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**Report on** **Progress,** **Recommendations and Future Activities of** **ET Operational Remote-Sensing (B1)**

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| **Summary and purpose of document**  This document provides information on improved layouts of operational weather radar network and wind profile radar network and upgraded related technology in CMA, progress of quality control and radar data exchange of operational weather radar network, wind profile radar and lightning observation network, some recommendations and future activities of operational remote-sensing were put forward. |

**Action proposed**

The Meeting is invited to note the information contained in this document. There are no direct recommendations or requests for decisions, but instead points brought to the attention of the CIMO MG, welcoming feedback.

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**Appendices:**I Special profiling techniques for the boundary layer and the troposphere

II Site Selection Specification for New Generation Doppler Weather Radar in China

III China--Unified Standards of Key Technology for CINRAD

**EXECUTIVE SUMMARY**

B1 - OWR focus on the construction, technology update, data quality control and their standards establishment in operational remote sensing network and the application of new technology and data in operation. This document mainly discuss the improvement ,technical upgrade ,quality control and standardization in operational remote-sensing network around world .But only CMA provides relevant progress on operational remote-sensing, until today didn't receive the progress from other countries.

**Report on Progress, Recommendations and Future Activities of ET Operational Remote-Sensing (B1)**

1. ***Progress***

**1.1 Achievements of special profiling techniques for the boundary layer and the troposphere**

Special profiling techniques have been developed to obtain data at high temporal and spatial resolution which is needed for analysis, forecasting and research on the smaller meteorological scales and for various special applications. ET-ORST, under the leadership Dr. Lehmann Volker , gives a general overview of current surface-based remote-sensing systems that can be used for these purposes. Some of these techniques can be used for measurements over the whole troposphere, and others are used in the lower troposphere, in particular in the planetary boundary layer. The main work of ET-ORST includes analyse these surface-based remote-sensing systems work principle ,main technical performance and specifications and actual application ability etc. ET-ORST focus on those surface-based remote-sensing systems , which they are of better effective in actual application, including acoustic sounders(sodars) ,wind profile radars, radio acoustic sounding system, microwave radiometer, laser radars (Lidar) and Global navigation satellite system.

* 1. **CMA has improved layouts of operational weather radar network and wind profile radar network and also upgraded related technology**

**1.2.1 Further improvement and optimization of weather radar network**

As of March 2018, there are a total of 198 radars operating in the network, of which 109 are in S-band , 89 in C-band and 250 X-band. Since the beginning of 2016, 18 new radars have been put in operation, including 12 S-band and 6 C-band radars.

**12.2 Upgrade of the dual-polarization technology of weather radar**

At present, CMA has upgraded the dual-polarization Doppler weather radars, represented by Guangdong Province and Fujian Province. By the beginning of March 2018, there are 9 radars in the network (8 in Guangzhou and 1 in Fujian), of which 3 are newly completed and 6 are upgraded, and all of them are of the CINRAD/SA type, adopting the SHV mode, which means transmitting and receiving simultaneously. The structure of the SHV mode can be seen from Fig.1. Unlike the U.S. WSR-88D radar, China's current dual-polarization upgrade is to move the receiver down into the equipment room. The main consideration is to reduce the impact of environmental changes on the performance and service life of the sensitive devices in the receiver, and is more conducive to the emergency repairs, daily maintenance, calibration and so on.

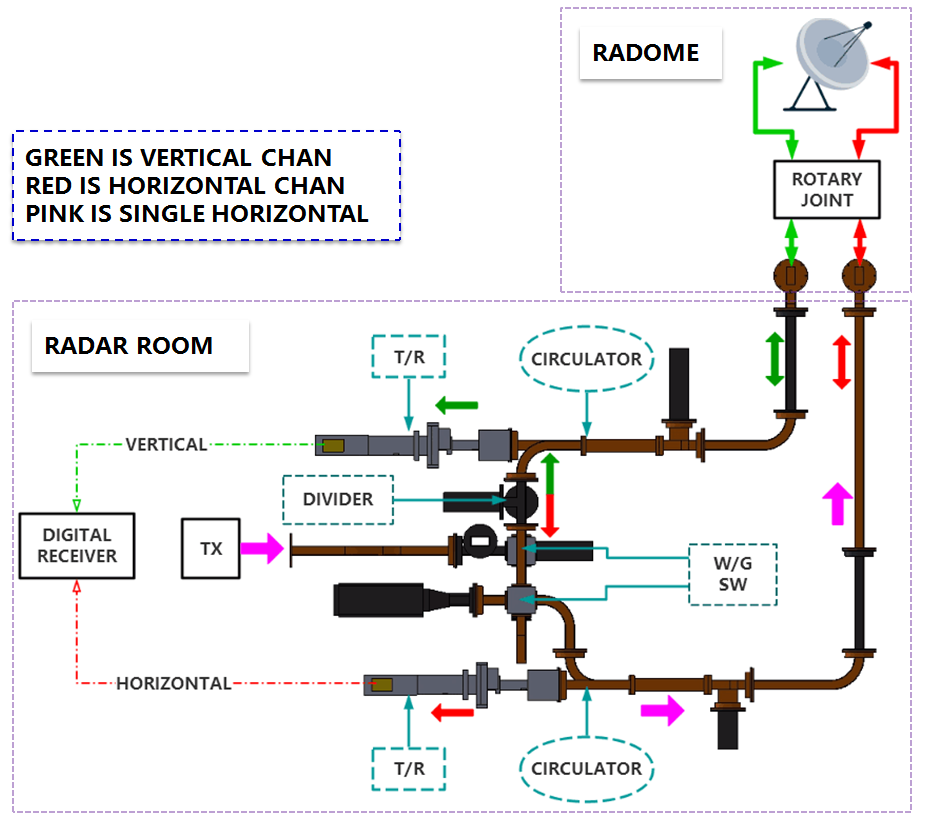


Fig.1 Structure of SHV mode for dual-polarization weather radar

**1.2.3** **Formulation of weather radar site standards**

Standards for CINRAD site selection are formulated mainly from five aspects, including site clearance environment, electromagnetic environment, lightning protection, communications and operating environment of radar equipment room. For details, please see the Appendix II.

