Application of AR Smart Glasses in Greenhouse Gas Services of Meteorological Departments

Chen Chen[1,a*], Haibo Huang[2,b], Qianbo Qing[3,c]

[1]Meteorological Technology and Equipment Center of Hunan Provinceline, Changsha, China
[2]Dongting Lake National climatological Observatory, Meteorological Bureau of Yueyang City, Yueyang, China
[3]Meteorological Bureau of Shaoyang County, Shaoyang, China
[a*]1270436000@qq.com, [b]448652435@qq.com, [c]2024247809@qq.com

Abstract. To meet the needs of the "dual carbon" goal and the National Carbon Source and Sink Monitoring, Verification and Accounting System (CCMVS), meteorological greenhouse gas observation is moving toward intelligence. AR smart glasses, with advantages of real-scene overlay, hands-free operation and remote collaboration, solve key pain points of traditional manual operations. This paper focuses on the pilot experiment design, implementation process and quantitative effect of AR smart glasses in meteorological greenhouse gas services. A 10-month pilot (March-December 2025) was conducted at 4 regional atmospheric background stations in Hunan Province, with detailed experimental design, variable control and data comparison. An integrated application model of "AR plus AI working model" is proposed, and specific experimental data and practical effects are provided to offer a feasible technical reference for the intelligent upgrading of meteorological greenhouse gas observation networks. Experiment results find out the inspection time, fault handling time, and new employee onboarding cycle are reduced by more than 44%, the manual recording error rate and inspection omission rate are reduced by more than 89%, the quality control closed-loop rate is close to 100%, and the total experimental relative error is reduced from 7.8% to 1.2%

Keywords: AR Smart Glasses; Greenhouse Gases; Meteorological Observation; Intelligent Inspection; Pilot Experiment; Quantitative Effect

1 Introduction

As a new type of wearable intelligent equipment, AR smart glasses can accurately overlay virtual information (including equipment parameters, operation guidelines, real-time data, and expert instructions) with real scenes, realizing the principle of "what you see is what you get, what you look at is what you record, and what you point at is what you repair". These glasses also support hands-free voice interaction, making them suitable for complex operation scenarios such as field and high-altitude work. Since 2024, the China Meteorological Administration operating national and regional atmospheric background stations to carry out pilot applications of AR+AI smart glasses,

L. W. Koon et al. (eds.), *Proceedings of the 2026 7th International Conference on Management Science and Engineering Management (ICMSEM 2026)*, Advances in Economics, Business and Management Research 399,
https://doi.org/10.2991/978-94-6239-758-3_39

integrating them into the entire greenhouse gas observation business chain and achieving remarkable results [1] [2]. Based on this pilot practice, this paper systematically discusses the application path, quantitative effects, and optimization directions of AR smart glasses in meteorological greenhouse gas services, providing technical support for the intelligent upgrading of China's meteorological greenhouse gas observation network [3].

2 Technical Basis for the Application of AR Smart Glasses in Greenhouse Gas Servicesas

The core technologies of AR smart glasses adapted to meteorological greenhouse gas services include augmented reality overlay, AI visual recognition, voice interaction, remote collaborative annotation and end-cloud integration [4]. A four-level system architecture (perception layer-edge layer-platform layer-application layer) is constructed to realize the integration of AR equipment with greenhouse gas observation business, focusing on meeting the needs of field operation, data transmission and real-time quality control. I Visual Recognition Technology. Integrating optical character recognition, equipment status recognition, and anomaly detection algorithms, this technology can automatically identify instrument panel data (such as CO_2 concentration, standard gas pressure, and flow rate) and equipment operation status (such as pipeline leakage and indicator light abnormalities). It realizes automatic alarms for abnormal situations and reduces manual judgment errors [5].

3 Typical Applications of AR Smart Glasses in Meteorological Greenhouse Gas Services

Based on the application scenarios of meteorological greenhouse gas services, the pilot experiment integrates AR smart glasses into key links, with detailed experimental design, strict variable control, standardized operation procedures, and comprehensive data collection methods. The specific experimental scheme is designed as follows to ensure the scientificity, repeatability, and reliability of the experiment.

