High-Power 1083nm Pulsed Laser-Based Metastable Helium Lidar and its Applications in Space Environment Monitoring

Zhao Ruocan, et al., USTC

SHAO, Shanghai, 17 Oct, 2025

ALAL 阵列式大口径激光雷达 Array Large Aperture Lidar

NSSC 中国科学院国家空间科学中心 National Space Science Center . CAS

中国科学技术大学 University of Science and Technology of China

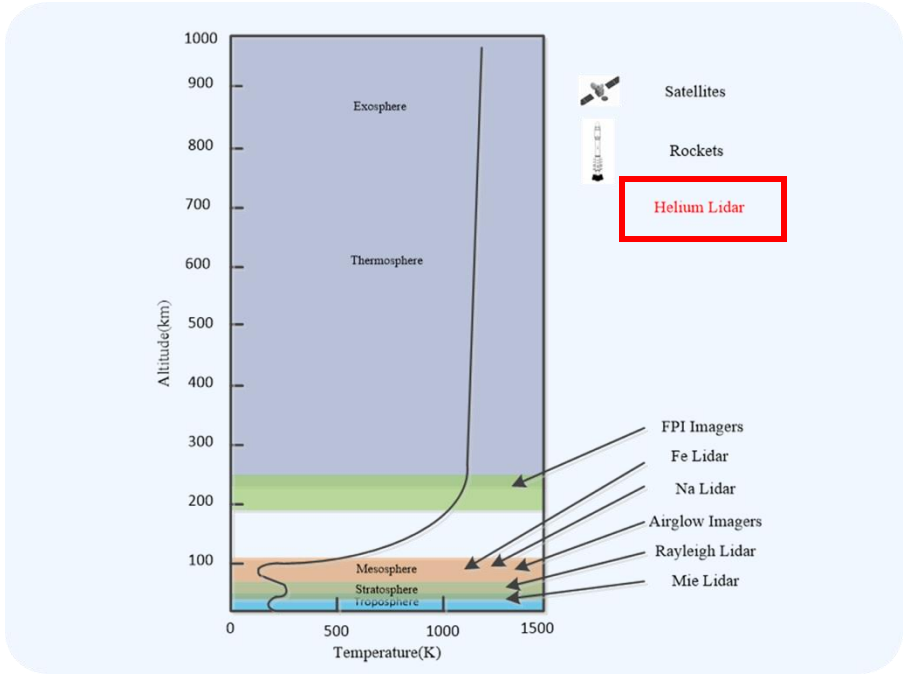
子午工程 MERIDIAN PROJECT

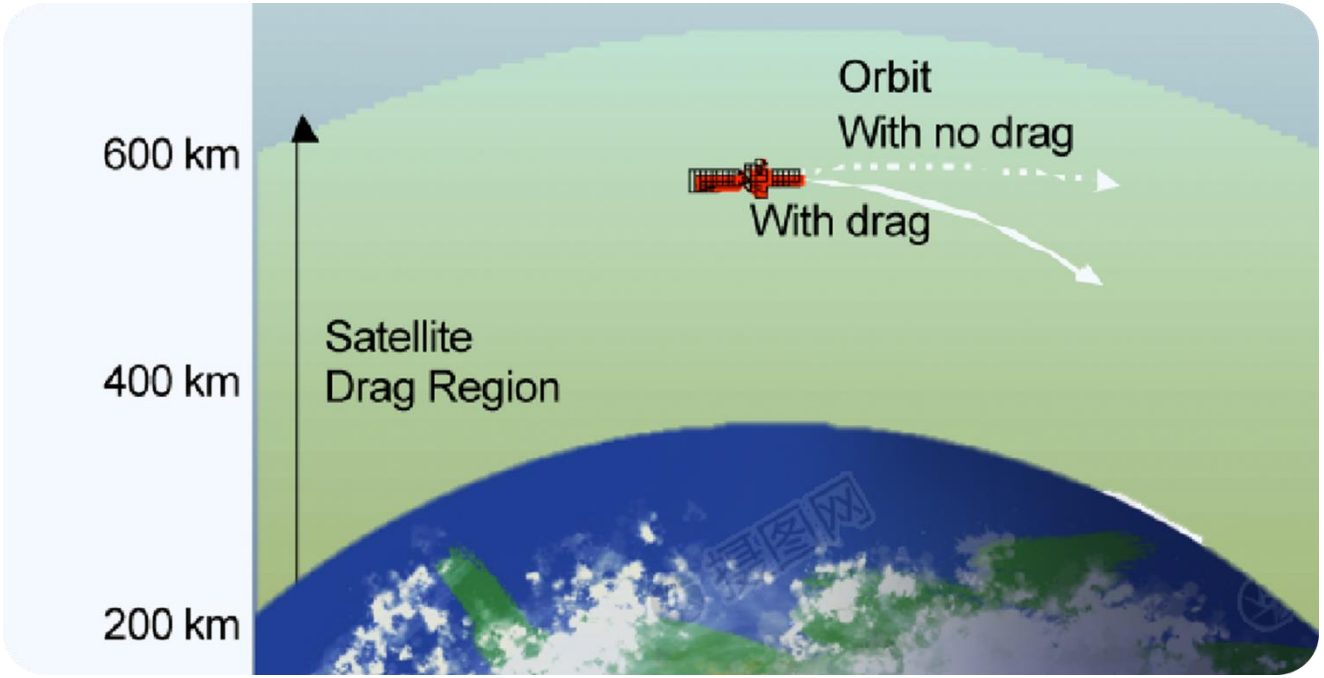
CONTENTS

Array Large Aperture Lidar

阵列式大口径激光雷达

Develop sensitive detection technologies for weak fluorescent signals (1083nm) from metastable helium atoms in the upper atmosphere, focusing on ultra-narrowband metastable helium fluorescence resonance lidar to enable detection of metastable helium density in the thermosphere at orbital altitudes.

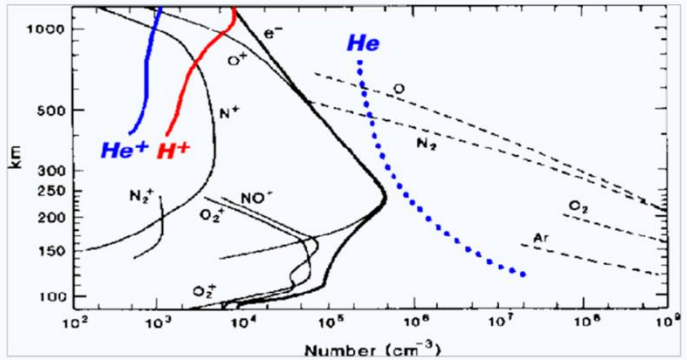


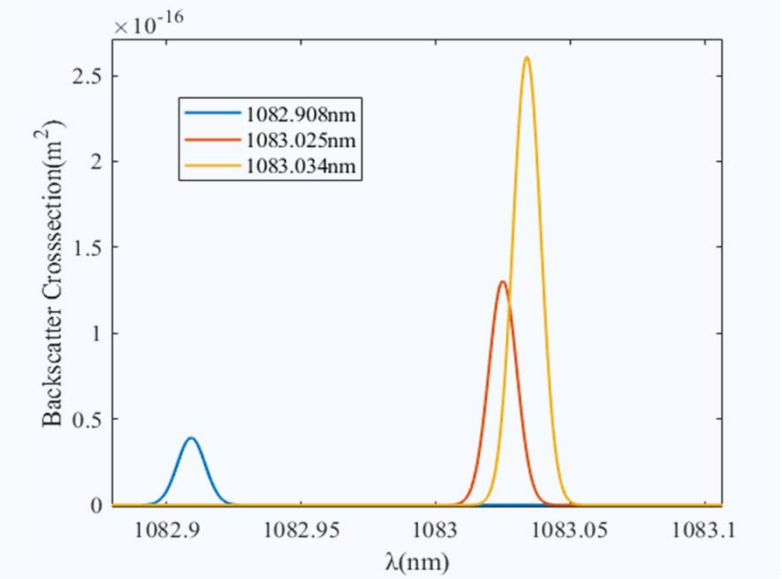


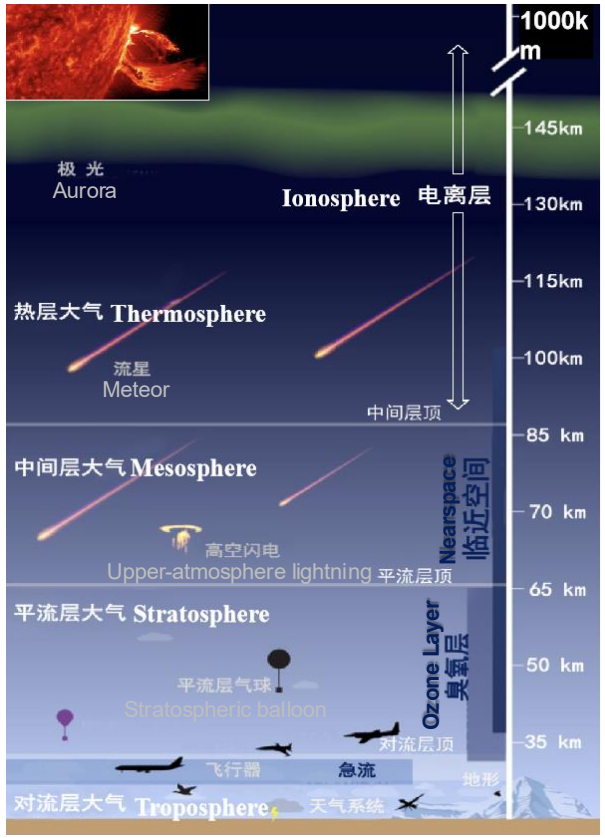
Scientific Background

阵列式大口径激光雷达

- Innovate laser remote sensing methods to construct a comprehensive physical model of material and energy transport across atmospheric layers, from upper/lower sources to the middle and upper atmosphere.







