Simulation of the performance of spaceborne hybrid Doppler wind lidar

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Abstract: Accurately measuring wind field is crucial for weather forecasting, climate and meteorological research, aeronautical flights and wind resource exploitation. Spaceborne Doppler wind lidar has become an important instrument for observing the vertical profile of the global wind field, with the successful operation of Aeolus. The spaceborne hybrid wind lidar uses both direct and coherent detection techniques, taking full advantage of the observational benefits of both methods to detect the global wind field with high resolution. Direct detection technique is used to observe the middle and upper troposphere and lower stratosphere, which are dominated by molecular scattering, while coherent detection technique observes the lower troposphere and the atmospheric boundary layer. The incoherent detection module operates at 355 nm and uses the dual-edge detection technique based on Fabry–Pérot etalon. And the coherent detection module uses heterodyne detection technique operating at 1064 nm. This paper simulates and analyses the key parameters of the spaceborne hybrid wind lidar for future satellite missions. And a method for detecting horizontal wind field based on dual-beam observation was developed to ensure the response of the lidar for wind speed detection in both longitudinal and latitudinal directions.

1. Introduction

Accurately measuring wind field is crucial for studying the dynamical structure and evolutionary characteristics of the atmosphere, as well as heat-momentum-matter exchange and balance [1–3]. According to the World Meteorological Organization (WMO), global observation of the 3D wind field is the primary factor for improving the accuracy of numerical weather prediction [4]. Due to the absence of aeronautical data, meteorological observation and forecasting capabilities are notably deficient in sparsely populated areas, the southern hemisphere, the polar regions, and the vast oceans. As a new technological development, spaceborne wind measurement lidar has been identified by the WMO as the primary direction for future global wind observation, based on its ability to continuously observe the wind field on a global scale in high accuracy vertical profiles [5,6].

Many countries are actively involved in the demonstration of spaceborne lidar technology and system development. In 2018, the European Space Agency launched the Aeolus [7]. The data analysis and numerical weather prediction assimilation assessment of the Doppler wind measurement lidar in orbit for four years and eight months showed that the technological maturity of wind measurement lidar and prospective capacity for model application reach the best expectations [8]. This has garnered extensive attention in the fields of meteorology and remote sensing worldwide. Spaceborne Doppler wind lidar has become an important instrument for observing the vertical profile of the global wind field, with the successful operation of Aeolus [9-11]. However, due to technical difficulties and limited funds, the spaceborne wind measurement lidar projects of the National Aeronautics and Space Administration (NASA), Japan Aerospace Exploration Agency (JAXA) and other agencies have remained at the simulation demonstration or airborne test stage [12,13].

As part of China's next-generation polar-orbiting meteorological satellite plan, FY-5 lists active wind measurement lidar as one of the new payloads to be developed on a priority basis. This technological programme will effectively promote the high-quality development of China's meteorological services, and is of great significance for strengthening global monitoring, global forecasting and global service system building. As a precision active optical remote sensing payload, spaceborne doppler lidar is a complex system with a lengthy research and development cycle, a substantial amount of engineering work and a significant investment. Consequently, the development of institutional demonstration and performance simulation models for the spaceborne doppler lidar is particularly important. According to the requirements of numerical weather prediction on the accuracy and resolution of global wind detection, there is an urgent need to strengthen the simulation and evaluation research of spaceborne wind measurement lidar.

2. Simulation Model

The spaceborne hybrid wind lidar uses both direct and coherent detection techniques, taking full advantage of the observational benefits of both methods to detect the global wind field with high resolution. Direct detection technique is used to observe the middle and upper troposphere and lower stratosphere, which are dominated by molecular scattering, while coherent detection technique observes the lower troposphere and the atmospheric boundary layer. The incoherent detection module operates at 355 nm and uses the dual-edge detection technique based on Fabry–Pérot etalon. And the coherent detection module uses heterodyne detection technique operating at 1064 nm. This paper presents a simulation model for wind measurement lidar that realizes gridded atmospheric parameters, scanning observation, and forward-inversion simulation. To simulate the wind field detection capability of the satellite load parameter design scheme under different atmospheric conditions, the simulation system is designed as shown in Fig. 1.

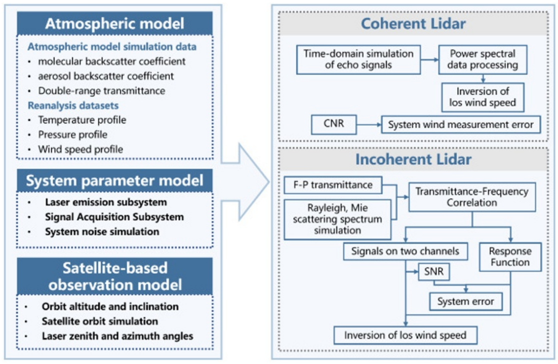

Figure 1. Simulation system for spaceborne hybrid mode wind measurement Lidar

The parameter input module of the simulation system is mainly divided into three parts: the atmospheric parameter model, the system parameter model and the satellite-based observation model. As shown in the table 1, there is a brief overview of the methods of simulation and index analysis, as well as the selection of a few combinations of system parameters.

