Research Progress in Microwave Remote Sensing Monitoring Technology for Dust Weather (Postprint)

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Abstract

Dust weather is an atmospheric natural phenomenon that frequently occurs in arid and semi-arid regions. When dust processes are intense or erupt on a large scale (such as severe dust weather or dust storm events), they lead to a significant increase in the concentration of particulate matter in the atmosphere, thereby exerting adverse effects on air quality, human health, and regional or even global climate. Therefore, accurate monitoring of dust weather is of great significance for environmental governance, disaster warning, and climate assessment.

However, under the influence of specific weather systems, dust weather may coexist and interact with cloud systems. In cases where cloud layers are situated above the dust, or when the dust layer is weak while the cloud signal is strong, it is difficult to penetrate the cloud layers to achieve accurate monitoring of sub-cloud dust using only traditional optical remote sensing means such as visible and infrared light. Microwave remote sensing technology possesses the advantage of penetrating cloud layers, demonstrating important application value in sub-cloud dust monitoring. Based on this, this paper summarizes relevant research achievements in monitoring dust weather using microwave remote sensing technology in recent years, provides a detailed introduction to different methods, analyzes the principles, advantages, and limitations of various methods, and offers an outlook on future research directions.

Full Text

Preamble

Future research directions are also discussed. Dust weather refers to a weather phenomenon where strong winds lift large amounts of dust and sand from the ground into the air under specific geographical and surface conditions, resulting in turbid air and reduced horizontal visibility. This type of hazardous weather primarily occurs in semi-arid, arid, and desert regions, characterized by sudden onset, short duration, and wide-ranging impacts. National standards categorize dust weather into five levels based on wind speed and visibility: floating dust (no wind or light wind, horizontal visibility $1 \text{ km} \leq V < 10 \text{ km}$), blowing sand (wind force > 3, horizontal visibility $1 \text{ km} \leq V \leq 10 \text{ km}$), dust storms ($500 \text{ m} \leq V < 1 \text{ km}$), severe dust storms ($50 \text{ m} \leq V < 500 \text{ m}$), and extreme dust storms (horizontal visibility $V < 50 \text{ m}$).

During dust weather events, large quantities of dust particles are transported into the atmosphere, forming dust aerosol layers. These aerosols can be transported over long distances via atmospheric circulation, significantly affecting regional and global atmospheric environments and climate change. Timely and accurate monitoring of the intensity and spatio-temporal evolution of dust weather is of great significance for environmental protection and climate research. Although the occurrence of dust weather is closely related to dry and cloudless atmospheric conditions, cloud cover often occurs during the transport process, resulting in mixed cloud-dust phenomena. When cloud layers are situated above the dust or when the dust signal is weak, traditional optical monitoring technologies such as visible light, infrared, and laser are limited in their ability to effectively monitor dust beneath the clouds. Microwave remote sensing technology, with its longer wavelengths, offers the advantages of all-weather and all-time observation, providing a new approach for the effective monitoring of sub-cloud dust.

Scholars both domestically and internationally have conducted a series of studies on microwave remote sensing observation techniques. Based on monitoring principles, existing microwave monitoring technologies can be divided into two categories: traditional microwave remote sensing and Global Navigation Satellite System (GNSS) microwave remote sensing. Depending on the sensor’ s operation mode and signal source, traditional microwave remote sensing can be further subdivided into passive and active microwave remote sensing. Passive microwave remote sensing primarily utilizes microwave radiation sensors onboard satellites to receive microwave signals emitted by the Earth’ s surface and the atmosphere.