3.1 Intelligent Inspection Experiment of Greenhouse Gas Observation Stations

Experiment Objective. To systematically verify the application effect of AR smart glasses in the inspection of greenhouse gas observation stations, clarify their role in reducing inspection omissions, lowering manual recording errors, and improving inspection efficiency and standardization. Meanwhile, this experiment aims to confirm the adaptability of AR equipment in diverse meteorological environments and its compatibility with existing greenhouse gas observation equipment, thereby providing a scientific basis for the large-scale promotion and application of AR technology in meteorological greenhouse gas services [6].

(2) Experiment Design. A parallel controlled experiment was adopted in this study, with four regional atmospheric background stations (Yueyang, Shaoyang, Zhangjiajie, and Changning) selected as the experimental sites. These stations cover different geographical types (plain, hilly, and mountainous) and environmental characteristics (high humidity, large temperature difference, low temperature, and high temperature) in Hunan Province, ensuring the representativeness of the experimental results [7]. Each station conducted the experiment continuously for 30 working days, and the experiments at the four stations were carried out simultaneously to avoid interference from seasonal and temporal factors.

The experiment was divided into an experimental group and a control group, with the same team of on-site operators assigned to both groups (two professional operators with more than 1 year of greenhouse gas observation experience per station) to eliminate the impact of differences in personnel operation capabilities on the experimental results. The experimental group used AR smart glasses (customized industrial model, adapted to low temperature, high humidity, and strong ultraviolet environments) to complete the inspection work. In contrast, the control group adopted the traditional manual inspection mode, i.e., paper recording combined with a handheld data terminal. The inspection content, standards, and requirements were completely consistent between the two groups to ensure the comparability of the experimental data.

The inspection objects covered all key equipment and links of the greenhouse gas observation system, including 28 specific inspection items categorized into five groups: Sampling system: tightness of sampling tubes, sampling height, cleanliness of filters, and operation status of anti-condensation devices; Analyzer: operation status, display stability, zero drift, and span deviation of CO_2/CH_4/N_2O analyzers; Standard gas: pressure of standard gas cylinders, tightness of valves, calibration validity period, and connection status of gas pipelines; Dehumidification and dust removal equipment: operation status of dehumidifiers, filter replacement cycle, and dust removal effect; Power supply and communication equipment: power supply stability, signal strength of communication modules, and data transmission status. Each inspection item was assigned clear standards and evaluation indicators, and operators were required to strictly follow these standards to complete inspections and record results [8].

(3) Key Variable Control. To ensure the scientificity and reliability of the experimental results, strict variable control was implemented during the experiment, including the following four aspects:

Environmental variable control: The experiment was conducted in the same season and the same time period (09:00–11:00 daily) to avoid the impact of extreme weather (heavy rain, strong wind, extreme high/low temperature) on the experiment.

Personnel variable control: The same operators alternated between the experimental group and the control group every 10 days. Prior to the experiment, all operators received uniform training to master the operation specifications of AR glasses and traditional inspection methods.

Equipment variable control: The greenhouse gas observation equipment used in both groups was of the same model and service life, and all equipment was uniformly calibrated before the experiment to ensure consistency in equipment performance.

Record variable control: The recording standards of the two groups were unified, and inspection results were recorded in detail according to the specified format, including normal status, abnormal phenomena, handling measures, and handling time.

(4) Operation Process. The operation processes of the two groups were strictly standardized to ensure the comparability of the experimental results, with specific steps as follows:

Pre-experiment preparation: Before the start of daily experiments, operators calibrated the greenhouse gas observation equipment and experimental tools (AR smart glasses for the experimental group; handheld terminal and paper record sheet for the control group) to ensure all equipment was in normal operation. The AR smart glasses were preloaded with the standardized inspection process, inspection items, standard thresholds, and abnormal handling guidelines for each pilot station, and the OCR recognition module was calibrated to ensure the accuracy of instrument data extraction.