Compared with the sodium fluorescence lidar

The altitude increases by one order of magnitude

The density decreases by more than four orders of magnitude

Scientific Background

- Principles and Challenges of Metastable Helium Resonance Fluorescence Lidar

Lidar Equation

Laser Energy　　Detector Efficiency

$$P \propto A \cdot E \cdot \rho \cdot \eta \cdot \frac{1}{R^2}$$

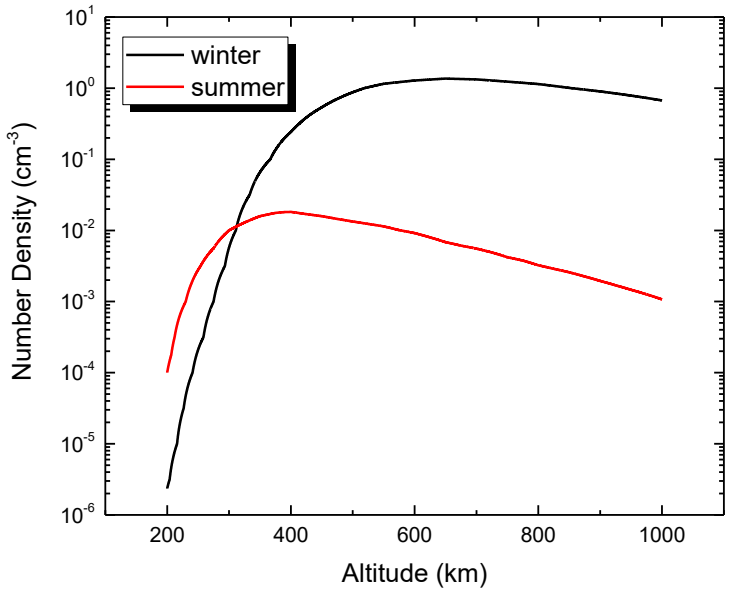
Effective Area of Telescope

Metastable Helium Density 1/cm³

Distance 800km

Metastable Helium Atom Density：1/cm³@800km

Analogy　Na Density：3000/cm³@92km



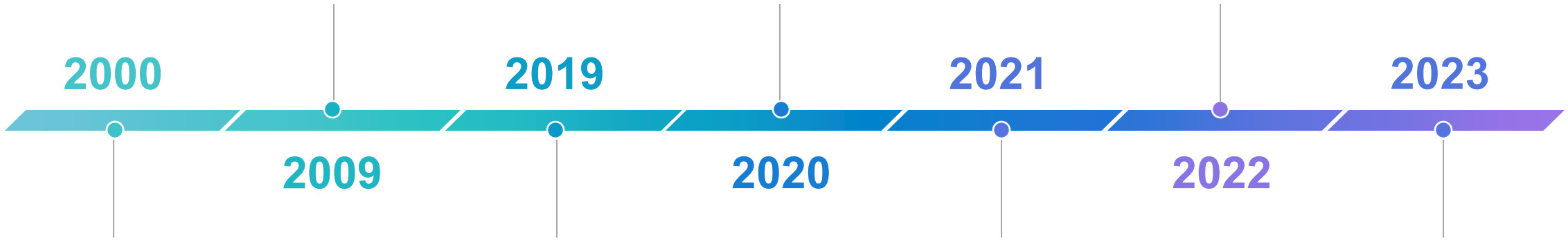
Achievements

Large Telescope Effective Area

High Laser Energy (1083 nm)

High Detection Efficiency

Domestic and International Status



Pennsylvania State University (USA): First proposed the method of using lidar to detect helium fluorescence at orbital altitudes

University of Illinois (USA): Refined system parameters for continuous-wave laser schemes

University of Science and Technology of China: Initiated development of continuous-wave laser-based helium fluorescence lidar (for density measurement)

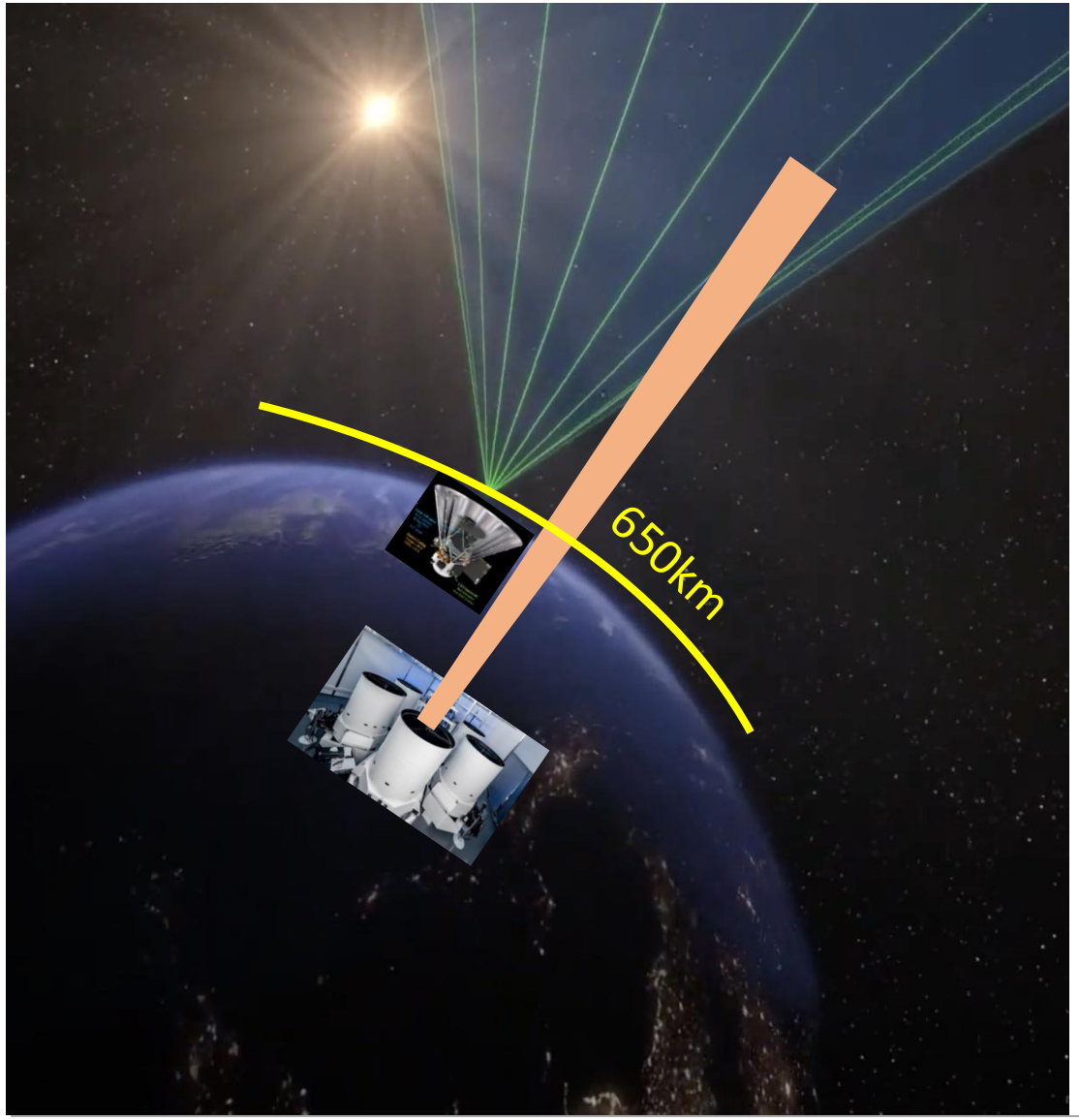
University of Science and Technology of China: Successfully validated key technologies of pulse-based helium lidar (density measurement)

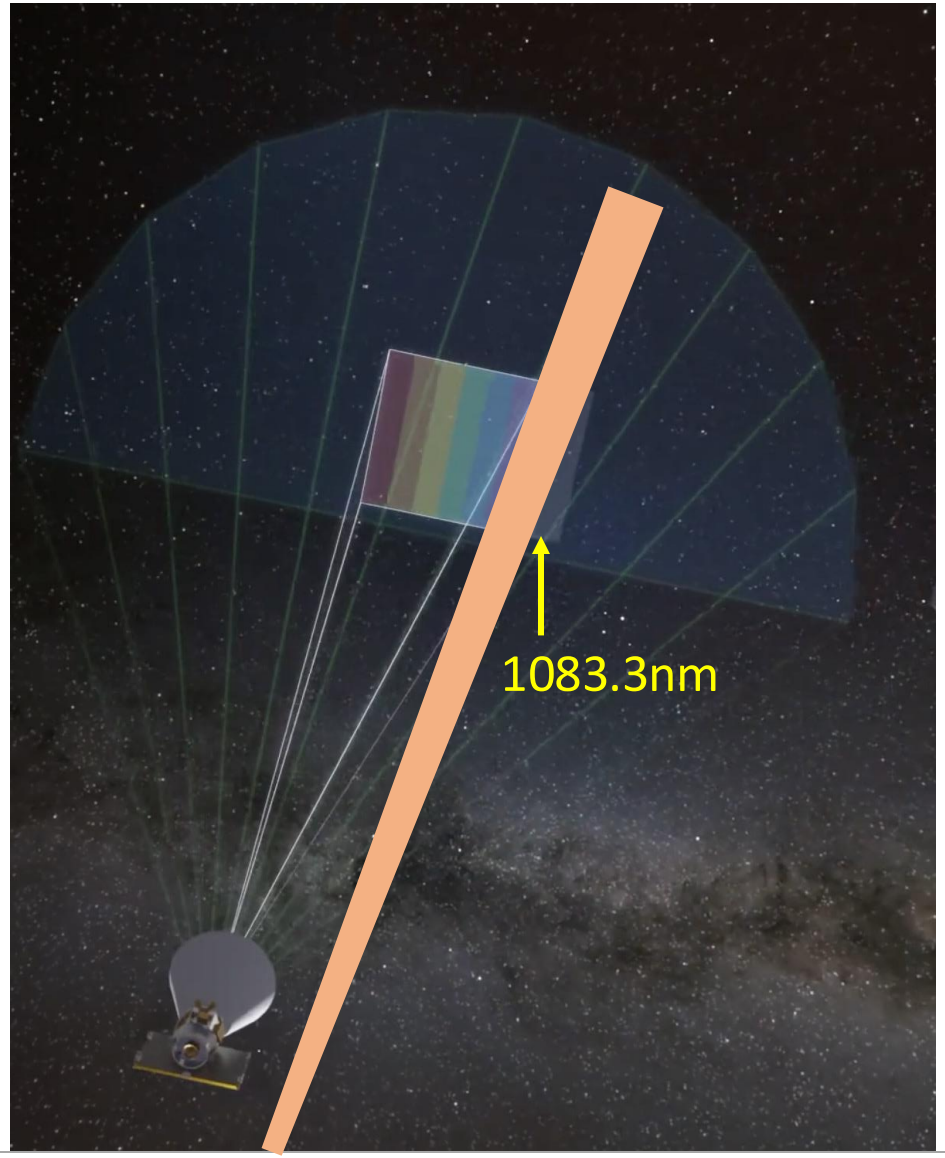
University of Science and Technology of China: Verified key technologies of ultra-narrowband helium fluorescence resonance guidance lidar

