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Research on wind field characteristics measured in inland city by Lidar

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Abstract

In order to study the wind characteristics in inland cities, a Wind3D 6000 Lidar which has many advantages in measuring wind parameters was placed on a campus in Xi’an city. Then, through filtering the original measurement data, the wind speed, wind direction, wind attack angle and turbulence intensity were analyzed using the data of nearly four months ranging from 64m to 610m. It is found that during the field measurement period, there is a linear correlation and Lorentz density function distribution between wind speed and height, but the power index law is not obvious. The wind direction changes obviously with the time and season but less along the height. The probability density of wind attack angle presents Gauss distribution, with an average value of about 1.35°, which is negatively linear correlated with height and wind speed. The probability density of turbulence shows the distribution characteristic of LogNormal density function, which increases first and then decreases with the height, and has a positive linear correlation with the wind attack angle.

Introduction

With the continuous advancement of urbanization, people's living areas are increasingly concentrated in cities, with viaducts and high-rise buildings, and the original landscape features and atmospheric boundary layer structure of cities are gradually changed by human activities$^1$. Urban air circulation, pollutant diffusion and wind resistance design of high-rise buildings are closely related to urban wind fields.

At present, there is a lot of research on the wind field characteristics of coastal areas or coastal cities$^{2-4}$, and most of them pay attention to strong winds or typhoons$^{5-7}$. The laws of wind parameters such as wind speed profile, wind direction and turbulence intensity are studied through numerical simulation or field measurement methods. However, there are few reports on the wind field of inland cities, so it is necessary to conduct more research on the characteristics of the wind field of inland cities.

On the other hand, wind field characteristics are mainly studied by wind tunnel test$^{8-10}$, numerical simulation$^{11-13}$ and field measurement$^{14-16}$. The wind tunnel test method is widely used, but the error of scale model manufacturing, the change of local structure and the simulation of incoming wind field will affect the reliability of the results. With the development of computer technology...
and performance, numerical simulation methods, especially Computational Fluid Dynamics (CFD), have been applied more and more. However, the accuracy of simulation results is affected by many aspects, such as grid quality, calculation domain size, boundary conditions and turbulence model. Generally, it needs to be checked and verified by experiments or measured data. In spite of the high cost and limited monitoring points, the field measurement can obtain the most reliable wind field data. With the development of testing technology, especially the application of remote monitoring technology, such as radar, the cost of field measurement is greatly reduced, and a large range of massive data can be obtained.

Specifically, the field measurement could be divided into direct measurement and indirect measurement. Direct measurements from tall mast with anemometers, balloons have been important in defining the profiles of atmospheric parameters of the atmosphere boundary layer. The ability to observe atmospheric variables with a minimum of assumptions has prompted expensive use of these filed measurement platforms despite the development costs and associated limitations on sample size.

Indirect observation is mostly made by remote sensors, for example, Radar, Sodar and Lidar, have been used in wind parameters measurements. Because of the advantages of volume sampling are becoming more widely recognized, and the availability of improved resolution and Doppler capabilities in these remote sensors has greatly increased their utility, those make remote sensors the observational platform of choice in many situations. Canadilias et.al studied the ground-based wind Lidar test results and found that the Lidar in close to a highly efficient reaches more than 98%, average wind speed of 10 min showed that the measurement results correlation coefficient between Lidar and meteorological tower at all height achieved 0.99, these results suggest that the Lidar is a reliable wind measured equipment.

Lidar is uniquely capable of collecting all-weather, high accuracy, large detection range, high spatio-temporal resolution and other excellent characteristics, is a powerful instrument for measuring wind parameters. Charland used the Doppler Wind Lidar (DWL) to research a wildland fire plume in complex terrain east of San Jose, California, vertical wind and turbulence profiles within 200m were measured to study the kinematic structure and spatial and temporal evolution of the fire plume, found that the velocity accelerates at the plume boundary. Kristoper et.al gained the profiles of the component of wind vector and aerosol/cloud optical properties on a global scale by using a novel atmospheric Lidar Doppler Instruments. Shu et.al studied the marine wind field with particular emphasis on wind veer characteristics by Wind Lidar Measurement (WLM), the variation of wind veer profiles up to a height of 180m was given. Duan et.al used the differential absorption Lidar in the Lintong district to measure the atmosphere concentration of polluting atomic mercury, the average concentrations were recorded and put in relation to weather condition, and vertical concentration profiles were given. Wang et.al used the Doppler wind Lidar (DWL) to study the wind speed and wind direction within 300m during a super Typhoon, and investigated the impact of factors (e.g., precipitation and humidity) on DWL-observed
wind data.