**1.2.4 Construction progress and technical upgrade of wind profile radar network**

By the end of 2017, CMA has built 92 wind profile radars which can upload data sta. bly, mainly located in the Beijing-Tianjin-Hebei region, the coastal provinces in East China and South China. Among them, there are 51 3-km wind profile radars, 38 6-km wind profile radars, 2 8-km wind profile radars and 1 12-km wind profile radar. The Meteorological Observation Center of CMA has preliminarily built a data processing platform of wind profile radar to provide quality control and assessment of radar data across the whole network.

Technical upgrade has been conducted to the original L-band 3-km antenna and transmitter of China’s wind profile radar. By increasing the antenna area (from 3.6 m to 4.8 m) and the transmission power of transmitter (from 2 kw to 6 kw), the detection height of wind profile radar is raised to 6 km on the basis of the original measurement accuracy. At present, 38 wind profile radars of this type have been deployed in operation.

**1.3 Progress of control quality of operational weather radar network and wind profile radar in CMA**

**1.3.1 Main purpose and contents of technical rectification of operational weather radar**

Some problems have been found in the existing weather radar system, such as the inconsistent technical status of the radar calibration system, signal processor and other aspects as well as the declining performance of key devices. So, to solve the problems, China Meteorological Administration (CMA) carried out a special control project in August 2016 for the quality of new generation Doppler weather radar (CINRAD) nationwide. The project mainly includes the following seven aspects: integrating the calibration and monitoring system, integrating the volume scan mode, integrating the key adaptation parameters, integrating the software testing platform, integrating the signal processor, adding the radar standard output controller uniformly and improving the performance of key devices uniformly, etc.. For more details, please see Annex 1.

**1.3.2 Installation of standard output controller for operational weather radar**

Aiming at the problems that the on-line monitoring function of each type of radar is not perfect, the key operational parameters of radar cannot be monitored and displayed in real time on-line and there is no performance on-line analysis, etc. the radar standard output controller (WRSOC) will be installed to each type of radar uniformly and unified algorithms will be used for on-line analysis. The processed data will be output according to unified formats, and the changes in radar performance will be dynamically grasped. By these means, the data quality of operational weather radar and the level of intelligent application are expected to improve. The hardware and software design is shown in Fig. 2.



Fig. 2 Appearance of WRSOC hardware and software home page

**1.3.3 Progress in quality control of wind profile radar**

A “station-nation” two-level quality control system for wind profile radar has been developed. The station-level part of the system includes signal processing, power spectrum data processing, radial data processing and rapid product quality control while the national part includes radial data processing and data quality assessment. The bimodal spectrum identification algorithm under precipitation conditions is formed. The surface wind data comprehensive identification and eliminating ground clutter algorithm and the radial data processing and quality control method are introduced.

**1.****4 Construction progress and quality control of lightning observation network in CMA**

Since 2015, with the support of small and medium-sized infrastructure projects, China Meteorological Administration (CMA) has built 56 new lightning stations in the blank areas of lightning monitoring in Heilongjiang, Inner Mongolia, Gansu, Tibet and Qinghai, having further improved the layout of lightening observation network. By the early 2018, there are 399 stations for checking the operation of the national lightning monitoring network, covering the inland areas of China basically. CMA has added three new kinds of data quality control algorithms, for the first time achieving the quality control of 14 items which belong to the three kinds of data including lightning return stroke data, location data and status data. The quality of lightning data can be improved by synthetically analyzing the equipment condition, waveform characteristics and spatial characteristics, and more than 90% of the location data can be utilized.

**1.5 The Progress of Weather Radar ,Wind Profile Radar and Lightning Location System in Hong Kong Region**

**1.5.1 Weather Radar Systems**

The Hong Kong Observatory (HKO) operates five weather radars (two S-band, two C-band and one X-band) round-the-clock to serve the public as well as the Hong Kong International Airport. The two S-band radars, operating at 2.82 and 2.92 GHz, work in tandem for real-time and uninterrupted monitoring of severe weather including rainstorms and tropical cyclones within about 500 kilometres of Hong Kong. One of the S-band radars was upgraded to dual-polarization in 2015 and the other one will also be replaced and upgraded in the next few years. The two C-band radars are Terminal Doppler Weather Radar (TDWR) operating at 5.625 GHz, one backing up the other, to detect low-level windshear and microburst near the aerodrome. The X-band radar is dual-polarization type operating at 9.49 GHz to support the windshear alerting services of the TDWRs.

**1.5.2 Lightning Location Information System**

HKO operates a Lightning Location Network comprising seven lightning stations jointly established by HKO, the Guangdong Meteorological Bureau and the Macao Meteorological and Geophysical Bureau. Each station is equipped with a low frequency lightning sensor. The stations are located diversely across Hong Kong, Guangdong and Macao to enhance detection performance. When all stations are operative, for lightning located within the network, cloud-to-ground and cloud-to-cloud lightning detection efficiencies are estimated to be >90% and ~50% respectively, and the position accuracy for cloud-to-ground strokes is about 200 to 300m. Two new sensors are scheduled to be installed in April 2018.

**1.5.3 Wind Profiler**

HKO operates a network of four radar wind profilers, all at the frequency of 1299.21 MHz, in Hong Kong to measure the vertical wind profile. The measured data serves to replace the 06UTC and 18UTC radiosondes wind observations. A Radio Acoustic Sounding System (RASS), comprising loud speakers emitting sound wave of frequency 2580Hz is also installed to measure the temperatures in the lowest 1-2 km height atmosphere continuously.