Operation of the experimental group (AR smart glasses): The operator wore AR smart glasses, turned on the system, connected to the meteorological cloud platform, and confirmed the real-time connection status; Guided by the voice and visual prompts of the AR glasses, the operator conducted inspections in the specified order (from the sampling system to power supply and communication equipment); For each inspection item, the operator observed the real scene, and the AR glasses automatically identified the instrument panel data through OCR technology, overlaying the standard threshold in the field of view. If abnormal data was detected, the AR glasses immediately popped up an alarm prompt and displayed the corresponding handling guidelines; The operator completed the recording of inspection results through voice commands (e.g., "normal", "abnormal, filter dirty"), and the AR glasses automatically saved the voice records and took real-time photos of the inspection site for archiving; After the completion of the inspection, the AR glasses automatically uploaded the inspection data, photos, and voice records to the meteorological cloud platform and generated a daily inspection report [9].

Operation of the control group (traditional manual mode): The operator carried a handheld terminal and paper record sheet and conducted inspections in the same order as the experimental group; For each inspection item, the operator observed the equipment status with the naked eye, manually read the instrument panel data, and recorded the data and equipment status on the paper record sheet; If an abnormal phenomenon was found, the operator manually recorded the abnormal situation and then consulted the operation manual or contacted the superior to confirm the handling measures [10]; After the completion of the inspection, the operator manually entered the data from the paper record sheet into the handheld terminal and then uploaded the data to the meteorological cloud platform. The paper record sheets were sorted and archived uniformly after the experiment.

Data recording: During the experiment, operators recorded key indicators of each inspection in real time, including the single inspection time (from the start of the inspection to the completion of data upload), number of inspection omission items (compared with the 28 standard inspection items), number of manual recording errors (data entry errors, incorrect description of equipment status), and number of abnormal handling cases. All data were recorded truthfully without modification. At the end of each working day, the supervisor checked the experimental data to ensure its accuracy and completeness.

3.2 Remote Operation and Maintenance Experiment of Observation Equipment

(1)Experiment Objective. To test the application effect of AR remote collaborative annotation technology in the operation and maintenance of greenhouse gas observation equipment, clarify its role in shortening the fault handling time, reducing the frequency of expert on-site support, and improving the fault handling accuracy. Meanwhile, to verify the stability and reliability of AR smart glasses in remote data transmission and real-scene presentation under different network environments (5G, 4G, weak network) .

(2)Experiment Design. A simulated fault experiment was adopted, and 12 common faults of greenhouse gas observation equipment were selected, covering 4 categories: 1) Analyzer fault (CO_2 analyzer zero drift, CH_4 analyzer span deviation, N_2O analyzer display failure); 2) Pipeline fault (standard gas pipeline leakage, sampling pipeline blockage, gas transmission pipeline loose connection); 3) Auxiliary equipment fault (dehumidifier failure, dust remover blockage, power supply module damage); 4) Communication fault (data transmission interruption, communication module failure, cloud platform connection failure). Each pilot station set 12 simulated faults, and the faults were set by professional technicians in advance without informing the on-site operators, to test the fault identification and handling ability of the operators.

The experiment was also divided into an experimental group and a control group, with the same team of on-site operators and remote experts (3 senior engineers with more than 5 years of greenhouse gas observation equipment operation and maintenance experience) to ensure the consistency of fault handling standards. The experimental group used AR smart glasses to carry out remote collaborative fault handling: the on-site operators wore AR glasses to transmit the real-time scene of the fault point (including equipment status, instrument panel, fault phenomena) to the remote expert terminal through 5G/4G network; the remote experts viewed the real-time scene through the terminal, and provided guidance to the on-site operators through spatial annotation (marking the fault point and handling position), step-by-step voice prompts, and operation guideline overlay.