Research Progress in Microwave Remote Sensing Monitoring Technology for Dust Weather

Dust weather is a common atmospheric phenomenon in arid and semi-arid regions. When dust processes are intense or occur as large-scale outbreaks, dust storms can lead to a significant increase in atmospheric particulate matter concentration, adversely affecting air quality, human health, and regional or global climate. Accurate monitoring of dust weather is essential for environmental management, disaster warning, and climate assessment. Under the influence of specific weather systems, dust may coexist and interact with cloud systems. When clouds are positioned above the dust, or when the dust layer is weak and the cloud signal dominates, traditional optical remote sensing methods (such as visible and infrared) struggle to penetrate the cloud layer for accurate monitoring. Microwave remote sensing technology, with its ability to penetrate clouds, demonstrates significant value for sub-cloud dust monitoring.

This paper summarizes recent research achievements in monitoring dust weather using microwave remote sensing, providing a detailed introduction to various methods. It analyzes the principles, advantages, and limitations of these techniques while looking forward to future research directions. By retrieving parameters related to dust weather, passive microwave remote sensing can effectively monitor the coverage and transport paths of dust storms. Examples include the Microwave Radiation Imager (MWRI) and the Advanced Microwave Scanning Radiometer (AMSR) on the Chinese Fengyun-3 (FY-3) satellites. However, this method has limited vertical sounding capabilities and is susceptible to the polarization characteristics of the underlying surface.

Active microwave remote sensing, such as cloud radar and wind profile radar, actively transmits microwave signals and receives backscattered echoes from dust particles to obtain vertical structure information, including the height and thickness of the dust layer. Nevertheless, this method faces limitations such as high equipment costs and complex data processing. Microwave remote sensing can compensate for the deficiencies of single-source techniques by fusing multi-source satellite observation data, thereby improving overall dust monitoring performance.

With the rapid development of GNSS and in-depth research into signal characteristics, GNSS-based environmental remote sensing has successfully been applied to precipitation and air quality assessment due to its advantages of multi-signal availability, wide coverage, and high efficiency. In this context, researchers have introduced GNSS technology into the field of dust weather monitoring to obtain relevant parameters. Based on the receiver’ s position, GNSS microwave remote sensing can be categorized into ground-based and space-borne methods. Ground-based GNSS utilizes receivers on the Earth’ s surface to receive satellite signals, solving for delay amounts through tropospheric delay models to retrieve dust-related parameters; this is suitable for describing the horizontal distribution of dust in the lower atmosphere. Space-borne GNSS Radio Occultation (RO) technology utilizes receivers on Low Earth Orbit (LEO) satellites to retrieve atmospheric profile parameters from satellite signals. This can identify anomalies caused by dust processes, such as temperature inversions, to describe the vertical distribution of dust storms in the upper atmosphere.

Currently, as the understanding of the interaction mechanism between dust and GNSS signals is still insufficient, GNSS-based dust remote sensing remains in the exploratory stage. Establishing quantitative relationships between GNSS data and the physical properties of dust aerosols remains a significant challenge. Although research in this area is still developing, a systematic review of domestic and international studies is of great scientific importance for promoting the application of microwave technology in dust remote sensing. This paper focuses

Figure 1

Figure 1: Figure 1

on microwave remote sensing technology, summarizing the key research progress in dust monitoring, elaborating on the response mechanisms of microwave signals to dust, and discussing the research priorities and future directions for microwave technology in this field.

1. Scattering and Attenuation Effects of Dust on Microwave Signals

The influence of dust on electromagnetic wave propagation is essentially a comprehensive effect of scattering and absorption by a large number of suspended dust particles during dust storm events. Accurate understanding of these effects, which cause attenuation and depolarization of electromagnetic signals, is not only fundamental to studying the impact of dust weather on wave propagation but also critical for obtaining accurate information through related remote sensing technologies. In research concerning the impact of sand particles on electromagnetic waves, Rayleigh scattering theory provides theoretical predictions for the electromagnetic extinction of sand particles. This theory primarily discusses the influence of electromagnetic wave frequency and is applicable when the particle size is much smaller than the incident wavelength (λ). The classical theory for electromagnetic scattering by spherical particles, where particle size is comparable to the wavelength, was first developed by Lorenz and Mie (Mie theory).

