Meteorological and Environmental Research 2026, 17(4): 33 – 35

Application of Panoramic Models for Meteorological Observation Environments Based on UAVs

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Abstract Traditional ground meteorological observation stations are vulnerable to anthropogenic interference from surrounding buildings, vegetation, and construction activities. Once an observation environment is compromised, the accuracy and representativeness of meteorological observation data will be directly impaired. Conventional environmental assessment methods relying on manual inspections and photo archiving have disadvantages of limited observation perspectives, fragmented information, and difficulties in reconstructing full-site scenarios. Remote sensing monitoring based on unmanned aerial vehicles (UAVs) features high mobility, low-altitude operation, and high-efficiency data acquisition, enabling rapid acquisition of multi-dimensional spatial information around meteorological stations. In this paper, the technical workflow for constructing panoramic models of meteorological observation environments based on UAV aerial-survey technology was introduced, and the application scenarios of panoramic models in meteorological observation environments were analyzed. Meanwhile, practical challenges in the process of the application were discussed, and targeted optimization countermeasures were proposed to provide a theoretical basis and practical references for the protection of grass-roots meteorological observation environments.

Key words Unmanned aerial vehicle; Meteorological observation environment; Panoramic model

DOI 10.19547/j.issn2152 – 3940.2026.04.007

Meteorological observation data constitute fundamental materials for weather forecasting, climate analysis, and meteorological research, and their quality largely depends on the condition of meteorological observation environments. With advancing urbanization and the continuous rise in the height of urban buildings, problems such as high building obstruction, local terrain alteration, and disorderly vegetation growth have emerged around some meteorological observation stations. Degraded observation environments introduce systematic deviations into observations of meteorological elements such as temperature, wind speed, and wind direction[1]. Meteorological authorities in China have issued multiple management regulations to normalize inspections for meteorological observation environment protection and identify potential risks posed by surrounding construction projects. Traditional inspection approaches mainly rely on on-site surveys by staff, flat-photo shooting, and paper-based records. Flat photographs only record partial perspectives and cannot fully reflect the spatial relationships between the azimuth, height, and distance of obstacles and observation stations, making historical environmental comparison difficult. Meanwhile, such materials provide limited persuasiveness for resolving environmental disputes. The rapid development of low-altitude aerial surveys of UAVs and three-dimensional panoramic-modeling technologies offers new solutions to the aforementioned practical bottlenecks. UAVs can fly around meteorological stations to collect multi-view images, which are stitched by software to generate real-scene panoramic models and realize visualized, digital archiving of observation environments[2-3]. At present, meteorological institutions across China have attempted to deploy UAVs for patrols of station environments. Nevertheless, standardized model production and operational application workflows remain to be improved. Accordingly, this study focuses on the construction and operational application of panoramic models for meteorological observation environments based on UAVs, striving to develop workable technical frameworks for panoramic-model operations and provide practical references for digital-driven supervision of the protection of grass-roots meteorological observation environments.

1 Technical workflow for constructing panoramic models of meteorological observation environments based on UAVs

1.1 Field investigation and flight scheme design Prior to UAV operations, field investigations shall be performed, such as collecting information on station coordinates, observation-site boundaries, and the distribution of surrounding buildings, and confirming airspace constraints (keeping away from hazardous areas such as airport clearance zones and high-voltage power lines). Meanwhile, the scope of aerial surveys is defined in accordance with meteorological observation protection standards. Aerial surveys generally cover investigation and assessment areas within a 500-m radius of the observation site. Operation windows are selected according to weather conditions. That is, the wind speed during operation shall not exceed force 4, and shooting is conducted in time slots with even illumination and no heavy backlight to avoid adverse shadow-related impacts on subsequent modeling results. For flight route planning, a composite operation mode combining circumferential flight and grid aerial surveys is adopted, and forward and side image overlaps are properly set to guarantee data quality for subsequent image stitching and three-dimensional modeling.

Received: May 18, 2026 Accepted: July 20, 2026

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1.2 Data acquisition of field images Consumer-grade multi-rotor UAVs equipped with visible light cameras are used to collect multi-angle images around meteorological observation sites. In addition to orthophotos, oblique shooting is implemented to acquire side texture information of buildings and trees. During shooting, it is ensured that core factors such as observation sites, wind poles, and temperature – humidity observation equipment are fully captured in images. Meanwhile, shooting time and weather conditions are recorded, and the original image datasets are preserved. For stations with complex terrain, flight altitude is appropriately reduced to improve ground-sampling resolution and ensure the recognizability of small-scale obstacles.