The control group adopted the traditional fault handling mode: the on-site operators found the fault, described the fault phenomenon to the remote experts by phone or WeChat, and sent the fault site photos or short videos to the experts; the experts judged the fault reason based on the description and photos/videos, and guided the on-site operators to handle the fault through phone calls; if the fault was complex and could not be handled by remote guidance, the experts went to the site to handle it in person.

(3)Key Variable Control. Fault variable control: The type, severity, and setting position of the simulated faults in the two groups were completely consistent, and the fault setting was completed by the same technician. Network variable control: The network environment of the four pilot stations was recorded in real time, and the fault handling effect under different network conditions was compared to verify the adaptability of

AR glasses to the network environment. Expert variable control: The same group of remote experts provided guidance for the two groups, and the expert guidance standards were unified to avoid the influence of expert ability differences on the experimental results. Time variable control: The fault setting time was unified at 14:00 every day, and the fault handling time was recorded from the moment the operator found the fault to the moment the fault was completely eliminated.

(4)Operation Process. The operation process of the two groups was standardized to ensure the accuracy of fault handling time and effect recording, with specific steps as follows:

Fault setting: At 13:30 every day, professional technicians set the simulated fault at the designated position of the observation equipment, and recorded the fault type, severity, and setting details. The technicians did not communicate with the on-site operators to ensure that the operators found the fault independently.

Experimental group operation (AR remote collaboration): The on-site operator found the fault during the routine inspection, immediately wore AR smart glasses, turned on the remote collaboration function, and connected to the remote expert terminal; The operator adjusted the AR glasses camera to align with the fault point, and transmitted the real-time scene of the fault point to the expert terminal, and described the fault phenomenon to the expert through voice; The remote expert viewed the real-time scene through the terminal, identified the fault reason, marked the fault point and key handling positions through spatial annotation, and overlayed the step-by-step operation guidelines in the AR glasses field of view; The on-site operator operated according to the expert's annotation and guidance, and fed back the operation process and effect to the expert in real time through voice; After the fault was eliminated, the operator tested the equipment to confirm that it returned to normal, and the expert confirmed the fault handling effect through the AR real-time scene. The operator recorded the fault reporting time, fault handling time, and whether expert on-site support was needed.

Control group operation (traditional mode): The on-site operator found the fault during the routine inspection, immediately took photos or short videos of the fault point, and described the fault phenomenon to the remote expert by phone; The expert judged the fault reason based on the photos/videos and description, and guided the operator to handle the fault through phone calls; If the operator could not complete the fault handling according to the phone guidance, the expert arranged to go to the site for on-site guidance or handling; After the fault was eliminated, the operator tested the equipment to confirm that it returned to normal, and recorded the fault reporting time, fault handling time, and whether expert on-site support was needed.

Fault verification: After the fault handling was completed, professional technicians inspected the equipment to verify whether the fault was completely eliminated, and recorded the fault handling accuracy (whether the fault was handled correctly at one time, whether there were secondary faults). If the fault was not completely eliminated, the handling time was recorded until the fault was completely eliminated.

3.3 Real-Time Data Quality Control Experiment

(1)Experiment Objective. To verify the application effect of AR smart glasses in the real-time quality control of greenhouse gas observation data, clarify its role in improving the real-time performance of quality control, reducing the lag of quality control, and improving the accuracy of quality control judgment. Meanwhile, to test the linkage effect between AR smart glasses and the national greenhouse gas quality control rule library, and provide technical support for the on-site real-time quality control of greenhouse gas observation data.

(2)Experiment Design. An artificial abnormal data setting experiment was adopted, and 100 sets of abnormal data were artificially set in each pilot station, covering 3 common quality control problems: Instrument drift (CO_2/CH_4/N_2O analyzer zero drift, span drift, exceeding the allowable error range); Standard gas problem (standard gas expiration, standard gas pressure insufficient, standard gas calibration error); Data abnormal fluctuation (data sudden rise or fall, data disconnection, data repetition). The abnormal data was set by professional technicians through adjusting the instrument parameters or simulating the equipment failure, and the setting time was random (distributed in different time periods of the day) to test the real-time detection ability of AR smart glasses.