At present, the research objects of urban wind fields are mostly strong winds or typhoons in coastal cities, and the data range is mostly within 400m. In this paper, we study the inland city wind features making use of high performance wind3D 6000 Lidar, a field measurement station was set up somewhere in Xi’an and observation continued for more than four months. Then, through the screening of raw data, analysis of wind data ranges from 64m to 610m, the wind speed, wind direction, wind angle of attack and turbulence intensity, wind parameters were analyzed from the perspective of temporal, spatial and probability distribution. The research methods and results can be reference for inland cities wind field research, it could provide data for air circulation, pollutant diffusion and wind resistance design of high-rise buildings in inland cities.

Topography features and equipment introduction

Terrain description

Xi’an city is a typical inland city of China, is located in the crescent-shaped Guanzhong Plain, belonging to the warm temperate zone semi-humid continental monsoon climate, with four distinct seasons, thunderstorm gales in summer and rapid temperature drops in autumn. The dominant wind directions in the urban area of Xi’an city are northeast wind and southwest wind each year. There are great differences in altitude within the terrain, with the Qinling Mountains in the south and the Weihe Plain in the north, as shown in Figure 1. With the Lidar as the center, from north to south, the altitude rises from 331m to 3551m in the area with a side length of 80km, but in the area with a side length of 800m, the altitude difference is 7m near the Lidar.
Lidar system

Compared with traditional wind measurement means, such as anemometer, Lidar and sodar, Wind3D 6000 3D scanning wind measuring Lidar has the advantages of higher measurement accuracy, higher spatial and temporal resolution, and lower detection blind area. With high pointing accuracy optical scanning mirror, 3D scanning detection can be realized, and the maximum detection radius can be up to 6km. The Lidar has the advantages of small size, light weight and low power consumption, which makes it easy to build stations and transport in the field, as shown in Figure 2.

Wind3D 6000 3D scanning wind measuring Lidar is a coherent wind measuring Lidar system, which is mainly composed of laser transmitting and scanning subsystem, receiving subsystem, real-time signal processing subsystem, communication subsystem, etc., as shown in Figure 3. Based on the principle of optical pulse coherent doppler frequency shift detection, after the use of aerosols in the atmosphere laser scattering signal and the laser emission system of the local oscillator optical heterodyne detection, get two beams of light heterodyne signal, doppler frequency shift is obtained to calculate the radial velocity, based on the assumption of the horizontal homogeneous wind speed \( \frac{25}{26} \), using the micro beam scanning system inversion boundary layer wind profile, visibility data are also provided.

The Lidar emits an eye-safe invisible light with a wavelength of 1550nm, transmits laser pulses into the atmosphere at a rate of 1~10 Hz, which is user-defined possible. The Lidar equipped an optical scanner enabling the scan of it from 0~360° azimuth angles and -90~270° pitch angles, and there are up to 398 user-defined range gates at 15m spacing with the minimum range at 45m and maximum range at 6000m, so it is called Wind3D 6000. In addition, various scan models are available, for example, Doppler Beam Swinging (DBS), Range Height Indicator (RHI), Plan Position Indicator (PPI) and so on. DBS is used in the paper to obtain wind speed and direction profiles, detailed in Tab.1.

![Figure 3. Diagram of Wind3D 6000 Lidar wind measuring system](image)

The Lidar emits an eye-safe invisible light with a wavelength of 1550nm, transmits laser pulses into the atmosphere at a rate of 1~10 Hz, which is user-defined possible.
The Lidar equipped an optical scanner enabling the scan of it from 0°~360° azimuth angles and -90°~270° pitch angles, and there are up to 398 user-defined range gates at 15m spacing with the minimum range at 45m and maximum range at 6000m, so it is called Wind3D 6000. In addition, various scan models are available, for example, Doppler Beam Swinging (DBS), Range Height Indicator (RHI), Plan Position Indicator (PPI) and so on. DBS is used in the paper to obtain wind speed and direction profiles, detailed in Tab.1.