DLR (Germany) : Achieved active detection up to 700 km

University of Science and Technology of China: Built lidar with optimal performance, achieving detection up to 1000 km

SPHEREx & Helium Lidar



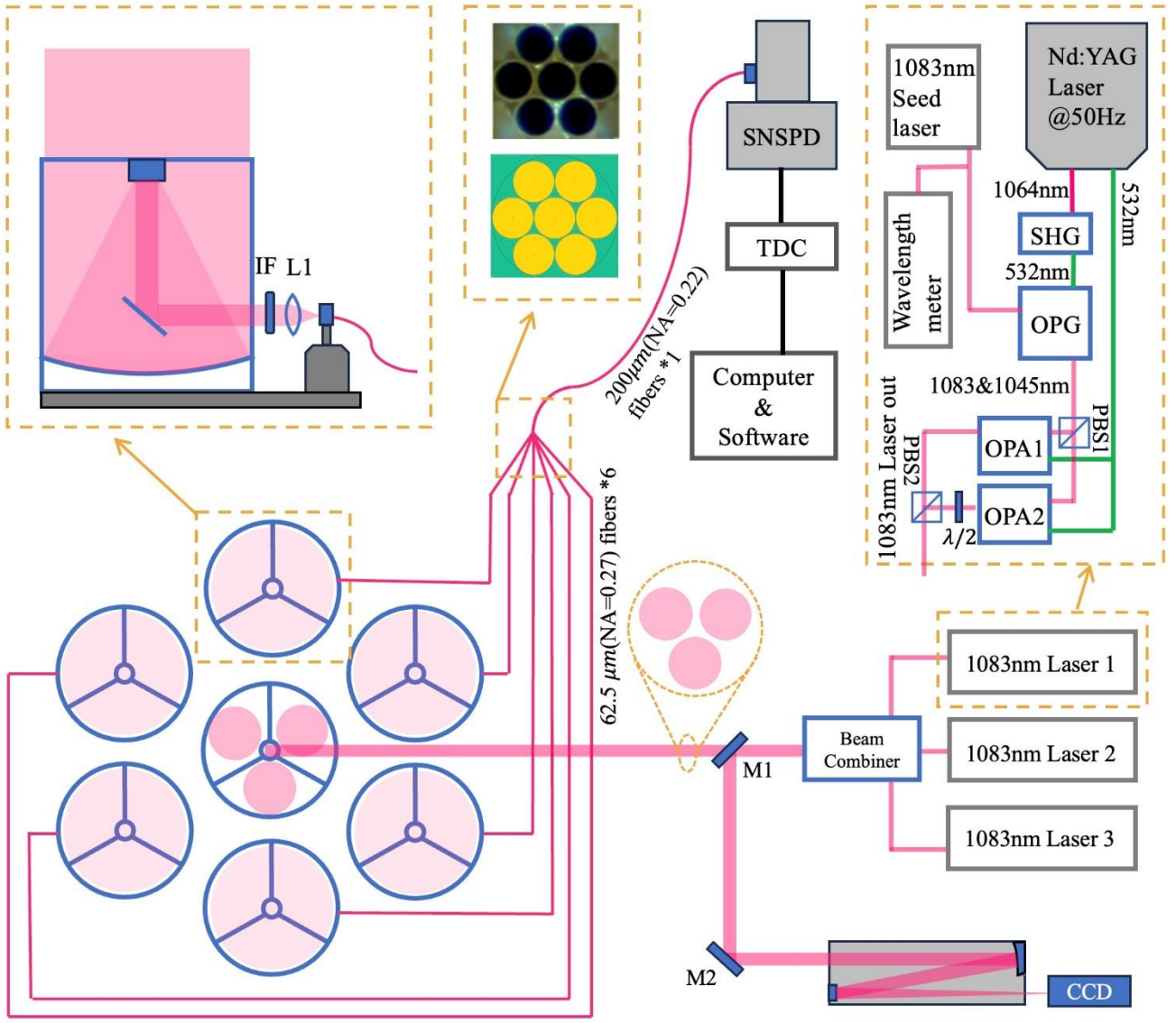


Lidar Principle

阵列式大口径激光雷达

- Pulsed Laser, Co-located Transmitting & Receiving

Subsystem	Parameter	Value
1083nm laser	Single 1083nm laser pulse energy	70-140mJ
	Three 1083nm lasers' total energy	200-400mJ
	Wavelength	1083.034 nm
	Frequency jitter	45MHz
	Linewidth	62MHz
	Repetitional rate	50Hz
	Beam expansion factor	30
	Beam divergence	1 mrad
	Single beam diameter	10mm
Nd: YAG laser	Pulse energy of residual 1064nm	320mJ
	Pulse energy of 532nm	900mJ
	Repetitional rate	50Hz
	Beam divergence	<0.7 mrad
	Beam diameter	9mm
Telescope	Telescope Aperture	1m
	Central distance of telescopes	1.75m
Fibers	Receiving fiber core diameter	62.5 mm
	Fiber NA	0.27
SNSPD	Quantum efficiency	>20.9%
	Dark counts	100 cps
	Coupling fiber core diameter	200 mm
	Fiber NA	0.22