**1.6 The progress on weather radar data exchange**

**1.6.1 CMA Weather Radar Data Exchange**

— CMA has offered the picture products of 7 weather radars to KMA, and the grid reflectivity products of 11 weather radars will be offered in future according to a new protocol. The distribution range of weather radars above mentioned is sketched. The green and red line respectively scope the 7 and 11 weather radars which have been offered.



**1.6.2** **Weather radar data exchange in Hong Kong Region**

Apart from exchange of radar data with CMA, HKO also exchange radar data with Korea Meteorological Administration (KMA) and Central Weather Bureau (CWB) where the exchanged data is gridded composite reflectivity or rain rate product data in binary format. Coverage is the entire area of South Korea and Taiwan.

We are also exchanging radar raw data with Macao Meteorological and Geophysical Bureau (1 radar).

1. ***Recommendations***

2.1 We suggest establishing integrated testbed under the WMO framework, promoting the development of ground-based remote sensing and marine meteorological observation equipment, and completing the selection of a number of testbed as soon as possible.

China is willing to provide the comprehensive test site in Changsha, Hunan Province, which is mainly for ground-based remote sensing, the marine meteorological comprehensive test site in Bohe, Guangdong Province, and the lightning detection and verification test site in Conghua, Guangdong Province, as testbeds to promote the development of observation technology around the world and to show China’s long-term support to the work of CIMO.

2.2 Lightning positioning network system has been built and applied in operation in many countries and regions and its role is becoming more and more important. However, its main operational specifications have not been compared internationally as in the case of the sounding system. Thus, we suggest carrying out an international comparison with reference to the GPS sounding system to promote the technical progress of the lightning positioning system.

2.3 We endorse the cooperation between CIMO and ISO and will continue to promote the standardization of ground-based remote sensing equipment with emphasis on the standardization of weather radar, wind profile radar, Lidar and cloud radar, which should be incorporated into the new version of the CIMO guidelines. Meanwhile, we pay close attention to the standardization of radar site determination, gradually establishing the standardization of various ground-based remote sensing equipment sites.

2.4 As Volker Lehmann suggested, rethink the structure of ET-ORST. The instruments the group has or had to deal with are quite diverse. While “weather radars” and “radar wind profilers” are both pulsed Doppler radars, the technical and scientific communities are very much separated. Furthermore, the lightning detection systems are totally disjunctive from radars. We suggest setting up small drafting teams of specialists, focusing only on a single technology. Integration and harmonization of materials prepared by these teams then needs another higher-level group of experts, who are able to bring all the specific information together in a consistent way. This will require an active editing of submitted contributions and a two-way communication with the specialist teams.

1. ***Future activities***

3.1 To continue to promote the technological development of the GPS sounding system, we suggested that a comparison experiment of the international operational sounding system should be organized in 2019 or 2020.

3.2 With respect to new types of observation technologies, attention should be given to the development of flux observation equipment and technology, such as the technical development of observing technologies and equipment for water vapor flux, radiation flux, and so on.

3.3 Focus on magacities influence on urban meteorological environment, especially for the influence of the atmospheric boundary layer. At same time ,also want to pay attention to the influence of haze on urban meteorological environment . By use of a variety of ground-based remote-sensing technology to observe the vertical structure characteristics of magacities meteorological environment and the aerosol .

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**APPENDIX I**

Chapter 5. Special profiling techniques for the boundary layer and the troposphere

5.1 General

Special profiling techniques have been developed to obtain data at high temporal and spatial resolution which is needed for analysis, forecasting and research on the smaller meteorological scales and for various special applications. This chapter gives a general overview of current surface-based systems that can be used for these purposes. It is divided into two main parts: remote-sensing and in situ direct measuring techniques. Some of these techniques can be used for measurements over the whole troposphere, and others are used in the lower troposphere, in particular in the planetary boundary layer.

Remote-sensing techniques are based on the interaction of electromagnetic or acoustic energy with the atmosphere. The measuring instrument and the variable to be measured are spatially separated, as opposed to on-site (in situ) sensing. For atmospheric applications, the technique can be divided into passive and active techniques. Passive techniques make use of naturally occurring radiation in the atmosphere (microwave radiometers). Active systems (sodars, windprofilers, RASSs – radio acoustic sounding systems – and lidars) are characterized by the injection of specific artificial radiation into the atmosphere. These surface-based profiling techniques are described in section 5.2. Other remote-sensing techniques relevant to this chapter are discussed in Part II, Chapter 7, and Part III.

Section 5.3 describes in situ techniques with instruments located on various platforms to obtain measurements directly in the boundary layer (balloons, boundary layer radiosondes, instrumented towers and masts, instrumented tethered balloons). Chapters 12 and 13 in Part I describe the more widely used techniques using balloons to obtain profile measurements.

The literature on profiling techniques is substantial. For general discussions and comparisons see Derr (1972), WMO (1980), Martner et al. (1993) and the special issue of the Journal of Atmospheric and Oceanic Technology (Volume 11, No. 1, 1994; see <http://journals.ametsoc.org/toc/atot/11/1>).

5.2 Surface-based remote-sensing techniques

5.2.1 Acoustic sounders (sodars)

Sodars (sound detection and ranging) operate on the principle of the scattering of acoustic waves by the atmosphere. According to the theory of the scattering of sound, a sound pulse emitted into the atmosphere is scattered by refractive index variations caused by small-scale turbulent temperature and velocity fluctuations, which occur naturally in the air and are particularly associated with strong temperature and humidity gradients present in inversions. In the case of backscattering (180°), only temperature fluctuations with a scale of one half of the transmitting acoustic wavelength determine the returned echo, while, in other directions, the returned echo is caused by both temperature and velocity fluctuations, except at an angle of 90°, where there is no scattering.

Useful references to acoustic sounding include Brown and Hall (1978), Neff and Coulter (1986), Gaynor et al. (1990) and Singal (1990).

A number of different types of acoustic sounders have been developed, but the two most common types considered for operational use are the monostatic sodar and the monostatic Doppler sodar.

