Operational Schematic of Underwater Detection Product by Canadian Company

In shallow water detection, ocean LiDAR has shown significant potential, surpassing sonar in many respects, and is regarded as an extremely promising new technology. Countries around the world have actively pursued related research and applications. For example, the CZMILSuperNova system developed by Canada's Optech, as shown in Figure 5, offers exceptional depth-sounding performance, high green laser point density, and real-time processing capabilities. It is suitable for inland water environments, coastal areas, and basic shoreline mapping, with strong penetration capabilities that enable accurate target detection in turbid waters. The ALMDS system developed by

Northrop Grumman in the U.S. can quickly detect and locate surface and near-surface moored mines, allowing for the preemptive removal or detonation of mines that may pose a threat. The Mapper 5000, developed by the Shanghai Institute of Optics and Fine Mechanics of the Chinese Academy of Sciences, is China's first airborne dual-frequency laser radar system for marine exploration and transmission applications. Since the late 1970s, Ocean University of China has researched ocean LiDAR, developing various shipborne and airborne systems and conducting experiments in the East China Sea, Yellow Sea, and Bohai Sea. The research team has also designed multi-channel LiDAR systems that successfully achieve precise detection of small targets in the ocean[13-15].

3.4 Atmospheric Prediction

LiDAR systems offer significant advantages over conventional microwave radar in atmospheric detection, including longer continuous detection times, higher measurement accuracy, and superior spatiotemporal resolution. These capabilities enable precise detection of atmospheric aerosols, temperature and humidity levels, wind fields, greenhouse gases, and pollutants. LiDAR thus plays a crucial role in supporting aviation and space missions, providing essential atmospheric parameters for defence applications, and offering foundational data for climate change research, weather forecasting, and atmospheric modelling.

The U.S. CALIPSO satellite, a joint mission by NASA and CNES, is a solar-orbiting Earth observation satellite equipped with the CALIOP LiDAR system. This system is designed to observe aerosols and micron-sized cloud particles and is regarded as one of the most successful atmospheric LiDAR systems launched by the U.S. The next-generation spaceborne Cloud-Aerosol Transport System (CATS), developed by NASA, has been deployed aboard the International Space Station (ISS) and represents a significant advancement in spaceborne laser remote sensing technology for atmospheric research[16-19].

China has also made significant progress in atmospheric detection. The Atmospheric Environment Monitoring Satellite (DQ-1), which carries the Atmospheric Detection LiDAR (ACDL) payload, has achieved the world's first global high-precision joint measurement of carbon dioxide concentrations and aerosols. This mission marks the first-ever spaceborne LiDAR for carbon dioxide detection and the first high-spectral aerosol detection LiDAR. Furthermore, Academician Xian-Kang Dou proposed at the "Yanqi Lake Conference" that enhancing the quantum efficiency of LiDAR systems could improve signal-to-noise ratios, potentially solving the challenges associated with middle and upper atmospheric detection through quantum LiDAR technology[20-23].

Given that environmental factors such as airspeed can affect bomb trajectories and flight resistance, the U.S. military uses LiDAR to measure wind fields and adjust flight paths for precise weapon delivery. The UK Ministry of Defence has developed a LiDAR system capable of measuring microburst wind shear and wake turbulence, which monitors flight runways and improves aircraft throughput. The B-2 bomber is also equipped with LiDAR to detect condensation wake turbulence, immediately alerting crews to any anomalies[24-25].

3.5 Obstacle Avoidance

In-flight missions, aircraft are often required to fly at lower altitudes to avoid detection while improving target environment sensing. However, low-altitude flight poses challenges due to complex environments and potential obstacles. LiDAR, with its high-resolution capabilities, has become a widely used technology for obstacle detection and avoidance. By acquiring information about the shape, distance, and position of obstacles, LiDAR enables aircraft to effectively navigate around obstructions, thereby enhancing flight safety.

Several countries have developed helicopter LiDAR systems for obstacle avoidance, successfully enabling low-altitude flight technology. For example, the "Hellas" LiDAR system, as shown in Figure 6, created by the German GmbH Aerospace company, boasts efficient detection capabilities, including detecting obstacles as small as 1 cm in diameter, ensuring helicopter flight safety[26]. The Clara LiDAR, jointly developed by Dassault Electronics of Germany and Marconi of the UK, uses

CO2 lasers to provide a 10-second warning of cables as thin as 5 mm in diameter, making it an essential tool for operations in adverse weather conditions. The French CLARA LiDAR system, mounted on a pod, can detect obstacles such as markers and cables while offering terrain-following, target designation, ranging, and moving target detection functions[27].