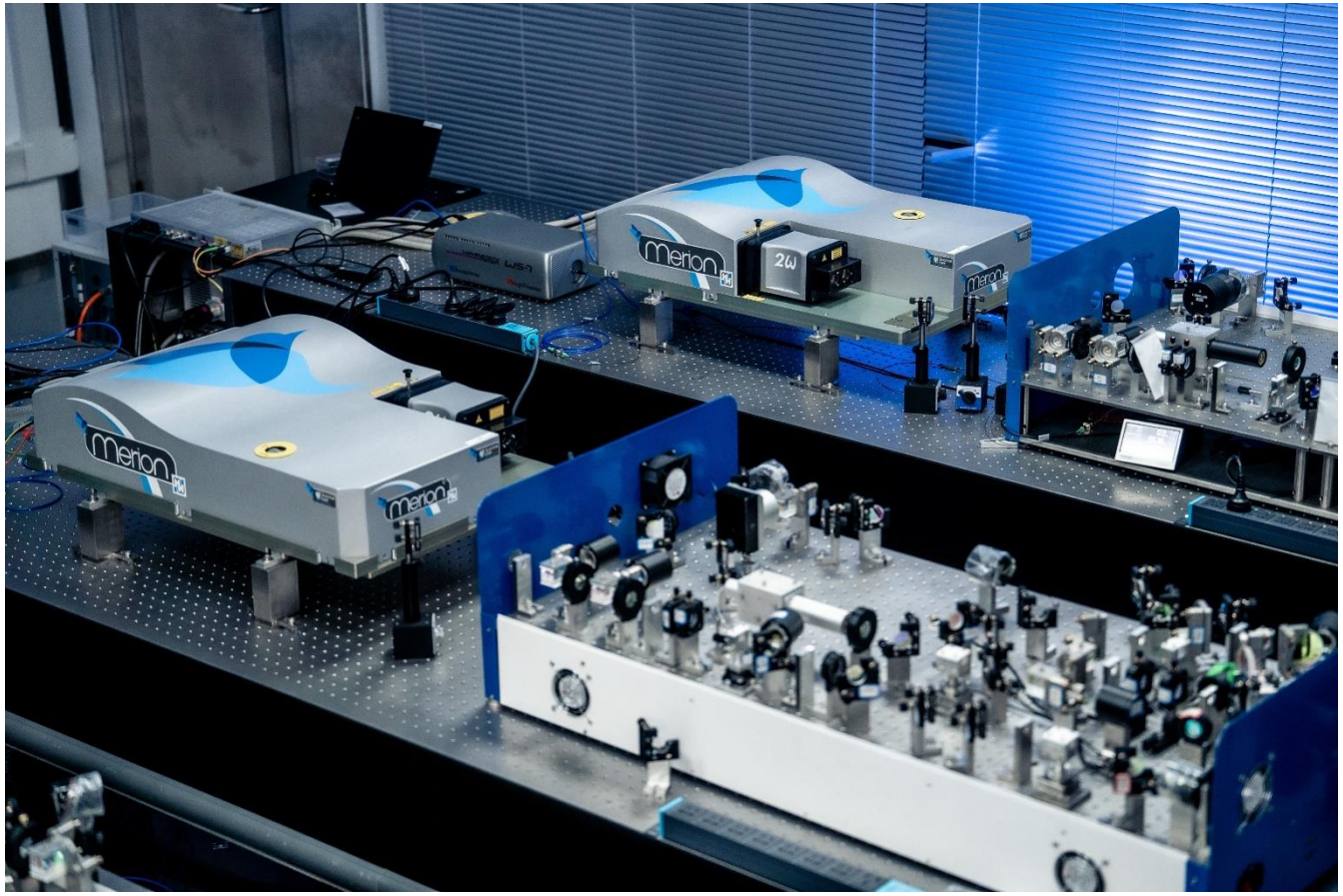


Core Technologies

阵列式大口径激光雷达

Laser Transmission System

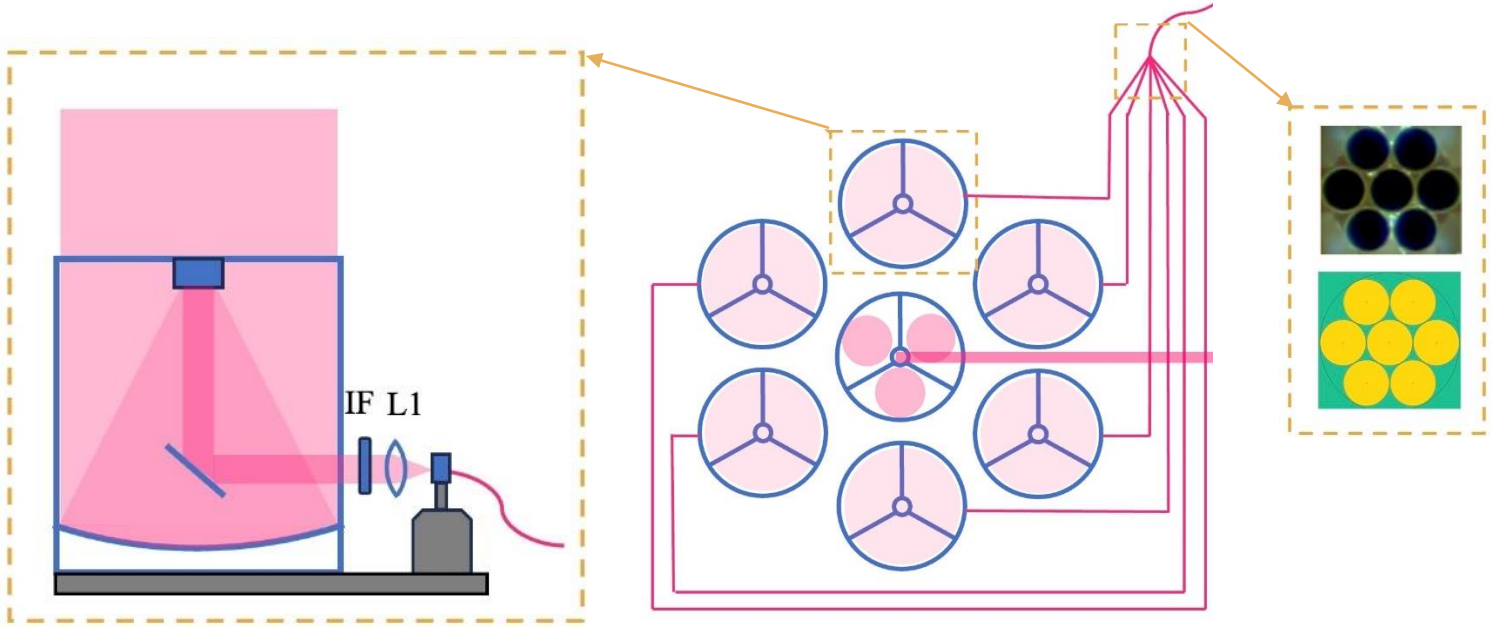
From 2019 to the end of 2022, R&D and integration of key technologies for the 1083nm pulsed laser system were continuously carried out. By 2022, three lasers were integrated, with stable operation. The OPG can stably output 10mJ single - longitudinal - mode 1083nm laser pulses, with a linewidth less than 3pm (3pm is the minimum detectable value of the wavelength meter). After 2 - hour continuous recording, the optical frequency stability is within 20MHz, and the output energy of a single unit reaches 135mJ.



20MHz
Optical Frequency Stability Range

135mJ
Single Laser Output Energy

Optical Receiving System



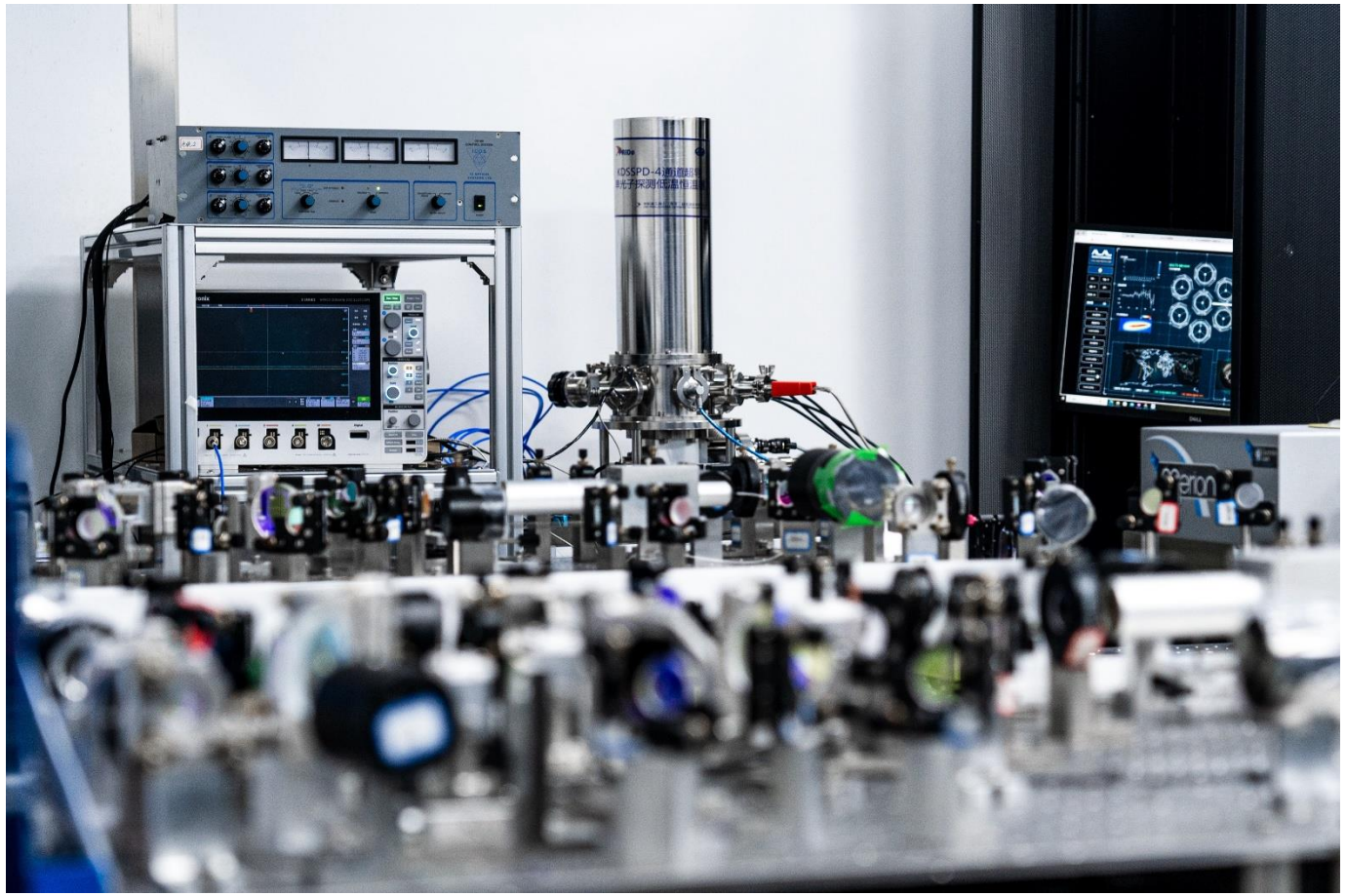
- One 1 - meter - diameter transmitting beam - expanding telescope and six 1 - meter - diameter receiving telescopes.
- Fiber array beam combination: 6 fibers of 62.5μm are combined into one 200μm fiber.

Core Technologies

阵列式大口径激光雷达

Near - Infrared Single - Photon Detection System

1. Superconducting nanowire detector, developed in collaboration with Nanjing University. Achieved 200μm large - fiber coupling, with controlled low dark counts. It is the optimal solution for detecting 1083nm (Disadvantages: Large volume, high cooling power).
2. Ultra - narrow - band FP filtering system, achieving 15pm filtering bandwidth and comprehensive optical efficiency greater than 30%.