The propagation characteristics of electromagnetic waves in dust environments are jointly influenced by various factors, including the parameters of the electromagnetic wave itself, the physical properties of the dust medium, and the propagation environment. Regarding the influence of electromagnetic frequency on microwave propagation, our understanding has evolved significantly. In

, the orange and green spherical particles represent dust particles, with their sizes indicating different diameters and their colors representing potential positive or negative charges carried by the particles. As the incident electromagnetic wave passes through the dust layer, the resulting wave exhibits a reduced amplitude, reflecting the combined effects of scattering and absorption by the dust particle system.

Early studies generally suggested that the impact of dust weather on microwave propagation was negligible, particularly at radar frequencies below 10 GHz. However, subsequent research has demonstrated that in strong dust storms, electromagnetic wave attenuation increases significantly and is positively correlated with frequency. Goldhirsh noted that at a given dust mass concentration, attenuation is minimal in the L-band, marginal in the X-band, and severe in the Ka-band. As frequency increases, attenuation in intense dust environments becomes more pronounced, making frequency selection a vital consideration in communication system design and remote sensing observations under dust conditions.

Regarding the physical properties of the dust medium, moisture content and charging state significantly influence electromagnetic scattering. Dust particles typically have diameters distributed within the range of 10^{-1} to $10^{2}\mu$m, and attenuation is approximately positively correlated with particle size. Since actual sand grains are mostly non-spherical, the T-matrix method was proposed based on optical theorems to accurately describe their scattering characteristics. Initially developed by Waterman, this method was limited to rotationally symmetric ellipsoidal particles with low asphericity or small scale parameters. Subsequent improvements by Wriedt and Mishchenko extended its applicability to larger scale parameters and more complex non-spherical particles. T-matrix studies indicate that the influence of shape on attenuation is most significant when the wavelength is less than 1 cm.

The moisture content of particles affects attenuation intensity by altering the equivalent complex permittivity. Research by Haddad showed that the attenuation of wet sand is approximately 10^{1} to 10^{2} times that of dry sand, further demonstrating that attenuation increases with moisture content and tends toward saturation at 10%. Furthermore, sand particles in motion often carry charges, with the polarity being size-dependent: larger particles typically carry positive charges while smaller particles carry negative charges. In modeling the scattering of charged particles, Bohren extended Mie theory to fully charged spherical particles. Kocifaj further analyzed their extinction coefficients, noting that charge effects are particularly significant when the scale parameter $x < 0.1$. Results indicate that at frequencies below 10 GHz, particle charging significantly enhances attenuation, with the attenuation coefficient increasing alongside the charge amount; at frequencies above 30 GHz, this influence becomes largely negligible. In strong dust storms, the coupling between electrostatic fields and charged particles cannot be ignored.

In terms of the atmospheric propagation environment, macroscopic conditions such as visibility and relative humidity play important roles in modulating wave propagation. A decrease in visibility reflects an increase in dust concentration and the total extinction coefficient, leading to significantly enhanced path attenuation. Relative humidity further exacerbates microwave signal attenuation by altering the equivalent dielectric properties of dust particles and increasing water vapor absorption. Research by Abuhdima showed that strong dust storms under different relative humidity conditions cause severe microwave signal attenuation when visibility drops to 100 m. Rayleigh approximation analysis indicates that large-scale strong dust storms significantly impact microwave communication links. Studies in the K-band further clarified that attenuation decreases as visibility improves. Experimental measurements have also found that traditional models based on the single-scattering assumption often underestimate actual attenuation. Under low-visibility conditions, multiple scattering effects in the dusty atmosphere must be considered. Monte Carlo simulations of multiple scattering processes in dust weather show that at high frequencies and low visibility, incorporating multiple scattering significantly narrows the gap between theoretical and measured results.