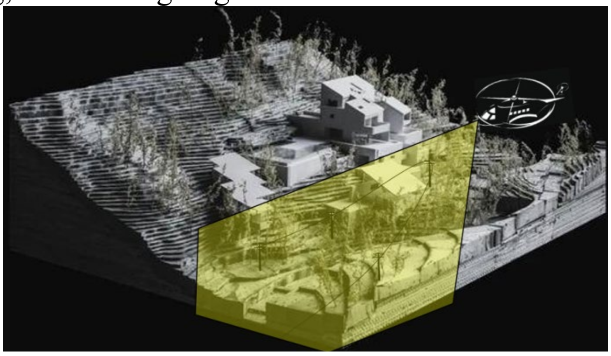

Figure 6 Detection and Identification of Cables by the "Hellas" LiDAR System

4. Advantages and Challenges of LiDAR

4.1 Advantages of LiDAR

4.1.1 High-Precision Measurement Capabilities

LiDAR systems can perform high-precision measurements, providing crucial data for precision targeting. Through advanced inertial navigation systems and laser emitters, commercial LiDAR systems can achieve measurement errors within 10 centimetres at an altitude of 1000 meters. They are widely used for surveying ground features such as buildings, roads, and bridges[28]. On the other hand, military systems can deliver even greater precision, making them suitable for large-scale battlefield monitoring and the detailed measurement of smaller targets, such as armoured vehicles and combat aircraft.

4.1.2 3D Point Cloud Data Acquisition

The three-dimensional point cloud data captured by LiDAR enhances target analysis by providing in-depth information, which increases the accuracy of pattern recognition while reducing reliance on human intervention[26]. This dataset integrates the spatial structure of the target, enabling the system to identify concealed objects, regardless of camouflage, based on colour or texture. Additionally, the 3D point cloud can be converted into 2D depth images, which can be fused with traditional optical imagery for improved analysis[29 ,30].

4.1.3 Multi-Echo Detection Capability

LiDAR systems can produce multiple reflections from obstacles at varying distances from the laser emitter. If only a single echo is recorded, only the closest target to the sensor will be detected. However, by capturing the reflected signals from targets behind obstacles, LiDAR enables the simulation and analysis of concealed objects, enhancing the ability to identify hidden targets. Moreover, employing different filtering algorithms in various environmental conditions makes it possible to effectively remove interference signals and accurately calculate the distance and shape of hidden targets[15,28].

4.1.4 Reflection Intensity Analysis

LiDAR provides positional information and records the amplitude of reflected light waves, i.e., the reflection intensity. With knowledge of the operational parameters of the LiDAR system, the intensity of the reflection from the identified target can be used to infer the object's material composition, such as stone, metal, or other materials. By analyzing the reflection intensity, LiDAR can effectively distinguish between real and camouflaged targets, providing multi-dimensional data for battlefield recognition and offering valuable support for subsequent decision-making.

4.2 Challenges of LiDAR

4.2.1 Environmental Sensitivity

Under the dynamic conditions of a battlefield, the performance of LiDAR systems can be significantly impacted by environmental factors. For example, raindrops can cause scattering and reflection of the emitted laser beams, reducing detection accuracy. Detection ranges can be drastically shortened in low visibility conditions or areas with heavy atmospheric pollution. Furthermore, low cloud cover or low-light conditions can substantially degrade detection precision. Strong winds, gusts, or sudden storms can also reduce the signal-to-noise ratio, negatively affecting image clarity and target detection capabilities[31].

4.2.2 Challenges in Target Recognition

Target recognition becomes particularly challenging when multiple objects are present in the field of view. Precision and speed of recognition are crucial, as various types of obstacles may occlude targets, complicating localization and reducing the efficiency of the sensor. Buildings, terrain features, and enemy camouflage techniques can all interfere with the accuracy of LiDAR systems. Additionally, deep learning-based target recognition models typically require large datasets for training. Obtaining sufficient training samples can be difficult for sensitive targets such as tanks or armoured vehicles. Therefore, it is essential to develop feature-matching techniques that do not rely on large data sets, enhancing recognition systems' adaptability and flexibility.

5. Military Development Trends of LiDAR

Upon summarizing the international development trajectory of LiDAR technology, the following three key trends in its military applications can be identified:

5.1 Achieving an Integrated "Air-Space-Ground" Multi-Platform LiDAR Payload System

The goal is to establish an integrated "air-space-ground" monitoring system. Ground-based and airborne LiDAR systems will be utilized within domestic boundaries to construct a ground monitoring network and an airborne measurement system, respectively. At the same time, by incorporating spaceborne LiDAR, the large coverage range of satellite platforms will enable global reconnaissance with full-domain coverage. This will facilitate multi-dimensional, precise measurements of targets, enabling continuous, real-time, all-encompassing three-dimensional information collection, thereby significantly enhancing operational monitoring capabilities.