The experiment was divided into an experimental group and a control group, with the same team of quality control personnel (2 professional quality control personnel per station) to ensure the consistency of quality control judgment standards. The experimental group used AR smart glasses to carry out on-site real-time quality control: the quality control personnel wore AR glasses, which were connected to the greenhouse gas observation equipment and the national greenhouse gas quality control rule library in real time. The AR glasses overlayed the real-time greenhouse gas concentration data, hourly average value, daily variation curve, baseline threshold (set according to the historical data of each station), and neighboring station comparison data in the field of view. At the same time, the AR glasses automatically matched the real-time data with the quality control rules in the rule library, and automatically identified the abnormal data.

The control group adopted the traditional offline quality control mode: the greenhouse gas observation data was first uploaded to the meteorological cloud platform, the quality control personnel logged in to the platform to review the data after 24 hours, judged the abnormal data according to the quality control rules, and then fed back the abnormal situation to the on-site operators, who then handled the abnormal problem.

(3)Key Variable Control. Abnormal data variable control: The type, number, and severity of abnormal data set in the two groups were completely consistent, and the setting was completed by the same technician.

Quality control rule variable control: The quality control rules adopted by the two groups were completely consistent, all in accordance with the national greenhouse gas quality control standards and the relevant technical specifications of the China Meteorological Administration.

Personnel variable control: The same group of quality control personnel were responsible for the two groups, and the personnel were trained uniformly before the experiment to master the quality control rules and operation methods.

Data variable control: The normal observation data of the two groups were consistent, ensuring that the only variable affecting the quality control effect was the quality control mode.

(4)Operation Process. The operation process of the two groups was strictly standardized to ensure the accuracy of quality control index recording, with specific steps as follows.

Abnormal data setting: Professional technicians set 100 sets of abnormal data in each station according to the experimental design, and recorded the type, setting time, abnormal value, and standard threshold of each set of abnormal data. The technicians did not inform the quality control personnel of the setting details to ensure that the quality control personnel detected the abnormal data independently.

Experimental group operation (AR real-time quality control). The quality control personnel wore AR smart glasses, turned on the real-time data linkage function, and confirmed that the AR glasses were connected to the observation equipment and the quality control rule library normally; The AR glasses automatically received the real-time greenhouse gas observation data, and overlayed the data, hourly average value, daily variation curve, baseline threshold, and neighboring station comparison data in the field of view; The AR glasses automatically matched the real-time data with the quality control rules, and if abnormal data was detected, immediately popped up an alarm prompt, marked the abnormal data type and corresponding quality control rule, and overlayed the abnormal handling steps; The quality control personnel judged the abnormal data according to the AR prompt and the real-time data, confirmed the abnormal reason, and recorded the abnormal situation and handling suggestions through voice command; The quality control personnel generated the on-site quality control report through the AR glasses, and uploaded it to the meteorological cloud platform with one click, and notified the on-site operators to handle the abnormal problem in time; After the abnormal problem was handled, the quality control personnel verified the data through the AR glasses, confirmed that the data returned to normal, and completed the quality control closed-loop recording.

Control group operation (offline quality control). The greenhouse gas observation data was automatically uploaded to the meteorological cloud platform in real time; The next day, the quality control personnel logged in to the cloud platform, reviewed the data of the previous day, and judged the abnormal data according to the quality control rules; The quality control personnel recorded the abnormal data type, occurrence time, and fed back the abnormal situation and handling suggestions to the on-site operators through the work group; The on-site operators handled the abnormal problem according to the feedback, and fed back the handling result to the quality control personnel; The quality control personnel verified the handling result through the cloud platform, confirmed that the data returned to normal, and completed the quality control closed-loop recording.

Data recording. The quality control personnel recorded the key indicators in real time, including the time from data abnormality to problem detection, the accuracy of quality control judgment (whether the abnormal data was correctly identified, whether the abnormal reason was correctly judged), and the quality control closed-loop rate (the proportion of abnormal data that completed the detection-handling-verification closed-loop within the specified time).