1.3 Generation and processing of indoor panoramic models All images captured by UAVs are imported into three-dimensional modeling software, and real-scene panoramic models for meteorological observation environments are generated through feature-point matching, aerial triangulation, and image stitching. Model repairing is conducted to eliminate distortion-induced noises caused by UAV operations and repair partial texture-missing regions. Station boundaries, protection range lines, and positions of observation equipment are marked on the panoramic models to realize the superposition of vector operational data onto real-scene models. Model outputs can be exported as web-based panoramic browsing files that are accessible without professional software, facilitating daily use by operational staff.

1.4 Quality verification of achievements Quality inspection is carried out after model generation. Firstly, whether the positions and height of observation sites and major buildings are consistent with on-site realities is verified. Secondly, the completeness of obstacle textures is inspected to avoid large-area voids, distortion, and deformation. Thirdly, accurate marking of protection range boundaries is confirmed. Qualified models shall be filed and archived to form digital archives of observation environments for corresponding stations.

2 Application scenarios of panoramic models in meteorological observation environments

2.1 Assessment of the current situation of meteorological observation environments Specifications for the protection of meteorological observation environments define clear requirements for the height and distance of obstacles. Traditional assessment relies on manual distance measurement and building-height estimation, which suffers from low efficiency and human-induced errors. Within panoramic models, horizontal distances and relative height between buildings or trees and observation sites can be directly measured to rapidly judge whether obstacles exceed protection limits. Staff can examine the surrounding environments of stations via panoramic models to comprehensively identify shelter risks, compensate for the perspective limitations of manual on-site inspections, and improve the objectivity and efficiency of environmental assessment.

2.2 Comparison of changes in observation environment and early warning of hidden dangers Periodic UAV aerial surveys can be conducted for individual stations on an annual basis to generate multi-temporal panoramic models. By comparing panoramic models from different periods, changes in environmental factors such as newly-built constructions, tree growth, and newly-added construction sites can be intuitively detected. Identified risks and hidden dangers within the models are marked, and early-warning notifications are sent to planning authorities to evade adverse impacts of new construction projects on meteorological observations. Compared with comparisons of scattered photographs, panoramic models can restore full-domain environments and reduce omissions of potential hidden dangers at marginal locations.

2.3 Support for law-enforcement evidence collection and dispute settlement When illegal construction projects impair meteorological observation environments and administrative law-enforcement actions are required, ordinary photographs can only provide partial views and can hardly prove the spatial relationships between construction projects and observation sites. Panoramic models can fully restore real-scene conditions before and after incidents, by which distances and height of obstacles can be directly measured. With high visualization, panoramic models serve as objective digital evidence to assist meteorological authorities in settling environmental disputes and improve the completeness of evidence materials.

2.4 Simulation of proposed-project impacts For proposed buildings around stations, planned architectural models can be superimposed onto existing real-scene panoramic models of meteorological observation environments to simulate shelter effects of buildings on observation sites. Impacts of the project on meteorological observation environments are evaluated to provide visualized evidence for the meteorological observation environment approval of the construction project, support decision making in planning examination and approval, and realize risk pre-disposal.

2.5 Digital archiving of station records Traditional archives for observation environments of stations mainly consist of texts and paper-printed photos, which may suffer from photo loss and difficulties in scene reconstruction after long-term storage. As visualized digital archives, UAV-generated panoramic models can be stored permanently. They fully record the full range of environmental information around stations at specific time nodes and facilitate business reviews, station-relocation demonstration, and historical-environment retrospectives, thus optimizing the archive system of stations.

3 Problems in the application of panoramic models

3.1 Restricted operation conditions for certain stations Some grass-roots meteorological stations are located in urban built-up areas with dense high buildings and complex electromagnetic environments. UAV flights face elevated safety risks caused by high buildings and high-voltage lines. Some stations lie within airport airspace control zones, and UAV flights require complicated approval procedures for airspace, which hinder regular inspection activities. Mountainous stations feature complex terrain and rapidly changing local wind conditions, increasing difficulties for aerial surveys by UAVs.