| Number | Items                          | Parameters                                      |
|--------|--------------------------------|-------------------------------------------------|
| 1      | Radial detection range         | 45~600m                                         |
| 2      | Radial range resolution        | 15m/30m/User defined                            |
| 3      | Laser wavelength               | 1550nm, invisible and safe to human eyes         |
| 4      | Data refresh frequency         | 1Hz~10Hz (Available software settings)           |
| 5      | Range of radial velocity       | -37.5~+37.5m/s                                  |
| 6      | Range of radial measured wind speed | 0~75m/s                                    |
| 7      | Range of wind direction        | 0~360°                                          |
| 8      | Accuracy of wind speed         | ≤0.1m/s                                         |
| 9      | Accuracy of wind direction     | <3°                                             |
| 10     | Scan modes                     | DBS /PPI/RHI/VAD/ scripting                      |
| 11     | Range of servo scanning        | Horizontal direction: 0~360°, vertical scanning: -90~270° |
| 12     | Servo accuracy                 | 0.1°                                            |
| 13     | Weight                         | <90kg                                           |
| 14     | Size (Length*Width*Height)     | 638mm*626mm*907mm                               |
| 15     | Power supply                   | 220V/50Hz                                       |
| 16     | Communication mode             | Ethernet/3G/4G/Modbus                            |

Table 1. Performance parameters of Lidar

Field measurement data analysis

Setup of Lidar

The setup of the Lidar system is divided into site selection, installation, debugging and testing. The details are as follows:

1) Site selection: through scheme selection, Wind3D 6000 Lidar system is determined to be installed in the school test site. The test site is flat and open with little shielding around it. It is about 20km to the Qinling Mountains in the south and 20km to the Weihe Plain in the north, located in the middle of the Guanzhong Plain, as shown in Fig 1, which is a good representative of the inland city of Xi'an. In addition,
equipment safety is guaranteed and the power supply is reliable.

2) Installation: the Lidar is installed in the open space of the test site, concrete ground or shrubs with a height of less than 2m within a radius of 200m. In the farther distance, there are libraries, residential buildings and other buildings, it does not interfere with the measurement. The Lidar system is equipped with power supply, monitoring and 4G network to facilitate data transmission and site monitoring, as shown in Fig 3.

3) Debugging: after field debugging, the Lidar system runs normally, with little interference from surrounding buildings, the signal-to-noise ratio (SNR) is greater than 5000, and the wind parameter measurement is normal;

4) Testing: from June 15, 2020 to October 22, 2020, from summer to autumn, the operating state of the Lidar system was real-time monitored, and continuous 129 days of data was measured and recorded.

**Raw data validity**

The effective distance of the Lidar pulse signal is related to the weather conditions, especially the aerosol content in the air, such as rain, snow, fog and haze, which will change the aerosol content and affect the transmission of the echo signal. In order to improve the quality and reliability of the data, the following screening work is done for the original data before data analysis:

1) Abnormal value data shall be removed, that is, when the wind speed or direction value exceeds the wind speed measurement range of 0 ~ 75m/s and the wind direction range of 0 ~ 360°, the wind speed or direction value is "999", it shall be removed;

2) Eliminate unreliable data. According to the suggestions of the equipment owner, the larger the SNR, the more reliable the data will be. When the SNR is less than 10dB, there may be greater interference, which will reduce the reliability of the measured data, so the data shall be eliminated.

3) Conduct data validity analysis for data with good continuity and reliability within the scope of concern, such as 64-610m.

The data effective rate is defined as follows. Taking 24h per day as the time unit, the total number of wind speed data at different heights and the total number of data excluded are counted to get the total number of effective data. Then, the total number of effective data is divided by the total number of data to get the effective rate of data at different heights, as shown in Eq. (1).

\[ \eta = \frac{N - N_{\text{error}}}{N} \times 100\% \]  \hspace{1cm} (1)