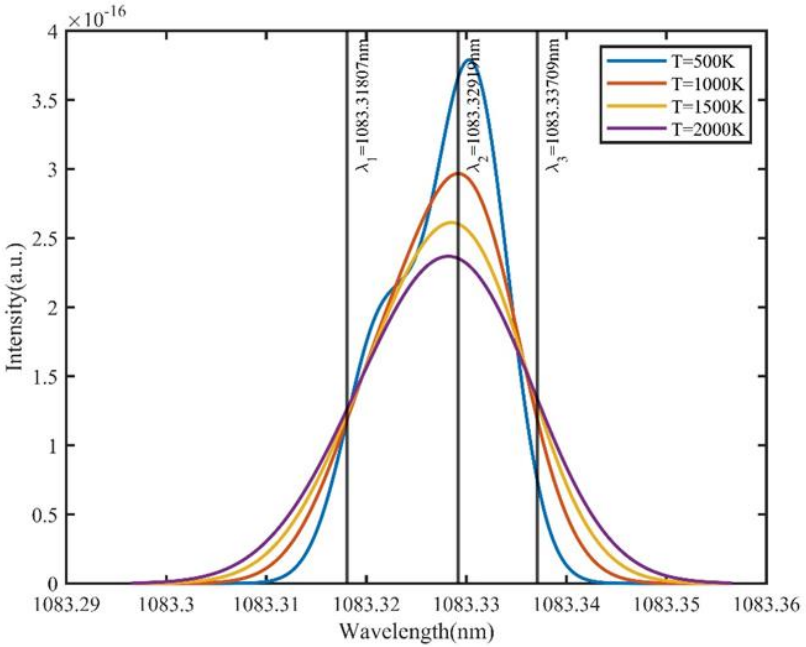
30%
Detection Efficiency

1000cps
Dark Counts

Core Technologies

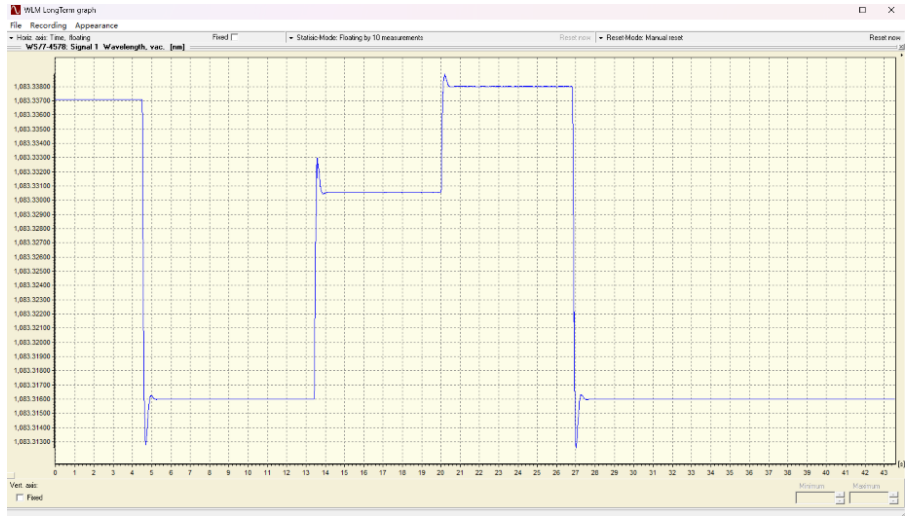
Temperature Measurement

To prepare for temperature measurement at 300 - 800km altitude, it is necessary to optimize and upgrade **the lidar's wavelength - tuning capability** and **improve the photoelectric detection system's measurement procedures**.



Scattering Cross - Section of Metastable Helium

Seed Laser



Wavelength Switching

Metastable Helium Lidar System

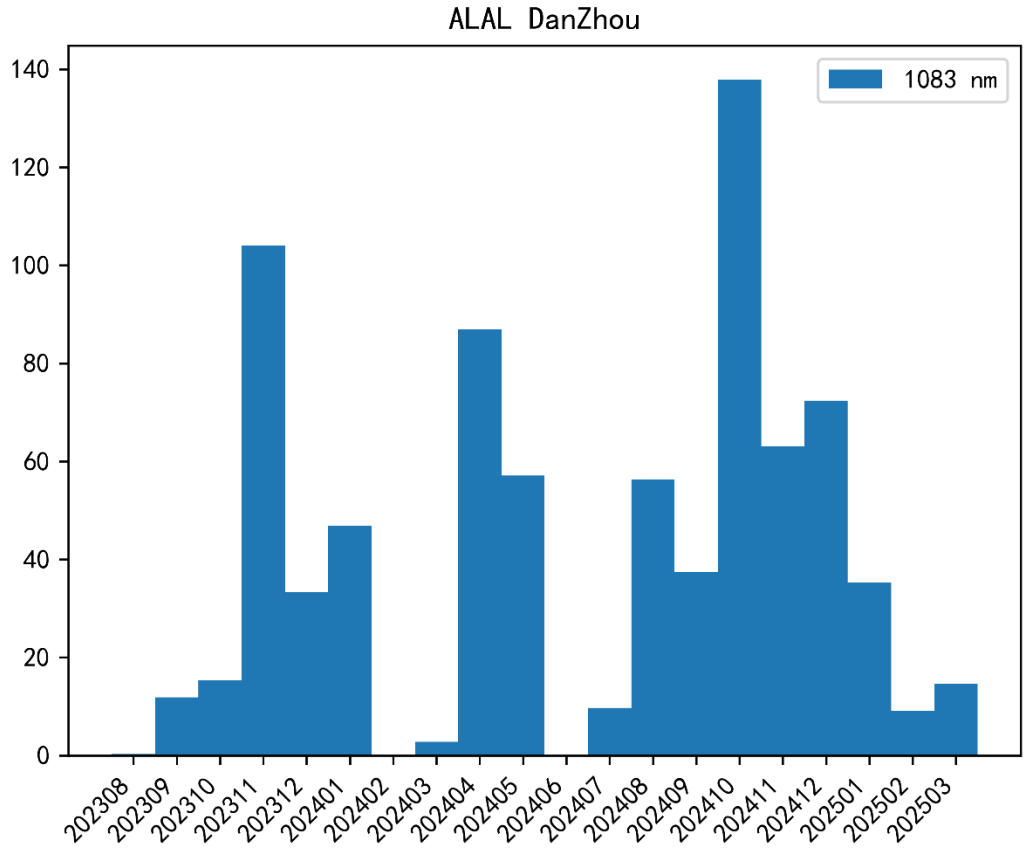
阵列式大口径激光雷达

Actual Layout of The Metastable Helium Lidar

CONTENTS

Current Data

Accumulation of Current Observation Data



Observation Duration (Hours) by Month

From acceptance (August 24, 2023) to March 23, 2025:

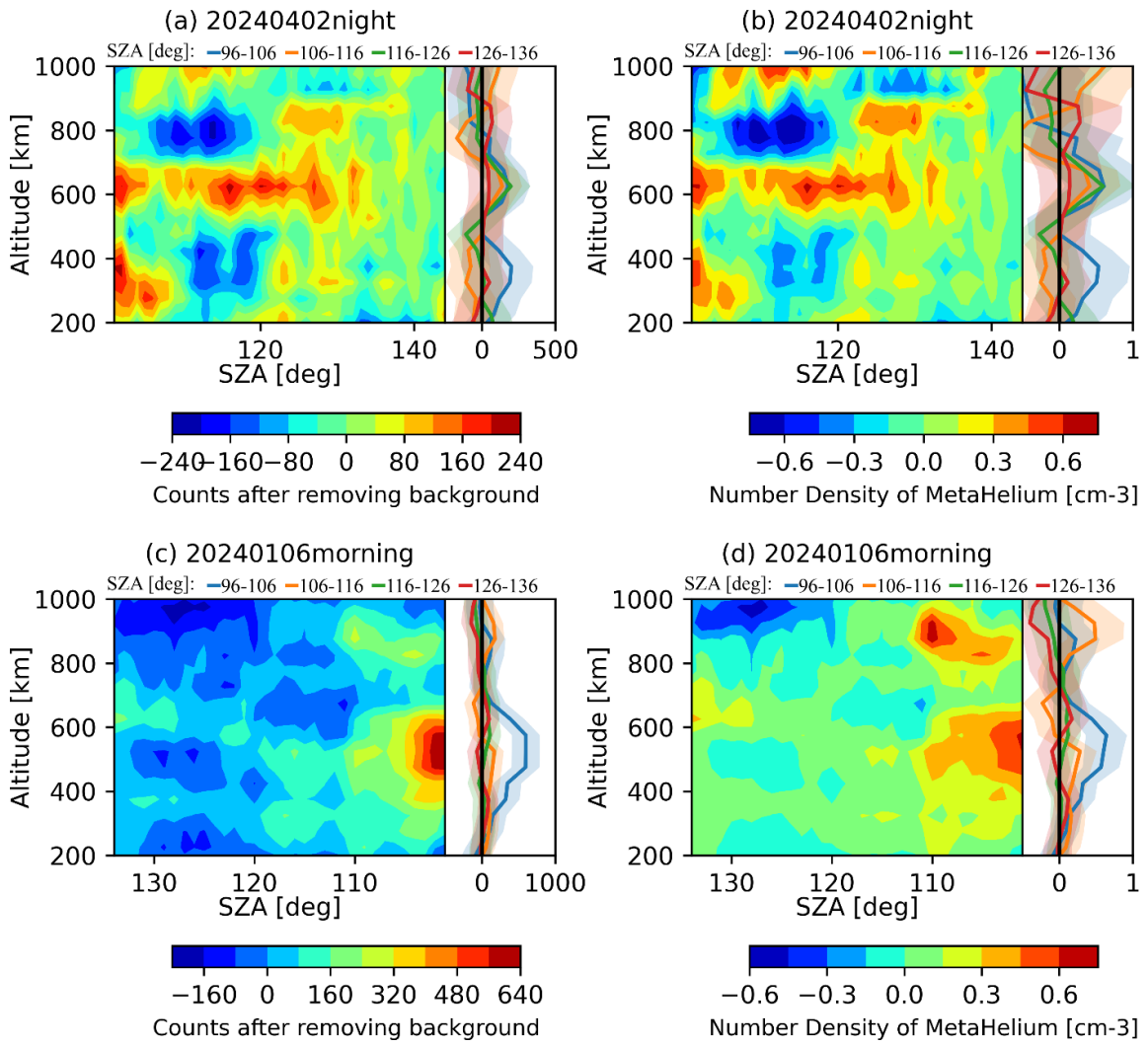
- Observation days: 167 days
- Observation time: 794.38 hours
- Number of observation files: 95325
- Size of observation data: 7162.7MB

Achievements

Observation Results

Using the acquired continuous metastable helium data, the team:

- **For the first time** captured the rapid changes of metastable helium within a single day and the fine structure of its vertical distribution.
- **For the first time** captured the detailed differences in the vertical distribution of metastable helium before and after sunset.
- **Hypothesis (to be verified)**: The photoelectrons transported by magnetic field lines at high latitudes in the Southern Hemisphere excite the metastable helium atom layer above 800km.