Fig. 1. Inspection With AR Glasses

4 Pilot Experiment Details and Quantitative Effects

4.1 Experiment Basic Information

Pilot Period: March 1, 2025 to December 31, 2025, covering spring, summer, autumn, and winter, to verify the adaptability of AR equipment in different seasons and environments.

Pilot Stations: 4 regional atmospheric background stations in Hunan Province, with different geographical and environmental characteristics (Table 1), ensuring the representativeness of the experiment.

Table 1. Basic Information of Pilot Stations

Pilot Station	**Basic Information of Pilot Stations**		
	Geographical Location	***Enviornmental Characteristics***	***Main Observation Indicators***
Yueyang	North Hunan, near Dongting Lake	High humidity, frequent rainfall, near water body	CO_2,CH_4
Shaoyang	Midwest Hunan, hilly area	Moderate humidity, large diurnal temperature variation	CO_2,CH_4
Zhangjiajie	Northwest Hunan, mountainous area	Low temperature in winter, high altitude, strong ultraviolet radiation	CO_2,CH_4
Changning	Mideast Hunan, plain area	High temperature in summer, near industrial areas	CO_2,CH_4

Experimental Equipment: Customized industrial AR smart glasses (battery life ≥8 hours, operating temperature -40°C~60°C, equipped with high-definition camera and OCR recognition module); greenhouse gas observation equipment (CO_2 analyzer, CH_4

analyzer, standard gas cylinder); 5G/4G communication module; meteorological cloud platform, as shown in figure 1.

Data Statistics Method: The experimental data were sorted and analyzed by Excel and SPSS 26.0 software to ensure the scientificity and accuracy of the data analysis. The specific statistical methods were as follows, Descriptive statistics to calculate the average value, standard deviation, and coefficient of variation of each key business indicator (inspection time, omission rate, fault handling time, etc.) of the experimental group and the control group, to reflect the central tendency and discrete degree of the data. Adopt independent sample test to compare the differences of each indicator between the experimental group and the control group , with $P<0.05$ as the standard to distinguish significant difference. Analyze the correlation between the application effect of AR smart glasses and the environmental characteristics of each pilot station (temperature, humidity, altitude), to verify the environmental adaptability of AR equipment. Calculate the data error of the two groups, analyze the main sources of error (personnel operation error, equipment error, environmental interference error), and evaluate the reliability of the experimental results. All experimental data were the average value of 4 pilot stations, and the abnormal data (outliers) were eliminated by 3σ principle to ensure the reliability and representativeness of the results.

Error Analysis Specific Data: To further verify the reliability of the experimental results, the error sources and error values of the two groups were systematically analyzed, and the specific data are shown in Table 2. The total error of the experimental group was significantly lower than that of the control group, with the average relative error reduced from 7.8% to 1.2%, indicating that the application of AR smart glasses can effectively reduce experimental errors and improve data reliability.

Table 2. Error analysis of experimental groups and control groups

Error Type	**Error analysis of experimental groups and control groups**		
	Control Group Average Error	***Experimental Group Average Error***	***Error Reduction Rate***
Personnel Operation Error	4.3±1.2%	0.5±0.2%	88.4%
Equipment Error	2.1±0.8%	0.4±0.1%	81.0%
Environmental Interference Error	1.4±0.5%	0.3±0.1%	78.6%
Total Relative Error	7.8±1.5%	1.2±0.3%	84.6%

Sub-Data of Each Pilot Station. To reflect the application effect of AR smart glasses in different environments, the key indicators of each pilot station were statistically analyzed separately, and the specific data are shown in Table 3. It can be seen that AR smart glasses have significant improvement effects in all four stations, and the improvement rate in mountainous and high-humidity areas (Zhangjiajie, Yueyang) is slightly higher, indicating that AR equipment has good environmental adaptability.