5.2 Multi-Payload Information Fusion for Target Detection

LiDAR offers distinct advantages over another remote sensing techniques such as visible light, microwave, infrared, and hyperspectral sensors. For example, while microwave beams have a larger divergence angle and stronger search capabilities, LiDAR excels in precision and resistance to interference. In future warfare, it is essential to integrate multiple payloads to complement each other's functions. In future early warning systems, for instance, microwave radar could be used for large-area searches to detect potential targets, then alert LiDAR systems for tracking, speed measurement, and distance estimation. Following this, visible-light cameras would be employed for target imaging reconnaissance. It would enable high-speed, high-precision, and multi-dimensional monitoring of targets.

5.3 Designing Miniaturized, Soldier-Level Situational Awareness Smart Equipment

Despite the increasing automation of weaponry and command systems, the effectiveness of small-unit operations continues to rely heavily on the combat potential of individual soldiers. LiDAR, with its high detection accuracy and strong anti-interference capabilities, is highly suitable for current military operations, including counterterrorism and peacekeeping. While LiDAR technology has been gradually applied across various military domains, such as battlefield monitoring, real-time intelligence gathering, and precision strikes, it has yet to be effectively integrated into developing miniaturized, soldier-level situational awareness systems. LiDAR is primarily due to limitations in technological maturity and the high costs associated with its design and implementation.

6. Conclusion

Although LiDAR technology has made significant breakthroughs in recent years, challenges remain in integrating it into specific military applications. The high technical barriers and costs are major obstacles hindering the widespread adoption and application of LiDAR technology. Since 2009, China has surpassed Germany and France, positioning itself as the second leading country globally in LiDAR research. However, domestic research focuses on fundamental optics, devices, and system development. While preliminary achievements have been made in meteorology, atmospheric science, environmental science, and ecology, top-tier research in other application areas remains relatively limited.

In light of this, the author suggests that domestic research institutions continue to deepen their exploration of LiDAR technology and facilitate its integration into specific military applications. The potential of LiDAR in military contexts signals the future trajectory of military advancements, and its possible applications in future warfare could fundamentally alter China's overall combat strategies and tactics. With the continued advancement of cutting-edge technologies, LiDAR is expected to play an increasingly pivotal role in the future of military technologies.

References

[1] Rivera G, Porras R, Florencla R, et al. LiDAR applications in precision agriculture for cultivating crops: A review of recent advances[J]. Computers and Electronics in Agriculture, 2023, 207: 107737.

[2] Bu Yuming, Du Xiaoping, Zeng Zhaoyang, et al. Research Progress and Trend Analysis of Non-Scanning Laser 3D Imaging Radar[J]. Chinese Optics, 2018, 11(05): 711-727.

[3] Zhao Yiming, Li Yanhua, Shang Yanan, et al. Applications and Development Trends of LiDAR[J]. Telemetry and Remote Control, 2014, 35(05): 4-22.

[4] Li N, HO C P, XUE J, et al. A progress review on solid-state LiDAR and nanophotonics-based LiDAR sensors[J]. Laser & Photonics Reviews, 2022, 16(11): 2100511.

[5] Milonni P W. Lidar. Range-Resolved Optical Remote Sensing of the Atmosphere, in the Springer Series in Optical Sciences, Vol. 102, edited by Claus Weitkamp: Scope: review. Level: specialist. 2009.

[6] Geng Lin, Zhang Zhongping. Research Progress in Foreign Space Laser Application Technology[J]. Laser and Infrared, 2010, 040(9): 919-925.

[7] Fahey T, Islam M, Gardi A, et al. Laser beam atmospheric propagation modelling for aerospace LIDAR applications[J]. Atmosphere, 2021, 12(7): 918.

[8] Qiu Pengyu. Research on 3D Imaging Algorithm Based on Interferometric Synthetic Aperture LiDAR[D]. Harbin Institute of Technology, 2018.

[9] Bao Haige. Development of Foreign Laser Semi-Active Homing Guided Weapons[J]. Shipborne Electronics Engineering, 2010, 30(05): 21-25.

[10] Yu Fengquan, Gong Yue, Zhang Gang. Overview of Airborne Laser Guided Weapon Development[J]. Command Control & Simulation, 2022, 44(04): 26-30.

[11] Li Kaipeng, Liu Fanghua, Chen Yongqiang, et al. Development Overview of Underwater Laser Detection Technology[C]//Shanghai Institute of Technical Physics, Chinese Academy of Sciences; Shanghai Infrared and Remote Sensing Society; Shanghai Sensing Technology Society. Proceedings

of the 2019 Infrared, Remote Sensing Technology, and Application Seminar and Cross-Disciplinary Forum, 2019: 8.