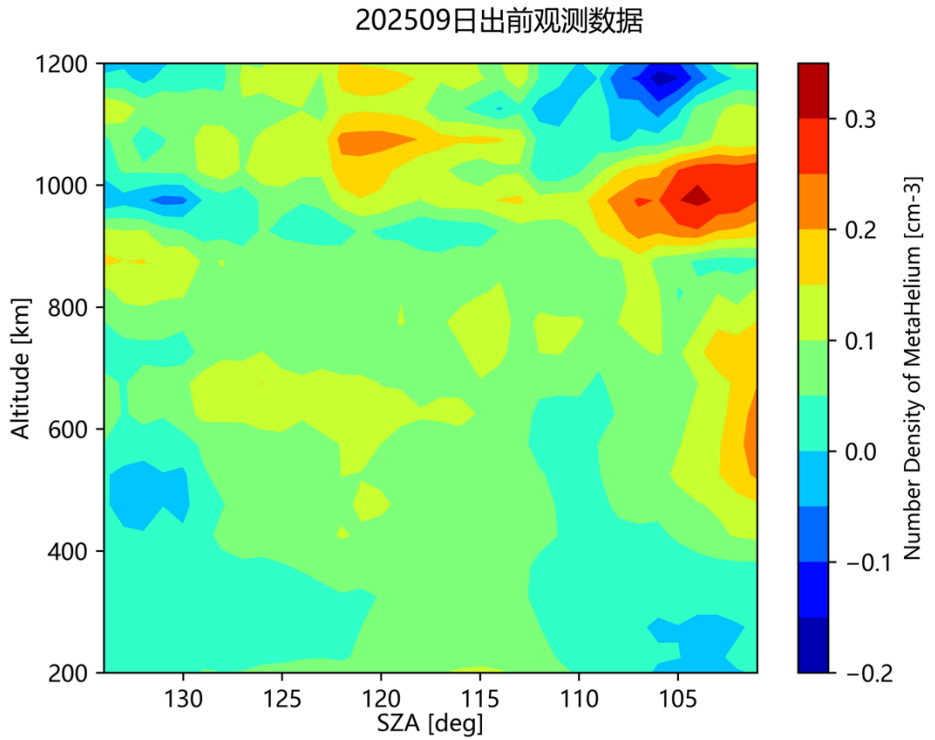
Inversion Results of Single - Day Observation Data

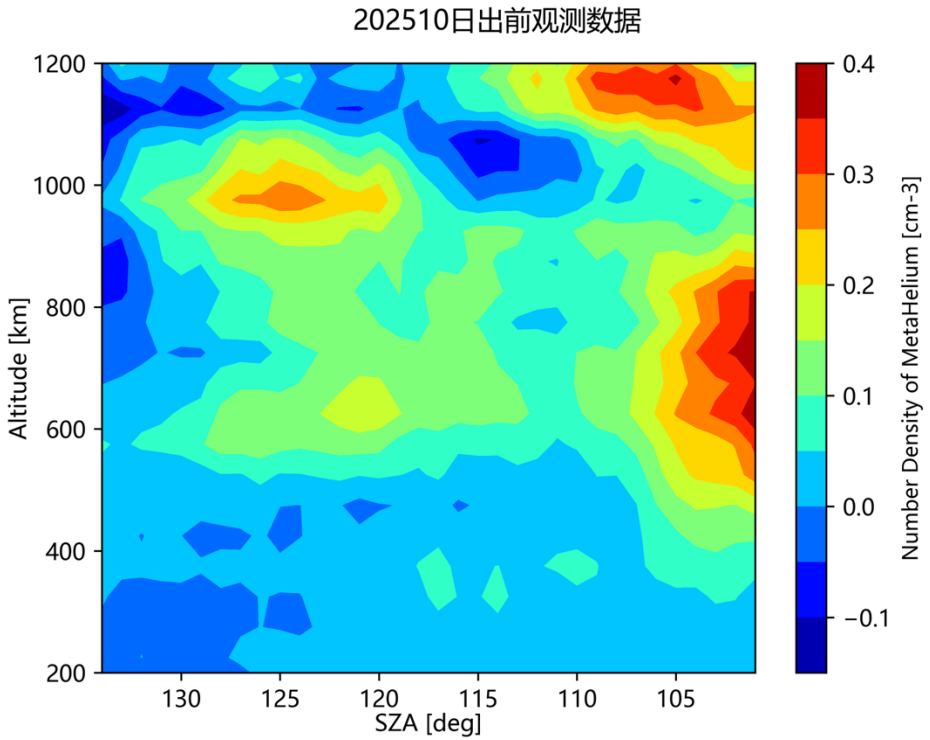
Achievements

Observation Results

Newest observation on September and October

- **Repeated Higher layer above 800km，sometimes up to 1200km;**



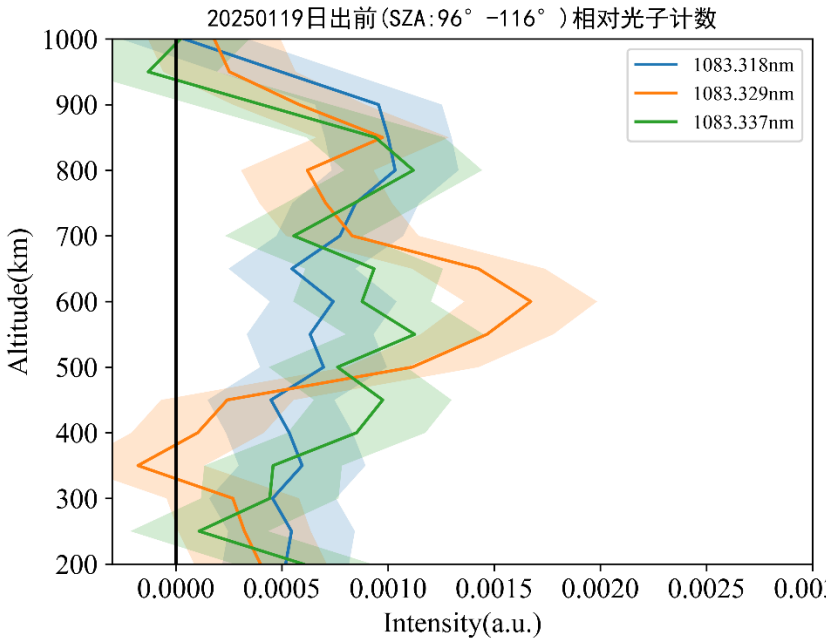


Current Data

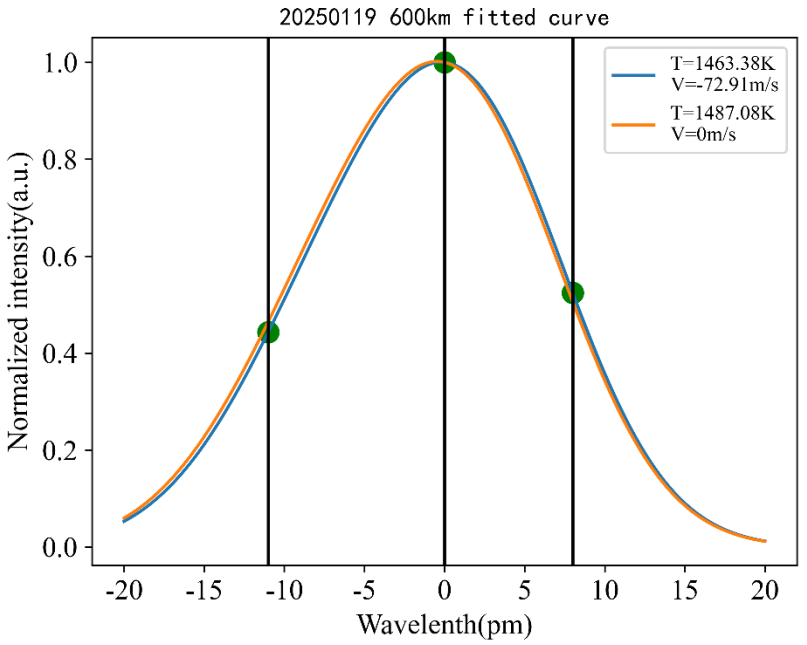
阵列式大口径激光雷达

Observation Results

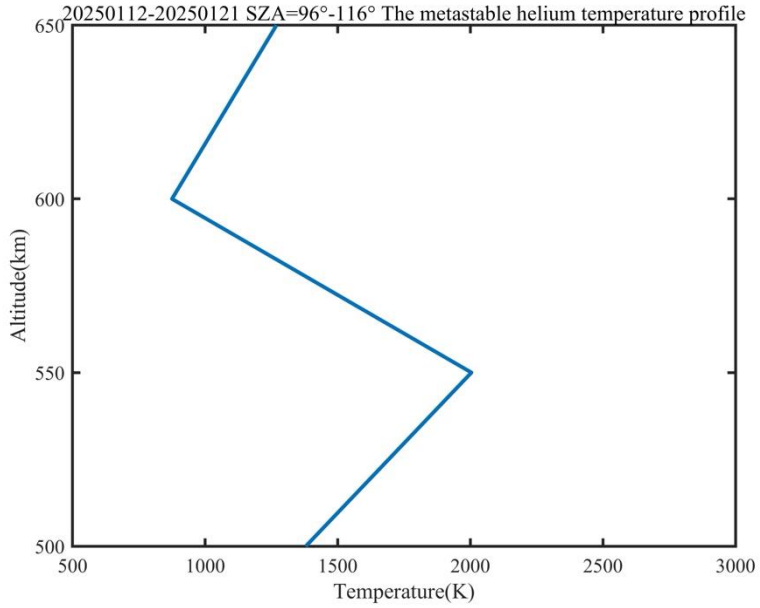
Preliminarily achieved temperature observation of metastable helium in the altitude range of 500 - 650km.