Table 1. Simulation parameters of hybrid wind lidar system

Detection system	Parameter	Value
Coherent	Wavelength	1064 nm
Direct	Wavelength	354.8 nm
	Pulse energy	30 mJ
	Pulse frequency	1000 Hz
	Orbital height	400 km
	zenith angle	45°
	azimuth angle	90°

The simulation results are shown in Fig. 2, (a1)(b1) are coherent detection simulation results; (a2)(b2) are direct detection simulation results. The simulation analysis indicates that in the atmospheric boundary layer with a high aerosol concentration, the wind speed observation error is less than 0.8 m/s. In the clear sky with a thin aerosol layer, the wind speed observation error is around 1.5 m/s. The single-satellite dual-beam scanning observation mode can meet the satellite observation capability of the global wind vector by combining coherent detection and direct detection.

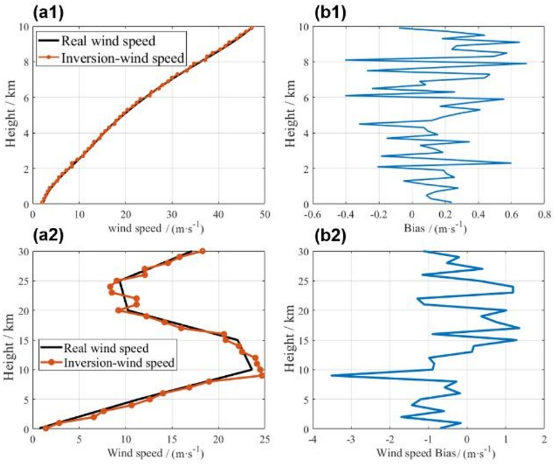

Figure 2. Simulation results of radial wind profile detection by hybrid wind lidar system

Direct observation of the horizontal wind field improves numerical prediction results near the observation point more than radial wind field detection with a single beam. To realize effective detection of the global vector wind field by spaceborne lidar, it is necessary to acquire a set of orthogonal wind speed components within each horizontal height layer in the detection profile to synthesize the horizontal wind speed and direction at that height.

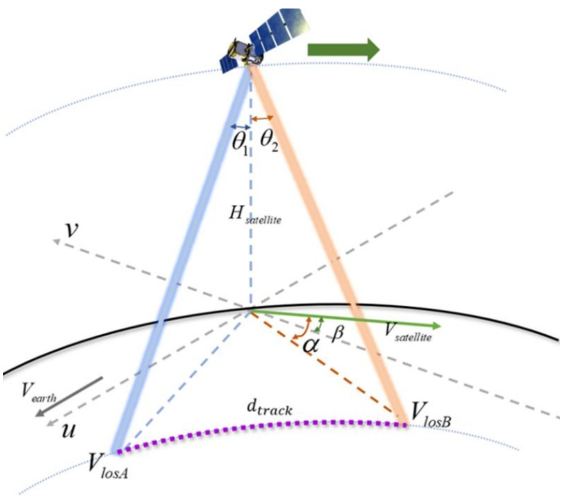

Figure 3. Schematic of two-beam stepper detection simulation system.

As shown in the Fig 3, a method for detecting horizontal wind field based on dual-beam observation was developed to ensure the response of the lidar for wind speed detection in both longitudinal and latitudinal directions.

When the u, v components of the wind speed profile are shown in Fig. 4(d), the direct detection lidar detection simulation is performed for the radial velocities of the A and B beams. During the satellite orbit operation to the equatorial horizontal plane, the simulation results of the A and B beam radial velocities are shown in Fig. 4(a)(b).

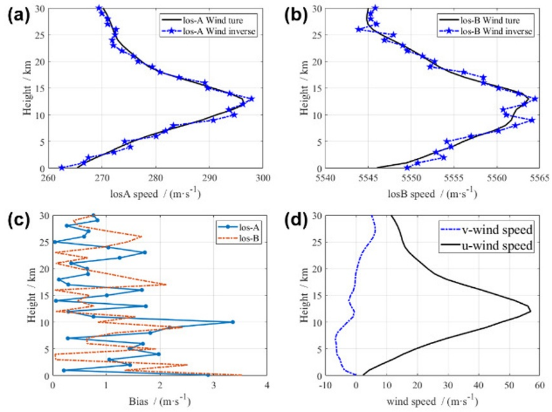

Figure 2. Simulation of incoherent lidar wind profile detection based on two-beam stepper detection

3. Summary and outlook

The spaceborne hybrid wind lidar uses both direct and coherent detection techniques through a dual-beam detection mode, taking full advantage of the observational benefits of both methods to detect the global wind field with high resolution and achieving a single-star wind vector detection capability. This paper provides parameter suggestions for the spaceborne wind measurement lidar, that based on the technical maturity and development trend of the current domestic space payload, to meet the temporal and spatial resolution and observation accuracy requirements for the assimilation of numerical weather prediction.

The system design and error analysis of the spaceborne wind measurement lidar is a complex and comprehensive undertaking. The actual on-orbit observation is contingent upon the performance of the payload, atmospheric characteristics, satellite system parameters, orbit settings, and scanning methods. This paper presents a simplified model of the spaceborne hybrid doppler wind lidar system, along with an error evaluation of system parameters, Further simulation experiments will be conducted in the future to achieve the overall scientific observation objectives of the satellite-based exploration mission. These experiments will enable a more comprehensive study of the global observation performance of the spaceborne wind measurement lidar.

4. References

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