Where: \( \eta \) is the effective rate, \( N \) is the total number of data at a measured height in a day, \( N_{\text{error}} \) is the total number of excluded data at a measured height in a day.
As can be seen from Figure 4 and Tab. 2, the measurement range of the Lidar is between 64 and 2183 m per day, and the effective rate of the data fluctuates greatly. Combined with the historical weather forecast, it was moderate rain on June 15, and the data efficiency is the worst, and the data efficiency of each height is less than 1. On July 3, August 5 and September 13, most of the days were cloudy, with occasional light rain. The data efficiency was high, both exceeding 750 m, and the highest reached 1390 m on July 3. October 7 is a sunny day, the lowest air index indicates the cleanest air, and the low aerosol content affects data efficiency. It can be found that Lidar data could be more efficient when measured on overcast and cloudy days.

| Date       | Weather           | Air quality index | Effective rate η turning point and Height |
|------------|-------------------|-------------------|------------------------------------------|
| 2020-06-15 | Moderate rain     | 67 (Good)         | 0.999 ~ 64 m                             |
| 2020-07-03 | Overcast to cloudy| 74 (Good)         | 0.999 ~ 1390 m                           |
| 2020-08-05 | Cloudy to drizzle | 60 (Good)         | 0.999 ~ 766 m                           |
| 2020-09-13 | Cloudy to light rain | 66 (Good)       | 0.999 ~ 1286 m                          |
| 2020-10-07 | Clear day         | 54 (Good)         | 0.999 ~ 402 m                           |

Table 2. Historical weather list

Due to 610 m is higher than the height of most existing buildings, except Burj Khalifa in Dubai which is 828 m high, and Shanghai Tower in China which is 632 m high, in the inland city Xi'an, there is no building with a height of more than 500 m, and the gradient wind height of 550 m of Type D surface roughness in the building code is less than 610 m. Therefore, the data with 100% efficiency within the range of 64 ~ 610 m is selected for the following analysis, which could reasonably describe the wind field of inland cities.

Results and discussion

The wind speed, wind direction, wind attack angle and turbulence intensity were analyzed in the view of correlation and probability distribution.
Wind speed

Six characteristic heights are selected, respectively 64m at the lowest height of Lidar detection range, 100m at the approximate height of the surrounding 30-storey buildings, and 4 gradient wind heights in the building code, 300m, 350m, 450m and 550m. Point 0 on the horizontal axis of the time chart is selected as 0:0:0 in the middle of the night every day, and the day is divided into 144 time periods with an interval of 10min.

Wind speed time history and spatio-temporal distribution of characteristic height of a certain day are shown in Figure 5 and Figure 6. It can be found that the spatial and temporal distribution of wind speed presents an obvious non-uniform pattern. As the disturbance effect of surface roughness decreases, the wind speed increases with the increase of height from 1m/s to 13m/s. Wind speed fluctuates with time, and its variability is smaller at noon than in the morning and evening, which may be caused by the temperature change caused by solar radiation.

Due to the noise of small wind data, the data accuracy is affected, and the influence on ventilation, wind resistance and other aspects of the structure is small. Combined with the data characteristics, the wind speed samples whose minimum wind speed is no less than 4m/s are analyzed below.

Since the wind speed changes at a height of 350m, the reference height is selected as 350m to conduct dimensionless processing on the wind speed data to obtain a dimensionless wind speed profile. Then, Eq. 2, Eq. 3 and Eq. 4 are used for wind profile fitting. The results are shown from Figure 7 to Figure 12.

\[ y = ax + bx \]  

(2)

where: \( x \) is wind speed (m/s); \( y \) is height (m); \( a \) and \( b \) are the parameters to be determined.

\[ \frac{U_2}{U_1} = \left( \frac{H_2}{H_1} \right)^\alpha \]  

(3)
where: \( H_1 \) and \( H_2 \) are the height (m); \( U_1 \) and \( U_2 \) are the wind speed (m/s) at the height \( H_1 \) and \( H_2 \); \( \alpha \) is the coefficient of surface roughness.

\[
X = Y_0 + \frac{2A}{\pi} \left( \frac{\omega}{4(Y - \lambda)^2 + \omega^2} \right)
\]

where: \( X \) is wind speed (m/s); \( Y \) is the height (m); \( A, \omega \) and \( \lambda \) are the parameters to be determined.