3.2 Incomplete operational standards for model achievements At present, panoramic modeling based on UAVs remains in the pilot-application phase, and there is no unified industrial specification. Divergences exist in the selection of UAV equipment, flight parameters, and modeling software adopted by different operators, resulting in inconsistent resolution and accuracy among panoramic models. Besides, unified standards for model-archiving formats, marking contents, and update cycles are absent, and inconsistent deliverable formats across stations hinder centralized management and batch invocation at provincial and municipal levels.

3.3 Insufficient technical capacity of grass-roots meteorological institutions Most grass-roots meteorological institutions lack full-time aerial survey technicians, and UAV operation and post-processing modeling involve certain learning thresholds. Some departments prioritize image acquisition yet overlook data processing. That is, only image shooting is completed, but panoramic models are not generated. As a result, image materials are accumulated and cannot be converted into usable operational outputs. Meanwhile, equipment maintenance and battery consumption impose certain financial burdens.

3.4 Inherent limitations of model accuracy Panoramic models are generated via image stitching. Swaying tree branches and leaves, as well as strong-light shadows, may trigger local distortion and voids within models. Models exhibit limited recognition capacity for tiny obstacles and low shrubs. Measurement results derived from panoramic models can only serve as references for operational judgment and cannot fully replace precise measurements obtained by professional instruments.

4 Optimization countermeasures for the application of panoramic models

4.1 Establishing a graded operation mechanism Targeted inspection schemes are developed for urban stations and stations subject to airspace restrictions. For stations with favorable operation conditions, full-range panoramic modeling shall be conducted annually. For stations with constrained flight conditions, partial circumferential aerial surveys targeting high-risk directions can be implemented to generate partial panoramas instead of pursuing full-domain modeling. Meanwhile, meteorological competent authorities shall communicate and coordinate with airspace management departments to simplify flight approval procedures for regular inspections and guarantee smooth implementation of operational patrols.

4.2 Formulating unified operational and technical specifications Meteorological competent authorities shall issue technical guidelines for panoramic models of meteorological observation environments based on UAVs, clarifying UAV selection, aerial survey image overlap, ground sampling resolution, marking elements, archiving formats, and update cycles, and unifying quality requirements for achievements. Besides, they shall clarify the application boundaries of model measurement results, distinguish auxiliary judgment data from precisely measured data, standardize operational workflows, promote achievement standardization, and facilitate centralized archive management.

4.3 Strengthening technical training for grass-roots personnel Meteorological competent authorities shall organize practical training covering UAV operation and image modeling, cultivating grass-roots staff who are familiar with both the protection of meteorological observation environments and the basic skills of aerial survey modeling. For regions incapable of independent operation, third-party services are procured via government procurement to complete aerial survey and modeling tasks, thereby reducing grass-roots technical pressure and guaranteeing achievement quality.

4.4 Integration and complementation of multiple means UAV-based panoramic models serve as an important auxiliary tool and cannot fully replace manual on-site investigations. Meteorological competent authorities shall build a combined working mode of "UAV-based panoramic models + manual field surveys + precise instrument measurement". Panoramic models are adopted for full-domain screening. After identifying suspicious hidden-danger points, field staff conduct on-site rechecks and use precise instruments for measurement at key positions. Multiple approaches are used for validation to ensure the authenticity and reliability of assessment results of meteorological observation environments.

5 Conclusion

Against the backdrop of advancing urbanization, the protection of meteorological observation environments faces growing pressures, and traditional inspection approaches can hardly satisfy operational requirements. Constructing panoramic models for meteorological observation environments via UAV aerial surveys enables full restoration of real-scene surroundings of stations and delivers prominent advantages in environmental assessment, early warnings of hidden dangers, collection of law enforcement evidence, and archive preservation, providing new digital approaches for the protection of meteorological observation environments. Nevertheless, practical deployment of such technology is constrained by airspace restrictions, absence of industrial standards, insufficient grass-roots technical capacity, and local model errors. Such constraints can be mitigated through graded aerial survey operations, improved technical specifications, enhanced personnel training, and integration of multiple observation approaches, so as to further unlock the operational value of panoramic models. With continuous iteration of UAV hardware and modeling algorithms, panoramic models will gain broader application in the protection of observation environments at grass-roots meteorological stations in the future.

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