A monostatic sodar consists of a vertically pointed pulsed sound source and a collocated receiver. A small portion of each sound pulse is scattered back to the receiver by the thermal fluctuations which occur naturally in the air. The receiver measures the intensity of the returned sound. As in a conventional radar, the time delay between transmitting and receiving an echo is indicative of the target’s range. In a bistatic sodar, the receiver is located some distance away from the sound source to receive signals caused by velocity fluctuations.

As well as measuring the intensity of the return signal, a monostatic Doppler sodar also analyses the frequency spectrum of the transmitted and received signals to determine the Doppler frequency shift between transmitted and backscattered sound. This difference arises because of the motion of the temperature fluctuations with the air, and provides a measure of the radial wind speed of the air. A Doppler sodar typically uses three beams, one directed vertically and two tilted from the vertical to determine wind components in three directions. The vertical and horizontal winds are calculated from these components. The vector wind may be displayed on a time-height plot at height intervals of about 30 to 50 m.

The maximum height that can be reached by acoustic sounders is dependent on system parameters, but also varies with the atmospheric conditions. Economical systems can routinely reach heights of 600 m or more with height resolutions of a few tens of metres.

A sodar might have the following characteristics:

| Parameter | Typical value |
| --- | --- |
| Pulse frequency | 1 500 Hz |
| Pulse duration | 0.05 to 0.2 s |
| Pulse repetition period | 2 to 5 s |
| Beam width | 15° |
| Acoustic power | 100 W |

Monostatic sodars normally produce a time-height plot of the strength of the backscattered echo signal. Such plots contain a wealth of detail on the internal structure of the boundary layer and can, in principle, be used to monitor inversion heights, the depth of the mixing layer – changes in boundary stability – and the depth of fog. The correct interpretation of the plots, however, requires considerable skill and background knowledge, and preferably additional information from in situ measurements and for the general weather situation.

Monostatic Doppler sodar systems provide measurements of wind profiles as well as intensity information. Such systems are a cost-effective method of obtaining boundary layer winds and are particularly suited to the continuous monitoring of inversions and winds near industrial plants where pollution is a potential problem.

The main limitation of sodar systems, other than the restricted height coverage, is their sensitivity to interfering noise. This can arise from traffic or as a result of precipitation or strong winds. This limitation precludes their use as an all-weather system. Sodars produce sound, the nature and level of which is likely to cause annoyance in the near vicinity, and this may preclude their use in otherwise suitable environments.

Some systems rely upon absorbent foam to reduce the effect of external noise sources and to reduce any annoyance caused to humans. The physical condition of such foam deteriorates with time and must be periodically replaced in order to prevent deterioration in instrument performance.

5.2.2 Wind profiler radars

The term wind profiler is often used as an abbreviation for a whole class of Doppler radars which are specifically designed for determining vertical profiles of the wind. Unlike conventional weather radars, these instruments are able to make useful measurements even in the absence of precipitation and clouds. This clear air sensing capability is a truly unique feature of this radar. The use of wavelengths ranging from about 0.2 m to 7 m (corresponding to frequencies between about 1300 and 40 MHz) makes it possible to detect echoes scattered from irregularities of the refractive index of air. If these have spatial scales of one half of the radar wavelength, then constructive interference occurs and makes the return strong enough to be detectable (Bragg condition). The efficacy of clear air scattering rapidly decreases towards smaller wavelengths, since the viscosity of air quickly dissipates all turbulent flow structures smaller than the inner scale of turbulence. In a first order approximation, the turbulent structures drift with the translational velocity of air, thus providing a direct measure for the wind.

Radar wind profilers not only receive electromagnetic waves backscattered at refractive index irregularities, but also echoes scattered from particles (mainly precipitation), airborne objects (birds, bats, airplanes) and even from the plasma in lightning channels. Also, echoes from the ground can be received through antenna side lobes. The relative contribution of these differing scattering processes is a function of radar wavelength.

There are two techniques for wind measurements by radar wind profilers, namely the Doppler method and the spaced antenna method (Fukao et.al., 2014), with most operational systems using the first method:

In the Doppler technique, the frequency shift induced by the motion of the scattering matter along the line of sight of a particular beam direction is measured and converted into a radial velocity. The horizontal and vertical wind components are obtained from sequentially made radial wind measurements in at least three linearly independent directions. The wind vector retrieval is based on further assumptions about the wind field structure: Horizontal homogeneity and stationarity of the mean wind field allows for a simple closed-form expression of this algorithm, see Teschke and Lehmann (2017). Simple Doppler-Beam-Swinging configurations use a vertically pointing beam and about 2-4 oblique (about 15° off-vertical) beams. A higher number of off-vertical beams yield generally better results than the simple three-beam technique (Adachi et al., 2005). Other sampling configurations, like VAD, are also possible.

The spaced antenna technique uses a vertically pointing radar beam and at least three independently receiving vertically directed antennas. This allows for a correlation-based estimate of the wind speed based on the apparent motion of the backscattered interference or diffraction pattern on the ground. Corrections have to be made for temporal changes of the scattering structures to obtain an estimate of the horizontal wind. This method has advantages at lower radar frequencies, but also a known bias issue (Dolman and Reid, 2014).

The choice of operating frequency depends on the required altitude coverage and resolution, but is strongly affected by regulatory constraints. In practice, most systems are built for the three frequency bands (around 50 MHz, 400 MHz and 1 000 MHz) identified in the relevant regulatory decisions for spectrum allocation made by the World Radio Conference 1997 (Resolution 217, WRC-97). Obtaining the necessary frequency clearances (operating licenses) can be an administrative problem and RFI contaminations from other in-band radio services can lead to an additional challenge for the operation of a radar wind profiler.