Signals of Three Frequency Channels



Fitted Spectrum at 600km Altitude



Temperature Profile of Metastable Helium

CONTENTS

Ground - based Lidar Networking

阵列式大口径激光雷达

- International Networking Plan

Personnel Requirements for Operation: Hainan and Qujing rely on students and hired engineers; Brazil relies on personnel from INPE (National Institute for Space Research).

Data Sharing Mode after Networking: Global sharing, encouraging international peers to use the data and strengthening exchanges with them.

Scientific Questions after Networking: Diurnal and seasonal variations at different latitudes, and responses to magnetic storms.

Qujing Station: Ultra - narrow - band metastable helium fluorescence resonance superconducting atmospheric lidar, achieving lidar detection of the temperature of atmospheric metastable helium at an altitude of 300 - 800km.

Station Name	Status	Measurement Parameters	Project
Hainan Station	Completed	Density (additionally expanded to temperature)	phase-2 Meridian Project
Qujing Station	Construction started at the beginning of the year	Density + Temperature (wind speed expansion expected)	2030
Brazil Station	Budget submitted	Density (temperature expansion possible)	International Meridian Circle Program（IMCP）
Arctic Station	To be determined	To be determined	To be determined

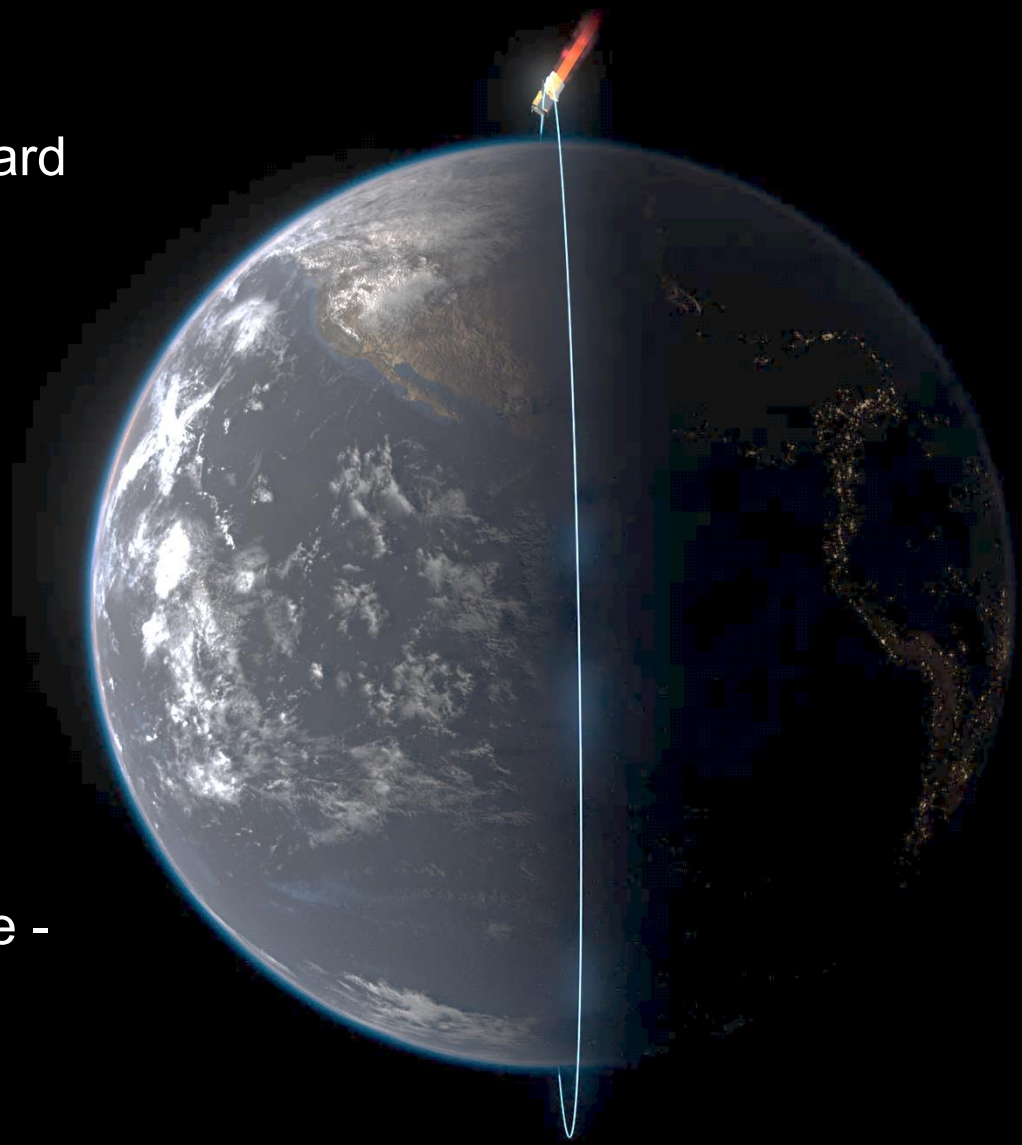
Feasibility Study of Space - borne Metastable Helium Lidar

阵列式大口径激光雷达

- Orbit Type: Dawn - dusk orbit
- Pointing Direction: Back to the Sun, obliquely upward
- Elevation Angle: 70 degrees
- Orbit Altitude: 400km
- Detection Range: 400 - 1000km

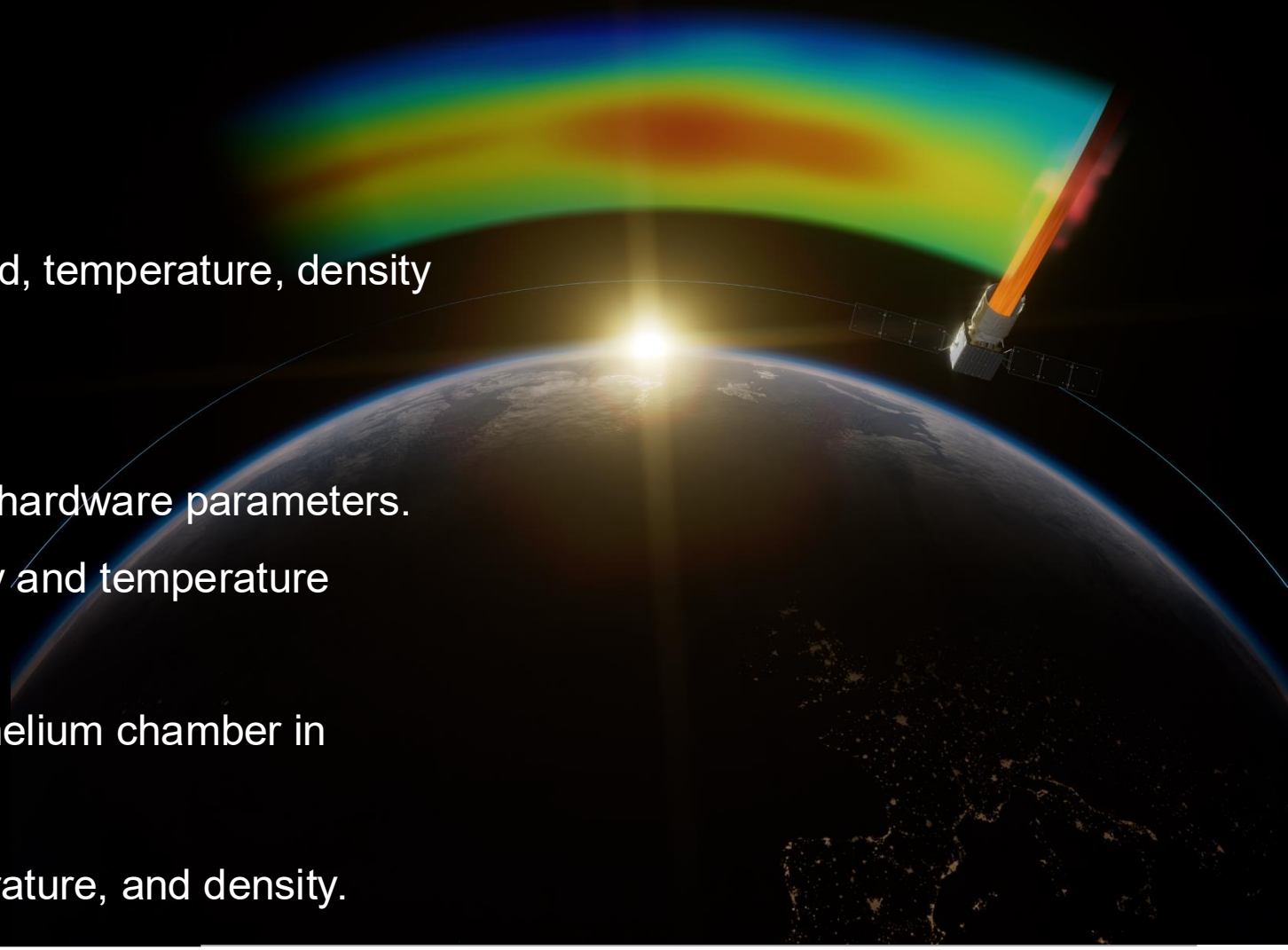
- Lidar Performance

1. Telescope Aperture: 1m
2. Laser Energy: 100mJ@75Hz
3. Detector: Superconducting nanowire/InGaAs single - photon detector
4. Detection Parameters: Wind, temperature, density



Feasibility Study of Space - borne Metastable Helium Lidar

- Coverage: Global local dawn - dusk time
- Temporal Resolution: 10min
- Altitude Resolution: 50 - 100km
- Altitude Range: 400 - 1000km
- Detection Parameters: Metastable helium wind, temperature, density



- Feasibility Demonstration

1. Signal Simulation: Optimize and design lidar hardware parameters.
2. Ground - based Observation: Provide density and temperature observations.
3. Laboratory Simulation Platform: Metastable helium chamber in thermospheric environment.
4. Error Analysis: Error analysis of wind, temperature, and density.