[12] Zhang Yin. Overview of Airborne LiDAR Shallow-Water Small Target Detection Technology[J]. Digital Ocean and Underwater Offense and Defense, 2023, 6(04): 450-457.

[13] Mullen, Linda J. Hybrid lidar-radar for enhanced underwater detection[D]. Drexel University, 1996.

[14] Li Peizheng. Simulation Study on Airborne Laser Underwater Detection Technology Based on Modulation Technology[D]. University of Electronic Science and Technology of China, 2014.

[15] Guo Husheng, Liu Qizhong, Tong Mingchen, et al. Research on Echo Signal Extraction Method for Laser Underwater Detection Optical Wake[J]. Laser and Infrared, 2010, 040(10): 1048-1052.

[16] Wu D., Tang J., Liu Z., et al. Simulation of coherent Doppler wind lidar measurement from space based on CALIPSO lidar global aerosol observations[J]. Journal of Quantitative Spectroscopy & Radiative Transfer, 2013, 122(null).

[17] Hongbin Y, Mian C, David M. W, et al. Global view of aerosol vertical distributions from CALIPSO lidar measurements and GOCART simulations: Regional and seasonal variations[J]. Journal of Geophysical Research, D. Atmospheres: JGR, 2011, 116(d4).

[18] Mccormick M P, Winker D M, Browell E V, et al. Scientific investigations planned for the Lidar In-space Technology Experiment (LITE)[J]. Bulletin of the American Meteorological Society, 1993, 74(2): 205-214.

[19] Fix A, Naletto G, Hutchinson I, et al. Space Lidar and Space Optics[J]. CEAS Space Journal, 2019, 11: 359-362.

[20] Fan Boxuan, Chen Guiming, Chang Liang, et al. Application Status and Development Trends of LiDAR Technology in the Military Field[J]. Aerospace Manufacturing Technology, 2021(03): 66-72.

[21] Wang Xijin, Xu Qingshan, Fan Chuanyu, et al. LiDAR Detection of Day and Night Aerosol Optical Thickness of the Entire Atmosphere[J]. Journal of Atmospheric and Environmental Optics, 2023, 18(1): 14-24.

[22] Liu Guangyuan. Retrieval of Atmospheric Aerosol Optical Thickness Using Satellite Visible Channels[J]. Meteorological Science, 1997, 000(2): 159.

[23] Gao Ling, Ren Tong, Li Chengcai, et al. Retrieval of Atmospheric Aerosol Optical Thickness Using Geostationary Satellite MTSAT[J]. Acta Meteorologica Sinica, 2012, 070(3): 598-608.

[24] Jain A R, Anandan V K. Applications of facilities at NMRF, Gadanki, in the area of meteorology and coupling processes in the atmosphereospheremospherellite MTSAT[prospects[J]. Indian Journal of Radio & Space Physics, 2002, 31(6): 357-368.

[25] Zhou Rundong, Xia Pan, Zhang Xiaohu, et al. Research Progress and Future Prospects of Atmospheric Wind Guidance with Meteorological Satellites[J]. Reviews of Earth and Planetary Physics (Chinese and English), 2024, 55(2): 184-194.

[26] Sun Jianfeng, Li Qi, Wang Qi. Role of 3D Imaging by LiDAR in Precision Guidance[C]//Proceedings of the 2004 National Optoelectronic Technology Academic Exchange Conference. 2004.

[27] Liu Shangfu, Hu Hui. Development Trends of Foreign LiDAR[J]. Shipborne Electronics Engineering, 2017, 037(6): 1-4.

[28] Wang Hai, Liu Mingliang, Cai Yingfeng, Chen Long. Vehicle Target Detection Algorithm Based on LiDAR and Millimeter-Wave Radar Fusion[J]. Journal of Jiangsu University (Natural

Science Edition), 2021, 042(4): 389-394.

[29] Han Bin, Cao Jie, Shi Moudan, et al. Research Progress on LiDAR 3D Imaging (Invited)[J]. Advances in Laser and Optoelectronics, 2024, 61(02): 46-63.

[30] Tan Zhiguo, Lu Min, Hu Yanping, Guo Yulan, Zhuang Zhaowen. LiDAR Target Recognition Based on Point Cloud-Model Matching[J]. Computer Engineering and Science, 2012, 034(4): 32-36.

[31] Ni Shuxin, Li Yifei. Development Trends of Military LiDAR[J]. Infrared and Laser Engineering, 2003(02): 111-114.