After statistical analysis, the wind speed is mostly distributed in the range of 4 ~ 15 m/s, and the rule of power index or logarithm of wind speed profile is not obvious. The measured wind velocity profile can be divided into two categories. The first category, named Type_A, is linear correlation, which may be due to the good uniformity of atmospheric circulation. The fitting results are shown in Eq. 2-1 and Eq. 2-2. It can be found that the slope is about 77, which means that the wind speed increases by 1 m/s for every increase of 77 m. In the second type, named Type_B, the wind speed reaches the maximum at the height of 350 m and then decreases with the increase of the height, which may be due to the reverse influence of local pressure gradient. Lorentz unimodal function can be used for fitting. The fitting results are shown in Eq. 4-1.

\[
y_{1a} = -271.95 + 77.01x_{1a}
\] (2-1)

\[
\frac{U_\sigma}{0.348} = \left( \frac{H_\sigma}{1.635} \right)^{0.59}
\] (3-1)
Figure 9. Wind speed profile of Type_A_2 Figure 10. Fitting results of Type_A_2 wind speed profile

\[ y_{1b} = -372.68 + 77.74x_{1b} \quad (2-2) \]

\[ \frac{U_b}{0.481} = \left( \frac{H_b}{0.421} \right)^{0.44} \quad (3-2) \]

Figure 11. Wind speed profile of Type_B Figure 12. Fitting results of Type_B wind speed profile

\[ X_1 = 3.409 + \frac{2 \times 7478.631}{\pi} \left[ \frac{414.242}{4(Y_i - 392.462)^2 + 414.242^2} \right] \quad (4-1) \]
Wind direction

Figure 13. Time history of wind direction
Figure 14. Spatio-temporal distribution of wind direction

As shown in Figure 13 and Figure 14, wind direction time history and spatio-temporal distribution of characteristic height on a certain day show that wind direction varies greatly in the morning and evening and has a higher consistency at noon, which may be caused by solar radiation in the daytime, temperature gradient in the night being larger than that at noon, and sharp changes in air pressure. In addition, the higher the height, the smaller the wind direction variation.

Figure 15. Rose diagram of wind direction
Figure 16. Probability density of wind direction

As can be seen from Figure 15 and Figure 16, during the measured period, the wind direction ranges from 165° to 255°, presenting an obvious double peak phenomenon. The wind direction gradually changes from the south wind in July to the southwest wind in September, with the mean wind direction of 185° in July, 206° in August and 240° in September. The measured wind direction is consistent with the prevailing wind direction in Xi’an, which matches well with the seasonal change.
Wind attack angle

As shown in Figure 17 and Figure 18, the time history and spatial and temporal distribution of wind attack angle at characteristic height on a certain day fluctuates from $-2^\circ$ to $+6^\circ$, and the variation range of wind attack angle decreases with the increase of height, which is greatly related to the small value and variation of low-height wind speed.

![Figure 17. Time history of wind attack angle](image1)

![Figure 18. Spatio-temporal distribution of wind attack angle](image2)

![Figure 19. Probability density of wind attack angle](image3)

$$g_{\text{Gauss}} = g_0 + \frac{C}{\sigma \sqrt{0.5\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}}$$

where: $x$ is the wind attack angle ($^\circ$), $g_0$ is the initial value of probability density, $g_{\text{Gauss}}$ is the probability density, $C$ is the undetermined parameter, $\mu$ is the mean value, $\sigma$ is the standard deviation.
The wind attack angle is statistically analyzed for the wind speed data no less than 4 m/s. Lorentz probability density function (Eq. 4) and Gauss probability density function (Eq. 5) are used to fit the probability density of the wind attack angle. The fitting results are shown in Eq. 5-1 and Eq. 4-2, but the square of correlation coefficient of Gauss function is closer to 1. This indicates that the distribution of wind attack angle in the period of high wind speed is more consistent with Gauss normal distribution. The initial value is 0.006, which can be ignored. The mean value of wind attack angle is 1.35°, and the standard deviation is 1.194. This indicates that in inland cities, the positive wind attack angle is the main attack angle, accounting for 81%, and the value is around 1.35°, as shown in Figure 19.