CONTENTS

Development Timeline

阵列式大口径激光雷达

2019

Metastable helium simulation device (collaboration)
Metastable helium temperature measurement (LIF)

2022

Metastable Helium Lidar construction starts
Development of laser and detectors begins

2023

Metastable helium simulation chamber (independent)
Metastable helium density, wind field and temperature measurement; Verify the feasibility of space - borne technology

2024

Metastable Helium lidar completed
Measured 650km - altitude density, laying the foundation for space - borne metastable helium lidar observation

2024

Electro - optical comb for helium measurement
microsecond - level rapid metastable helium measurement

2025

Temperature - measuring metastable helium lidar
Hainan lidar upgraded for temperature measurement

2026

Wind - measuring metastable helium lidar verification
Using the 2030 metastable helium lidar telescope's axial tilt configuration to verify wind - measurement capability

2027

2030 Temperature – measuring metastable helium lidar
Higher - performance temperature measurement

FUTURE

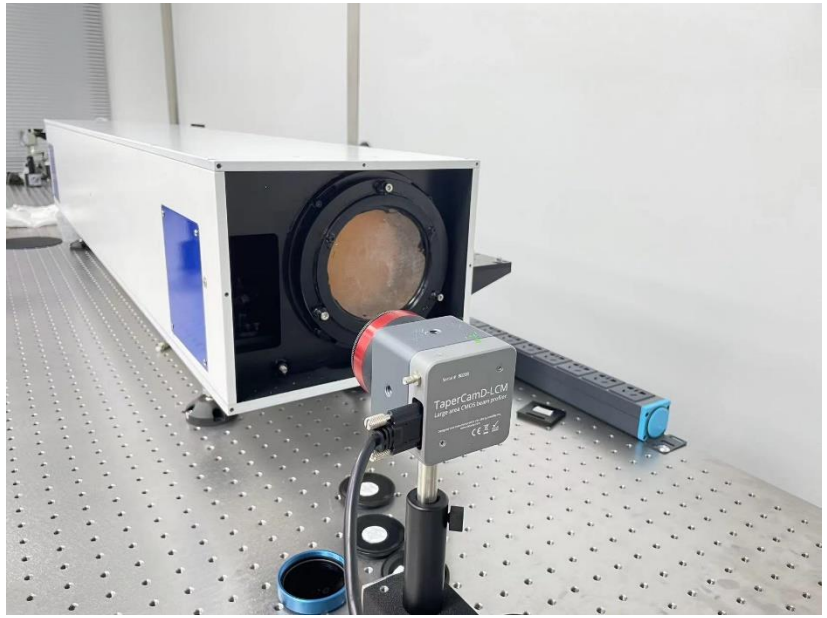
Space - borne metastable helium lidar
400km dawn - dusk orbit

Implementation Project

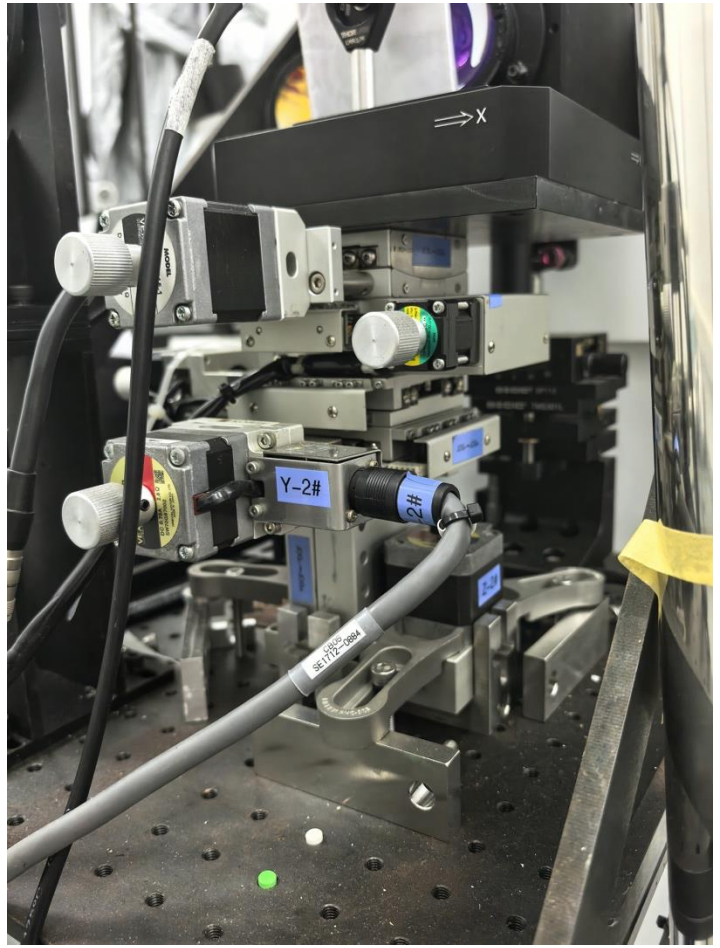
Automation (Next 3–5 Years)

To ensure the stability of equipment performance during daily observations, after the system solution matures, **more operations should be automated**, and **the system's self - inspection capabilities should be enhanced**.

- Operation Automation: Includes automatic startup/shutdown, automatic debugging, etc.
- System Self - inspection: Includes optical axis monitoring, signal monitoring, environmental monitoring, etc.



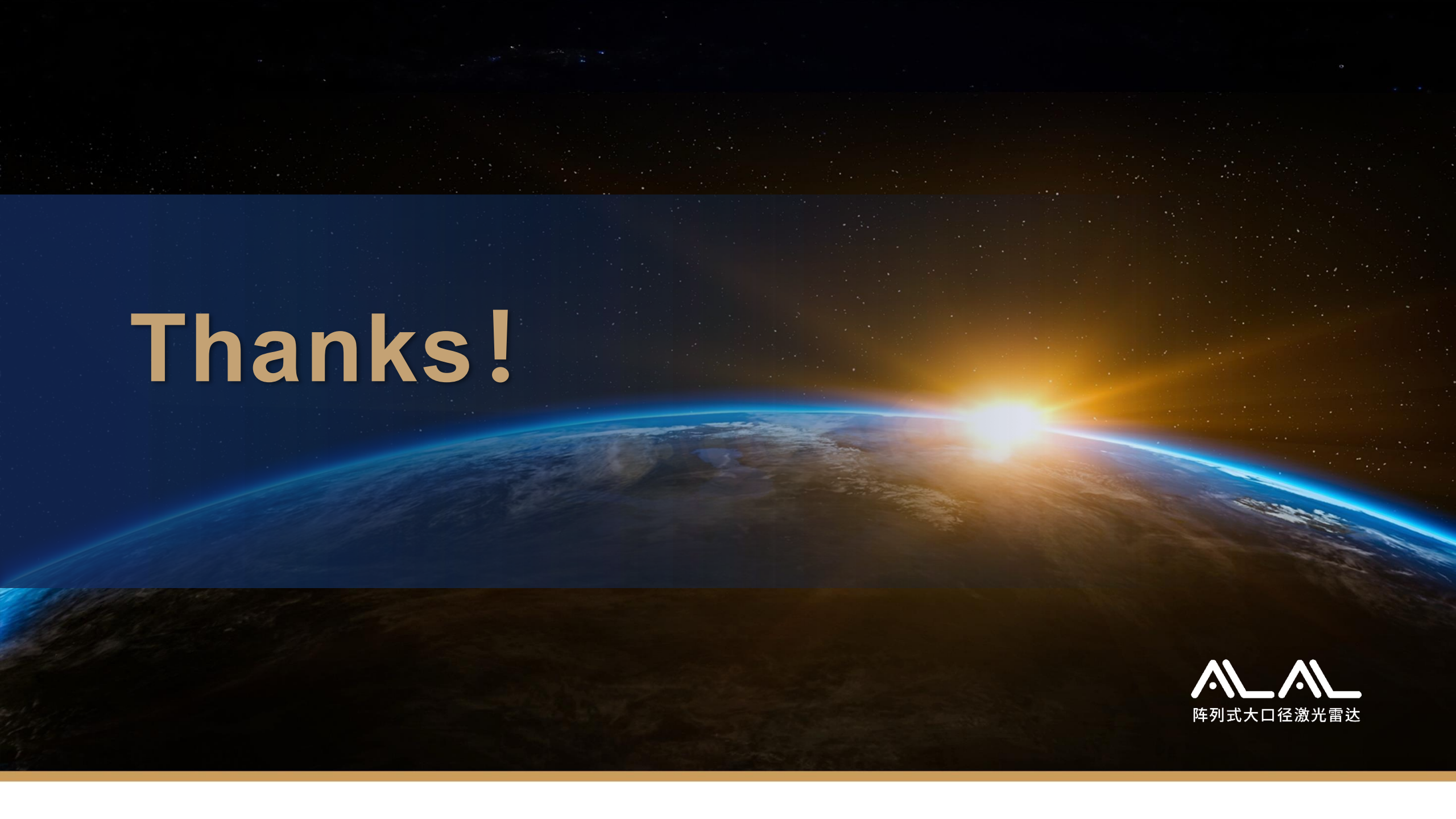
Multi - laser Beam Optical Axis Monitoring System



Motorized Displacement Stage

Summary：

1. Complete the temperature - measuring metastable helium lidar in 1 year, and verify wind - measuring technology in 2 years.
2. Build international multi - stations, encourage international peers to use metastable helium lidar data, and enhance international influence.
3. Develop space - borne metastable helium lidar, expected to achieve better detection performance (global coverage) with smaller power and aperture.


Thanks!
ALAL
阵列式大口径激光雷达