2. Traditional Microwave Remote Sensing for Dust Monitoring

Timely and accurate monitoring of the spatiotemporal evolution of dust weather is of great significance for deeply understanding dust emission mechanisms and transport processes. Optical remote sensing technologies based on visible, infrared, and laser spectra can effectively monitor dust under clear-sky conditions; however, their signals suffer severe attenuation in the presence of thick clouds and intense dust storms. Due to their longer wavelengths, microwave remote sensing techniques possess strong penetrative capabilities and can effectively penetrate cloud layers. Depending on the sensor' s operating mode and signal source, it can be categorized into passive microwave remote sensing and active microwave remote sensing.

2.1 Passive Microwave Remote Sensing for Dust Monitoring

Passive microwave monitoring techniques primarily utilize radiative brightness temperature data acquired by microwave radiometers to infer sub-cloud dust information. Because the scattering of microwave radiation by dust particles is enhanced, high-frequency brightness temperatures significantly decrease; thus, brightness temperature data can be used to monitor the evolution of dust storms. Passive microwave remote sensing monitors sub-cloud dust by capturing the scattering and depolarization effects of dust on microwave signals, utilizing the differences in brightness temperature responses across different frequency and polarization channels. The core of this approach lies in constructing microwave indices sensitive to dust characteristics, which are generally divided into two categories: scattering indices and polarization difference indices.

Regarding scattering index methods, monitoring indicators are primarily constructed by exploiting the strong scattering effect of dust on high-frequency microwaves. [**?**] analyzed the scattering characteristics of dust using brightness temperature data from the TRMM/TMI 85.5 GHz band, finding a significant correspondence between decreased brightness temperatures and increased scattering indices during dust events. Regarding polarization difference index methods, monitoring indicators are constructed based on the attenuation effect of dust on the polarization characteristics of surface radiation. Under clear-sky conditions, there is a significant difference between the vertical and horizontal polarization brightness temperatures of surface radiation; however, the depolarization effect in dust weather reduces this difference. [**?**] proposed the Microwave Polarized Index (MPI), which utilizes dual-frequency polarization differences to achieve sub-cloud dust monitoring.

While passive microwave remote sensing can effectively penetrate clouds, it is difficult to achieve independent sub-cloud dust monitoring with this technology alone, often requiring synergy with optical remote sensing. Moreover, surface emissivity and temperature can affect microwave brightness temperatures, leading to signal interference from the underlying surface.

2.2 Active Microwave Remote Sensing for Dust Monitoring

Active microwave monitoring techniques primarily involve the active emission of radio signals in the microwave band by radar. The backscattered power of the radar during dust weather is determined by the scattering and extinction of radar waves by suspended dust particles along the propagation path. Existing active microwave monitoring of dust weather mostly centers on meteorological radars such as wind profile radars and Doppler weather radars (relevant parameters are shown in).

Millimeter-wave (MMW) radar enables long-term continuous observation of sand and dust weather. By utilizing the power spectrum to invert reflectivity, particle size distribution, and dust mass concentration, research indicates that this radar is highly sensitive to high-concentration sand and dust. Doppler weather radar and wind profiling radar provide high spatial and temporal resolution for monitoring and forecasting. Wind profiling radars offer high temporal resolution and vertical spatial resolution, providing higher detection accuracy for atmospheric targets in the vertical direction compared to standard Doppler weather radar.

In the fields of polarimetric radar and joint detection, polarimetric weather radars enhance target identification capabilities by comparing the echo characteristics of different polarization channels. Furthermore, joint quasi-synchronous observations from CALIPSO, CloudSat CPR, and Aqua/MODIS have been used to analyze the optical properties of dust aerosols during severe dust storms. Under intense dust conditions, the CALIPSO lidar signal often suffers from severe attenuation; in such cases, the combined use of CloudSat radar can provide more complete information on dust aerosol distribution.