Typical characteristics are summarized in the table below.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Profiler parameter | Stratosphere | Troposphere | Lower troposphere | Boundary layer |
| Frequency (MHz) | 50 | 400-500 | 400-500 | 1 000 |
| Operating height range (km) | 2–20 | 0.5–16 | 0.3–10 | 0.2–3 |
| Vertical resolution (m) | 150-500 | 150-500 | 150-300 | 50–300 |
| Typical antenna size (m) | 100×100 | 10×10 | 6×6 | 3×3 |

Radar wind profiler antennas typically employ a phase array design with electronic beam steering, with the exception of a few mechanically steered dish-type antennas. The vertical resolution is depending on the width of the transmitted pulse, and different pulse widths are typically used for specific low- and high-mode settings, to trade range resolution for height coverage. Pulse compression methods are also frequently used to improve height coverage without compromising range resolution, but may suffer from imperfections and can potentially generate self-clutter (Wakasugi and Fukao, 1985).

The minimum usable height range depends on the antenna size, the pulse width, the recovery time of the radar receiver and the strength of possible near-range ground clutter returns. The strength of the received signal generally decreases with increasing height. This limits the height to which measurements can be taken. In contrast to the minimum range, the maximum range is a statistical quantity depending on both the characteristics of the radar hardware and the state of the atmosphere. It typically increases with the product of the mean transmitter power and the antenna aperture, but is mainly subject to a physical (clear air scattering) limit given by the wavelength used. The maximum height varies considerably with the meteorological conditions and gaps in the coverage at lower heights may sometimes occur.

Care must be taken in siting profilers so as to minimize ground returns and to avoid possible in-band RF emissions of other radio services.

Large stratospheric profilers require large antenna arrays and high power transmitters. It is therefore difficult to find suitable sites, and their minimum heights are not good enough for certain applications. They have the advantage of being able to routinely make wind measurements to about 20 km in height, and the measurements are not strongly affected by precipitation. Tropospheric profilers operating in the 400–500 MHz frequency band are likely the best compromise between height range covered and system size. Boundary layer profilers are less expensive and can use rather small antennas. Their vertical height range for clear air measurements is typically limited to the lower atmosphere, however the useable vertical range can increase significantly during precipitation, when scattering from hydrometeors becomes the dominant echoing mechanism.

The signal processing for Doppler wind profilers is similar to the processing employed in other Doppler radars. In contrast to weather radars, Doppler velocity resolution is typically better due to the longer dwell times, and the possibility of range and frequency aliasing can be fully avoided with a prudent sampling configuration. Since wind profilers are designed to receive the very weak returns from fluctuations of the refractive index, special algorithms for the filtering of ground and intermittent clutter echoes are mandatory. Intermittent clutter is comprised of unwanted echoes from aircraft, birds and insects. Especially migrating birds can lead to grossly erroneous wind estimates if intermittent clutter suppression is not implemented (Bianco et al.; 2013).

Radial wind measurements can be made with a resolution of a few seconds. As hydrometeors present a more efficient radar target than refractive index inhomogeneities for most profiler wavelengths, the measured radial velocity can be a weighted average of air velocity and the velocities of scattering particles. Practical experience has demonstrated that the horizontal wind vector can be estimated with sufficient accuracy from both clear-air and particle scattering, since the scattering particulates usually follow the horizontal wind field almost instantaneously. Thus the horizontal wind can indeed be obtained in almost all weather conditions. Larger errors occur only if the implicit assumptions used the wind estimation algorithm are violated. Note that the vertical wind can only be measured in a clear (particle-free) atmosphere.

Radar wind profilers are proven systems allowing for continuous, unattended operational measurements of the mean (upper-air) vertical wind profile directly above the site. The typical time resolution for a single wind profile ranges from about 10-60 minutes, depending on the instruments characteristics and configuration. The positive impact of such data in NWP has been successfully demonstrated; see e.g. Illingworth et al. (2015)

For further discussion see Gossard and Strauch (1983), Hogg et al. (1983), Weber et al. (1990), Weber and Wuertz (1990), WMO (1994), Wilczak et al. (1996), Muschinski et al. (2005), Hocking (2011), Doviak and Zrnic (2014) and Fukao et al. (2014).

5.2.3 Radio acoustic sounding systems

A radio acoustic sounding system is used to measure the virtual temperature profile in the lower troposphere. The technique consists in tracking a short high-intensity acoustic pulse that is transmitted vertically into the atmosphere by means of a collocated microwave Doppler radar. The measuring technique is based on the fact that acoustic waves are longitudinal waves that create density variations of the ambient air. These variations cause corresponding variations in the local index of refraction of the atmosphere which, in turn, causes a backscattering of the electromagnetic energy emitted by the microwave Doppler radar as it propagates through the acoustic pulse. The microwave radar measures the propagation speed of these refractive index perturbations as they ascend at the local speed of sound. The acoustic wavelength is matched to one half of the microwave wavelength (the Bragg condition), so that the energy backscattered from several acoustic waves adds coherently at the receiver, thus greatly increasing the return signal strength. By measuring the acoustic pulse propagation speed, the virtual temperature can be calculated as this is proportional to the square of the pulse propagation speed minus the vertical air speed.

The extensive literature on this technique includes May et al. (1990), Lataitis (1992a, 1992b) and Angevine et al. (1994).

A variety of experimental techniques have been developed to sweep the acoustic frequency and then to obtain a virtual temperature profile. A number of RASSs have been developed by adding an acoustic source and suitable processing to existing profiler radars of the type mentioned above. For radar frequencies of 50, 400 and 1 000 MHz, acoustic frequencies of about 110, 900 and 2 000 Hz are required. At 2 000 Hz, acoustic attenuation generally limits the height coverage to 1 to 2 km. At 900 Hz, practical systems can reach 2 to 4 km. At 110 Hz, by using large 50 MHz profilers, maximum heights in the range of 4 to 8 km can be achieved under favourable conditions.