Table 3. Key indicators of each pilot station (AR group)

Pilot Station	Key Indicatiors of each Pilot Stations (AR Group)			
	Inspection Time Reduction Rate	*Manual Recording Error Rate (AR Group)*	*Fault Handling Time Reduction Rate*	*Quality Control Closed-loop Rate (AR Group)*
Yueyang	47.2%	0.7±0.2%	58.9	99.3±0.7%
Shaoyang	44.1%	0.8±0.2%	55.7	99.1±0.8%
Zhangjiajie	48.5%	0.9±0.3%	59.2%	99.0±0.9%
Changning	41.8%	0.8±0.2%	52.6%	99.4±0.6%

Experiment Repeatability Verification Data. To verify the repeatability of the experimental results, each pilot station repeated the core experiment (intelligent inspection and fault handling) 3 times, with an interval of 15 days between each repetition. The relative standard deviation (RSD) of the key indicators was calculated, and the results showed that the RSD of all indicators in the experimental group was less than 3.0% (inspection time RSD: 2.1%, fault handling time RSD: 2.7%, manual recording error rate RSD: 2.4%), and the RSD of the control group was 8.3%~10.5%. The low RSD value indicates that the experimental results are stable and repeatable, and the application effect of AR smart glasses has good consistency.

4.2 Quantitative Effect Comparison

The key business indicators of the experimental group (AR application) and the control group (traditional mode) were compared, and the specific data are shown in Table 4. The results show that AR smart glasses can significantly improve the efficiency and quality of greenhouse gas services. Meanwhile, the coefficient of variation (CV) of each indicator in the experimental group is 8.2%~12.7%, which is significantly lower than that of the control group (11.9%~18.2%), indicating that the application effect of AR smart glasses is more stable. All indicators show significant differences ($P<0.01$), confirming the effectiveness of AR smart glasses in improving meteorological greenhouse gas service quality.

One-way analysis of variance (ANOVA) was conducted to test the statistical significance of differences in fault handling time under 5G, 4G and weak network environments. The results showed significant differences among the three groups ($P<0.05$). The fault handling duration under 5G network was significantly shorter than that under 4G and weak network conditions.

Table 4. Quantitative comparison of key business indicators between experimental group and control group.

Business Indicator	**Quantitative comparison of key business indicators between experimental group and control group.**			
	Control Group (Traditional Mode)	***Experimental Group (AR Application)***	***Improvement Rate/Reduction Rate***	***Significance (P Value)***
Single Station Daily Inspection Time (min)	128.6±15.3	70.2±8.9	45.4%	<0.01
Inspection Omission Rate (%)	8.7±2.1	0.9±0.3	89.7%	<0.01
Manual Recording Error Rate (%)	9.2±2.3	0.8±0.2	91.3%	<0.01
Fault Handling Time (min)	156.3±28.5	67.8±12.4	56.6%	<0.01
Expert On-site Support Rate (%)	72.5±8.6	13.2±3.5	81.8%	<0.01
Data Quality Control Response Time (min)	185.7±32.1	32.4±7.8	82.6%	<0.01
Quality Control Closed-loop Rate (%)	78.3±7.9	99.2±0.8	26.7%	<0.01
New Employee Onboarding Duration	45.2±6.8	25.3±4.2	44.0%	<0.01

4.3 Practical Effect Cases

Yueyang Station Pipeline Leakage Handling. In July 2025, the AR smart glasses of Yueyang Station detected abnormal pressure of CH_4 standard gas during routine inspection, and immediately popped up an alarm and leakage handling guidelines. On-site personnel transmitted the real scene to remote experts through AR glasses, and experts completed spatial annotation of the leakage point through remote collaboration. The fault was handled in 48 minutes, while the average handling time of the same type of fault in the traditional mode was 142 minutes, saving 66.2% of the time.

Zhangjiajie Station Low-Temperature Adaptability Test. In December 2025 (average temperature 1℃), the customized AR smart glasses maintained normal operation for 8.5 hours, with stable OCR recognition accuracy (≥99.1%) and no lens fogging or battery failure. The equipment adaptability met the requirements of alpine area observation, solving the problem that traditional AR equipment could not work normally at low temperature.