3. GNSS Microwave Remote Sensing for Dust Monitoring

GNSS (Global Navigation Satellite System) sensing offers advantages such as all-weather capability and high spatiotemporal resolution. The underlying principle lies in the precise analysis of the bending or attenuation delay effects generated when satellite signals traverse the atmosphere. Based on the position of the receiver, existing GNSS dust remote sensing technologies can be categorized into ground-based and space-borne methods.

Figure 1

Figure 2: Figure 1

3.1 Ground-based GNSS Dust Monitoring

Ground-based GNSS dust monitoring technology utilizes receivers installed on the ground to collect signal data. By constructing a Zenith Tropospheric Delay (ZTD) model, tropospheric delay parameters are resolved from the signal data to invert parameters related to dust weather.

The ZHD-based method extracts dust storm information from atmospheric hydrostatic delay. This method, first proposed by Shi et al., establishes a correlation model between ZHD and dust content to invert the dust concentration. It assumes that during dust weather, the additional delay caused by dust is primarily reflected in the ZHD. The ZNHD-based method extracts dust weather information from the atmospheric non-hydrostatic delay. This method is based on the correlation between ZNHD (and its derived parameters, such as GNSS Precipitable Water Vapor, PWV) and the abnormal changes in atmospheric particulate matter concentration. Researchers have developed a series of effective methods for monitoring dust events centered on the correlation analysis between GNSS PWV and air quality parameters. To reduce water vapor interference, an innovative “GNSS PWV Difference” method was proposed, which effectively isolates the contribution of dust to the GNSS delay.

3.2 Space-borne GNSS Dust Monitoring

Space-borne GNSS dust monitoring is based on the phase delay and bending angle of GNSS signals to obtain the atmospheric refractive index, which is then used to invert dust-related atmospheric profile parameters. The principle of GNSS Radio Occultation (RO) involves signals transmitted by high-orbit navigation satellites being received by receivers onboard low-orbit satellites.

illustrates the occultation principle, where n represents the atmospheric refractive index and a is the impact parameter.

The basic process of RO atmospheric retrieval is shown in

Figure 2 first, the excess phase delay is calculated; second, the bending angle profile is derived; third, an integral transform is used to solve for the refractive index; finally, the temperature profile is retrieved. By analyzing inversions and vertical gradients within the temperature profiles, researchers can identify atmospheric thermal anomalies induced by dust weather. Research indicates that during severe weather outbreaks, strong inversion layers can extend upward to several kilometers. This finding confirms the impact of dust on the atmospheric thermal structure and reveals a direct correlation between inversion intensity and the severity of dust weather.

Figure 3

Figure 3: Figure 3

Figure 4

Figure 4: Figure 4

4. Summary and Outlook

This paper reviews domestic and international research progress in dust weather monitoring using microwave remote sensing. In the field of traditional microwave remote sensing, active radar can directly acquire echo signals from dust aerosols to characterize the vertical distribution of intense dust events. Passive microwave radiometry utilizes changes in brightness temperature across different frequencies and polarization channels to monitor the coverage and transport paths of dust weather, offering unique advantages in identifying dust beneath cloud layers.

Regarding GNSS remote sensing monitoring, ground-based GNSS technology utilizes existing networks to retrieve dust-related parameters by solving for tropospheric delay. This method offers low cost and high spatiotemporal resolution. Meanwhile, atmospheric profiles retrieved via GNSS RO technology possess high vertical resolution and long-term stability, enabling the effective capture of thermodynamic anomalies caused by intense dust weather.

Future research should focus on several areas: first, the synergistic application of multi-source remote sensing data to construct a fusion and complementary retrieval framework. Second, the introduction of artificial intelligence and machine learning methods to enhance the efficiency and accuracy of dust identification. Third, relying on long-term observational experiments to improve the collection of individual dust cases, providing a richer dataset for model training and validation. Timely and accurate monitoring of dust weather remains a prerequisite for achieving precise forecasting and effective prevention of dust disasters.

Figures

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