Comparisons with radiosondes show that, under good conditions, virtual temperatures can be measured to an accuracy of about 0.3 °C with height resolutions of 100 to 300 m. However, the measurements are likely to be compromised in strong winds and precipitation.

The RASS technique is a promising method of obtaining virtual temperature profiles, but further investigation is required before it can be used operationally with confidence over a height range, resolution and accuracy that respond to user requirements.

5.2.4 Microwave radiometers

Thermal radiation from the atmosphere at microwave frequencies originates primarily from molecular oxygen, water vapour and liquid water and is dependent on their temperature and spatial distribution. For a gas such as oxygen, whose density as a function of height is well known, given the surface pressure, the radiation contains information primarily on the atmospheric temperature. Vertical temperature profiles of the lower atmosphere can be obtained by surface-based passive microwave radiometers measuring the microwave thermal emission by oxygen in a spectral band near 60 GHz. Spectral measurements in the 22–30 GHz upper wing of the pressure broadened water vapour absorption band provide information on the integrated amount of water vapour and liquid water, and the vertical distribution of water vapour. In addition, spectral measurements in both bands, combined with infrared cloud-base temperature measurements, provide information on the integrated amount and the vertical distribution of liquid water. For further information, see Hogg et al. (1983), Westwater et al. (1990), Solheim et al. (1998), Ware et al. (2003) and Westwater et al. (2005).

Individual downward-looking radiometers operating at different frequencies are maximally sensitive to temperature at particular ranges of atmospheric pressure. The sensitivity as a function of pressure follows a bell-shaped curve (the weighting function). The frequencies of the radiometers are chosen so that the peaks in the weighting functions are optimally spread over the heights of interest. Temperature profiles above the boundary layer are calculated by means of numerical inversion techniques using measured radiations and weighting functions. The relatively broad width of the weighting function curves, and radiation from the terrestrial surface, precludes accurate temperature profiles from being obtained near the surface and in the boundary layer when using space-based radiometer soundings.

The principles of upward-looking radiometric temperature and humidity sounding from the terrestrial surface are well established. The temperature weighting functions of upward-looking profiling radiometers have narrow peaks near the surface that decrease with height. In addition, sensitivity to oxygen and water vapour emissions is not degraded by radiation from the terrestrial surface. This allows accurate temperature and humidity profile retrievals with relatively high resolution in the boundary layer and lower troposphere. Inversion techniques for upward-looking radiometers are based on temperature and humidity climatology for the site that is typically derived from radiosonde soundings. The scanning configuration of microwave temperature profilers provides the highest resolution in the first few hundred metres. A multichannel system with fixed angle gives a better response at height greater than 1 km, but with a much coarser resolution (Cadeddu et al., 2002).

Surface-based and space-based radiometers are highly complementary. Space-based measurements provide coarse temporal and spatial resolution in the upper troposphere, and surface-based measurements provide high temporal and spatial resolution in the boundary layer and lower troposphere. Retrieved profiles from surface-based radiometers can be assimilated into numerical weather models to improve short term (1–12 h) forecasting by providing upper-air data in the interval between radiosonde soundings. Alternatively, raw brightness temperature from terrestrial radiometers can be assimilated directly into numerical weather models. This approach improves results by avoiding errors inherent in the profile retrieval process. A similar method, which assimilates raw satellite radiometer radiances directly into weather models, demonstrated improved results years ago and is now widely used.

The main advantages of surface-based radiometers are their ability to produce continuous measurements in time, and their ability to measure cloud liquid. Continuous upper-air temperature, humidity and cloud liquid measurements can be used to improve nowcasting and short-term precipitation forecasting. These continuous measurements can be also used to detect the development or time of arrival of well-defined temperature changes (for studies of gas emissions, air pollution, urban heat islands, severe weather forecasting and warnings) (Kadygrov et al., 2003).

Profiling radiometer reliability and accuracy have been widely demonstrated during long-term arctic, mid-latitude and tropical operations (Güldner and Spänkuch, 2001; Liljegren et al., 2005). The result of the 13-month operation of the Radiometrics MP3000 (Gaffard and Hewison, 2003) shows that the root mean square value of the difference between the temperature observed by the radiosonde and that retrieved by the microwave radiometer ranges from 0.5 K (near the surface) to 1.8 K (at a height of 5 km). Güldner and Spänkuch (2001), who operated the Radiometrics TP/WVP-3000 for 18 months and compared retrievals with four radiosonde soundings daily, also shows a similar root mean square value from 0.6 K (near the surface) to 1.6 K (at a height of 7 km in summer and 4 km in winter). The root mean square value of water vapour profile is not more than 1 g m–3 in all altitudes (Gaffard and Hewison, 2003; Güldner and Spänkuch, 2001).

Terrestrial profiling radiometers demonstrate significant economic and practical advantage whenever lower tropospheric temperature, humidity and cloud liquid measurements with high temporal resolution are required, and where moderate vertical resolution is acceptable. Commercial profiling radiometer prices have dropped significantly over the past several years, and are now less than the typical annual cost of labour and materials for twice daily radiosonde soundings.

5.2.5 Laser radars (lidars)

Electromagnetic energy at optical and near-optical wavelengths (from ultraviolet through visible to infrared) generated by lasers is scattered by atmospheric gas molecules and suspended particles. Such scattering is sufficient to permit the application of the radar principle to make observations of the atmosphere by means of lidar (light detection and ranging). Optical scattering can generally be divided into inelastic and elastic. When the wavelength of the laser energy, scattered by atmospheric constituents, differs in wavelength from the incident laser wavelength, the process is called inelastic scattering. The most widely used inelastic scattering process used in experimental atmospheric lidar systems is Raman scattering, which results from an exchange of energy between incident photons and the molecular rotational and vibrational states of the scattering molecules. In elastic scattering processes, the incident and the scattered wavelengths are the same. This scattering may be Rayleigh or Mie scattering and depends on the species and size of particles with respect to the incident laser wavelength (see Part II, Chapter 7). Both of these major scattering processes can occur simultaneously in the atmosphere.