Data Quality Control Case. In September 2025, Changning Station had CO_2 analyzer zero drift (abnormal data deviation ≥5μmol/mol). The AR smart glasses detected the abnormality in real time, overlayed the zero drift correction steps in the field of view, and on-site personnel completed the correction within 25 minutes. The data was restored to normal, and the quality control response time was 86.3% shorter than the traditional mode.

5 Conclusions and Prospects

The 10-month pilot experiment at 4 regional atmospheric background stations in Hunan Province shows that AR smart glasses can significantly improve the efficiency and quality of meteorological greenhouse gas services. Compared with the traditional manual mode, the inspection time, fault handling time, and new employee onboarding cycle are reduced by more than 44%, the manual recording error rate and inspection omission rate are reduced by more than 89%, the quality control closed-loop rate is close to 100%, and the total experimental relative error is reduced from 7.8% to 1.2%. The repeatability verification shows that the relative standard deviation of key indicators is less than 3.0%, indicating stable and reliable application effects. AR smart glasses provide an effective intelligent tool for meteorological greenhouse gas observation. The potential limitations of this study before nationwide deployment recommendation, including the battery life of AR glasses in long-duration continuous operation, initial equipment procurement cost, and professional training requirements for field operators are issues have to be considered.

In the future, combined with 5G/6G, AI large models, and digital twin technology, AR smart glasses will be further integrated into the whole chain of greenhouse gas services, realizing the transformation from "auxiliary inspection" to "intelligent decision-making and collaborative command", and providing more accurate and efficient technical support for the national "dual carbon" strategy and climate governance.

References

1. China Meteorological Administration. China Greenhouse Gas Observation Annual Report (2024) [R]. Beijing: China Meteorological Administration, 2025. DOI: 10.19778/j.cnki.issn.1006-009x.2025.01.001.
2. Zhang Xiaoye, Wang Gengchen, Liu Hongli. Construction and Development of China's Greenhouse Gas Observation Network [J]. Acta Meteorologica Sinica, 2024, 82(3): 567-578. DOI: 10.11676/qxxb2024.032.
3. Li Jianke, Zhang Lei, Wang Yan. Current Situation and Optimization Suggestions of Operation and Maintenance of Meteorological Greenhouse Gas Observation Equipment [J]. Meteorological Science and Technology, 2024, 52 (2): 289-295.
4. Jihong Kong, Xi Luo, et al. Research on Intellgenct Technology Based on Augmented Reality[J]. 2024 Boao New Power System International Forum - Power System and New Energy Technology Innovation Forum (NPSIF), 2024, DOI: 10.1109/NPSIF64134.2024.10883487
5. Abderahman R, G. J K, Keong G L, Potentials and challenges of augmented reality smart glasses in logistics and supply chain management: a systematic literature review[J]. International Journal of Production Research, 2021, 59 (12): 3747–3776.

6. YUAN Yu-Feng; LIAO Zhen; ZHOU Bai-Quan; ZHAI Pan-Mao. High-impact regional extreme events in China under intensified global warming and attribution research progress [J]. Advances in Climate Change Research, 2025, 21: P44-55. DOI: 10.12006/j.issn.1673-1719.2024.260.
7. Chouchene A et al (2022) Augmented reality-based framework supporting visual inspection for automotive industry. Appl Syst Innov 5(3):48.
8. Marques B et al (2022) Remote collaboration in maintenance contexts using augmented reality: insights from a participatory process. Int J Interact Design Manuf (IJIDeM) 16(1):419–438.
9. Xiaotao Wu, Guihua Lu, Zhiyong Wu. Remote Sensing Technology in the Construction of Digital Twin Basins: Applications and Prospects[J]. 2023, 15(11), 2040; https://doi.org/10.3390/w15112040.
10. Shaw, J.T. et al (2022) A case study application of machine-learning for the detection of greenhouse gas emission sources. Atmospheric Pollution Research, 13(10), p.101563. https://doi.org/10.1016/j.apr.2022.101563.