In addition, as shown in Figure 20 and Figure 21, Eq. 2 is used to fit the relationship between wind attack angle and height and wind speed respectively, and the results are shown in Eq. 2-3 and Eq. 2-4. Although the linear relationship is very weak, it can be seen that the dispersion of wind attack angle decreases gradually with the increase of height and wind speed. This may be due to the lower level disturbance at high altitude.
Turbulence intensity

The spatio-temporal distribution of turbulence at the characteristic height of a certain day, as shown in Figure 22 and Figure 23, is similar to the wind attack angle, with large value and strong variability at low height, fluctuating between 0 and 0.5. Eq. 2 is used for linear fitting of turbulence and wind attack angle, as shown in Figure 24, the square of correlation coefficient is 0.358, indicating that turbulence and wind attack angle have a weak linear correlation.

Through statistical analysis, it is found that the probability density of turbulence intensity showed a single peak decay shape, so Eq. 4, Eq. 6 and Eq. 7 are used to fit probability of turbulence intensity. The fitting results are shown in Figure 25. Compared with Lorentz probability density function and Extremen probability density function, LogNormal probability density function has the highest correlation coefficient square value, 0.919, indicating that it can better describe the rule of turbulence intensity.

Figure 22. Time history of turbulence intensity Figure 23. Spatio-temporal distribution of turbulence intensity

Through statistical analysis, it is found that the probability density of turbulence intensity showed a single peak decay shape, so Eq. 4, Eq. 6 and Eq. 7 are used to fit probability of turbulence intensity. The fitting results are shown in Figure 25. Compared with Lorentz probability density function and Extremen probability density function, LogNormal probability density function has the highest correlation coefficient square value, 0.919, indicating that it can better describe the rule of turbulence intensity.

Figure 24. The relationship of turbulence intensity and wind attack angle Figure 25. Probability density of turbulence intensity
\[ y_4 = 0.802 + 5.332x_4 \]  

(2-5)

\[
L_{\text{LogNormal}} = L_0 + \frac{D}{\sqrt{2\pi \rho x}} e^{-\frac{(\ln x - \ln \eta)^2}{2\rho^2}}
\]

(6)

where: \( x \) is the turbulence intensity, \( f_0 \) is the initial value of probability density, 

\( L_{\text{LogNormal}} \) is the probability density, \( D \), \( \eta \) and \( \rho \) are the parameters to be defined.

\[
f_{\text{Extremen}} = f_0 + Be^{-(e^\left(-\frac{1}{\zeta}\right) - \frac{x - \tau}{\zeta})}\]

(7)

where: \( x \) is the turbulence intensity, \( f_0 \) is the initial value of probability density, 

\( f_{\text{Extremen}} \) is the probability density, \( B \), \( \zeta \) and \( \tau \) are the parameters to be defined.

\[
L_{\text{LogNormal}}^{(6-1)} = 0.007 + \frac{0.016}{\sqrt{2\pi \times 0.663x}} e^{-\frac{(\ln x - \ln 0.088)^2}{2\times 0.663^2}}
\]

(6-1)

\[
f_{\text{Extremen}}^{(7-1)} = 0.013 + 0.137e^{-(e^\left(-\frac{1}{0.035}\right) - \frac{x - 0.063}{0.035})}\]

(7-1)

\[
Y_3 = -0.009 + \frac{2\times 0.019}{\pi} \left[ \frac{0.086}{4(X_3 - 0.068)^2 + 0.086^2} \right]
\]

(4-3)

**Conclusion**

1) Lidar is small in size and light in weight, is easy to build measurement stations in the field, can measure and record wind speed, wind direction and other wind parameters for a long time, a wide range with high efficiency, is a reliable equipment for wind parameter measurement research. In addition, measurements taken when the weather is clear can obtain higher quality data.

2) The objective speed wind field data of the test period were selected and analyzed, and it was found that the wind field parameters of inland cities are a function of time and space, showing uneven characteristics in time and height, which was different from the recommended in the specification.

Specifically: the relationship between wind speed and height is linear and Lorentz nonlinear, and the regularity of power exponent is not obvious. The wind direction has a strong correlation with time and season, and does not change significantly along the height. The probability distribution of wind attack angle can be described by Gauss probability density function. The wind attack angle has negative linear correlation with height and wind speed. LogNormal probability density function is a better method to
characterize the turbulence intensity distribution, and there is a positive linear correlation between turbulence intensity and wind attack angle.

3) Currently, in view of the functions and characteristics of the Lidar, no research has been done on wind speed power spectrum and spatial coherence, etc., and further update of equipment or advanced analysis method is needed.

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