For further reference see Hinkley (1976), WMO (1982), Thomas (1991) and Syed and Browell (1994).

The majority of lidars are operated in a monostatic mode, whereby the receiver is collocated with the laser transmitter. A typical lidar system uses a pulsed laser to transmit pulses of coherent light into the atmosphere. The average power of the laser used varies from a few milliwatts to tens of watts. An optical telescope mounted adjacent to the laser is used to capture the backscattered energy. The light collected by the telescope is focused onto a photomultiplier or photoconductive diode. The received information is normally made available on a display for real-time monitoring and is transferred to a computer for more detailed analysis.

The strength of the return signal is dependent both on the amount of scattering from the target and on the two-way attenuation between the lidar and the target — this attenuation depends on the proportion of the beam’s energy scattered from its path and on the absorption by atmospheric gases. The scattering and absorption processes are exploited in different lidars to provide a variety of measurements.

Lidars based on elastic scattering (called Rayleigh or Mie lidars, or simply lidars), are mostly used for studies on clouds and particulate matter. The measurement of cloud-base height by a lidar is very straightforward; the rapid increase in the signal that marks the backscattered return from the cloud base can be readily distinguished; the height of the cloud base is determined by measuring the time taken for a laser pulse to travel from the transmitter to the cloud base and back to the receiver (see Part I, Chapter 15).

Lidars are also used to detect the suspended particles present in relatively clear air and to map certain structural features such as thermal stability and the height of inversions. Natural atmospheric particulate levels are sufficiently high in the lower atmosphere to allow lidars to measure air velocities continuously in the absence of precipitation, like weather radars. They can also be used to map and measure the concentration of man-made particulates, such as those originating from industrial stacks.

Lidar observations have made very extensive and the best-documented contributions to the study of stratospheric aerosol particulate concentration, which is strongly influenced by major volcanic eruptions and is an important factor in the global radiation balance.

It is much more difficult to obtain quantitative data on clouds, because of the variations in shape and distribution of droplets, water content, discrimination between water, ice and mixed phases, and the properties of suspended particles and aerosols. Indeed, such measurements require complex multiparameter research systems making several measurements simultaneously, using hypotheses concerning the optical properties of the medium, and complex mathematical data-reduction methods.

Differential absorption lidars (DIALs) work on the principle that the absorption coefficient of atmospheric gases varies greatly with wavelength. A DIAL system normally uses a laser that can be tuned between two closely-spaced frequencies, one which is strongly absorbed by a particular gas, and one which is not. The differences in the measurements as a function of range can be used to estimate the concentration of the gas under study. This is a most promising remote-sensing technique for the measurement of atmospheric composition and has been successfully used to measure concentrations of water, sulphur dioxide, nitrogen dioxide and, in particular, ozone.

The application of Raman scattering is of particular interest because the scattered radiation is frequency shifted by an amount which depends on the molecular species (Stokes lines). The strength of the backscattered signal is related to the species concentration. Raman lidars do not require a particular wavelength or tuned laser; laser wavelengths can be selected in a spectral region free from atmospheric absorption. By measuring the Raman spectrum, spatially resolved measurements can be taken of preselected atmospheric constituents, which have been used to obtain tropospheric profiles of water vapour, molecular nitrogen and oxygen, and minor atmospheric constituents. The main disadvantages are the lack of sensitivity over long ranges owing to the small scattering cross-sections and the requirement for high power lasers, which can lead to eye-safety problems in practical applications.

Lidar systems have provided a great deal of useful information for research studies but have had limited impact as operational tools. This is because they are relatively expensive and require very skilled staff in order to be developed, set up and operated. In addition, certain lidars are able to operate only under restricted conditions, such as in darkness or in the absence of precipitation.

5.2.6 Global Navigation Satellite System

The main purpose of the Global Navigation Satellite System (GNSS) is positioning, but since an atmospheric term influences the accuracy of the position estimate, meteorological content can be inferred from the estimated error. The time delay experienced by a signal originating from a satellite and measured by a receiver on Earth is related to the refractivity along the signal path, and thus also to the temperature and humidity along this path.

Meteorological information inferred from ground-based GNSS requires a surface network of GNSS receivers, a data connection and a processing facility. In general, a GNSS network of receivers is installed for land surveying purposes, and as a result close collaboration with national surveying institutes has been established in several countries. The collaboration is generally based on sharing sites and/or sharing information.

Additional information on processing techniques is available in WMO (2006b).

5.2.6.1 Description of the Global Navigation Satellite System

The GNSS consists of three segments: the space, the ground and the user segment. The space segment comprises a number of satellites in orbit. Currently four systems are deployed or are being deployed: GPS (United States), GLONASS (Russian Federation), Galileo (European Union) and Compass (China). GNSS satellites transmit time coded signals in a number of carrier wave frequencies which differ for different satellite systems.

The principle of GNSS is the same for all four systems. On-board atomic clocks control all signal components in the satellites. The ground segment controls the satellites for orbit adjustment and provides the broadcast ephemerides, which are disseminated to the user segment via the navigation message of the GNSS signal. A GNSS antenna and receiver (surface-based or space-borne) form the user segment. The receiver compares the time coded signal from the GNSS satellites with its own internal clock, from which the receiver can compute the pseudo ranges (P) to each satellite in view. When at least four pseudo ranges are observed the receiver can compute its position and its clock error. The standard positioning technique using the time coded signals has an accuracy of about 3–5 m.

The GNSS main observables are pseudo range (P) and carrier phase (L). For example, the GPS signals are broadcast at two different frequencies: namely L1 (1 575.42 MHz) and L2 (1 227.60 MHz). Both frequencies transmit P and L observables. Thus, for a dual-frequency receiver, four observables are available per epoch. Equations 5.1 and 5.2 present both P and L expressed as a sum of all error contributions forming the GNSS measurement, that is:

 (5.1)

 (5.2)

where c is the speed of light, ρ is the geometric distance between the satellite phase centre and the receiver phase centre, dtsat is the satellite clock offset, dtrec is the receiver clock offset, Latm is the tropospheric delay, or slant total delay, due to the refractive nature of the atmosphere, I is the ionospheric delay along the ray path, δrel is the relativistic error, K is the receiver instrumental error, M is the multipath effect, δtide is the receiver position error due to polar tide, solid Earth tide and ocean loading, N is the ambiguity term (only relevant for carrier phase measurements, equation 5.2), ωL is one wavelength contribution due to circular polarization of the signal and ε is the unmodelled noise error.

The observables have different uncertainty levels and different characteristics. In particular, phase measurements have a noise level of a few millimetres and are very accurate in comparison to pseudo range, which has an uncertainty of a few metres. Carrier phase is the primary and most important observable for low uncertainty parameter estimation, but pseudo-range observables are better suited for the observation and removal of specific receiver-related errors (multipath, etc.). Linear combination of the same kind of observable (P or L) measured at the two different frequencies is used to remove the first order of the ionosphere effect. Other techniques, such as double differencing, can remove the satellite and receiver clock error. However, this requires careful processing of the GNSS data.

5.2.6.2 Tropospheric Global Navigation Satellite System signal

The atmospheric excess path is caused by refraction and bending of the signal due to gradients in refractive index n. According to Fermat's principle, this excess path is:

 (5.3)

where D (=sʃ ds) is the geometric distance and ΔS the excess path due to bending; the latter can be neglected for elevations larger than 10 degrees. The refractivity N is defined as N = 106 (n – 1) and, according to Smith and Weintraub (1953) and Thompson et al. (1986),

 (5.4)

for the neutral atmosphere. Here, ρ is air density (kg m–3), ρw is water vapour density (kg m–3), T is temperature (K) and Rd = 287.05 J kg–1 K–1 and Rv = 461.51 J kg–1 K–1 are the gas constants for dry air and water vapour. The empirical constants are k1 = 77.6 K hPa–1, k2 = 70.4 K hPa–1 and k3 = 373 900 K2 hPa–1 (Thayer, 1974). The first term in equation 5.4 is the hydrostatic refractivity, Nh, and the second term is called the wet refractivity, Nw.

Within a so-called network solution of GNSS data, the tropospheric delay is mapped to the zenith for all elevation and azimuth angles. In this way the number of unknowns is reduced and the position of the receiver can be estimated accurately. The mapped slant total delay to the zenith is called the zenith total delay (ZTD). When the precise position is estimated, an estimate of the atmospheric part of the signal can be retrieved. The ZTD can be considered as the sum of the zenith hydrostatic delay (ZHD) and the zenith wet delay (ZWD) (or, better, zenith non-hydrostatic delay). The integrals in the zenith direction of the hydrostatic and wet refractivity (expressed in metres) are:

 (5.5)

 (5.6)

5.2.6.3 Integrated water vapour

Zenith hydrostatic delay is related to the dry part of the atmosphere and, due to its stationary nature, can be estimated very accurately using the surface pressure measurements (ps) and the location of the receiver (height h and latitude φ), using for example the Saastamoinen (1972) approximation, that is:

 (5.7)

The ZHD represents approximately 90% of the entire tropospheric path delay. On the other hand, the ZWD cannot be sufficiently well modelled by surface data acquisition due to the irregular distribution of water vapour in the atmosphere. The ZWD can be rewritten as (following Davis et al., 1985):

 (5.8)

and by defining the weighted mean temperature as:

 (5.9)

then:

 (5.10)

where IWV is the vertically integrated column of water vapour overlying the GPS receiver. Based on, for example, radiosonde observations, the weighted mean temperature can be estimated by the surface temperature (Ts), that is k’(Tm) ≈ k(Ts) (Bevis et al., 1994). Thus, the IWV can be estimated using the estimated ZTD, surface pressure (ps), antenna height (h) and latitude (φ) of the receiver:

 (5.11)

The value of k(Ts) is approximately 6.5 kg m–3.

5.2.6.4 Measurement uncertainties

Since ZTD is estimated, its accuracy depends on the method used, the accuracy of a priori information used, the stability of the receiver position and many other things. For example, the accuracy of the position of the satellite orbits will in general be higher after approximately 14 days when the so-called final orbits are available. Therefore, a distinction has to be made between near-real-time and post-processed estimates of ZTD. The accuracy of IWV is obviously closely related to the accuracy of the ZTD estimate.

The measurement uncertainty of near-real-time estimates is about 10 mm. For post-processed estimates, this value is about 5 to 7 mm. The measurement uncertainty of IWV is dependent on the total amount of water vapour and is of the order of 5%–10% (Elgered et al., 2004). The mean values have a clear seasonal signature: at mid latitudes very low values can be observed in winter (below 5 kg m–2) and values of 40 kg m–2 can be seen during summer. In the tropics, values higher than 50 kg m–2 are not uncommon.

5.3 In situ measurements

5.3.1 Balloon tracking

Balloon tracking is frequently used to obtain boundary layer winds and is usually performed by optical theodolites or a tracking radar. Part I, Chapter 13, gives a more general account of windfinding.

When making lower tropospheric soundings, it is desirable to use a slow rate of balloon ascent in order to give high vertical resolution. The reduced rate of ascent may be achieved either by means of a brake parachute or by a reduced free lift.

For radar tracking, a small radar reflector is suspended below the balloon. For lower tropospheric soundings, the radar should be able to provide data at ranges as short as 100 m, and ideally the launch point must be farther away in a downwind direction than this minimum range.

A basic wind measurement can be taken using a single optical theodolite, but, in order to obtain reasonably accurate winds, a two-theodolite system is required. The baseline between the theodolites should exceed 1 km. In order to facilitate the sounding procedure and to ensure height accuracy, the theodolites should be equipped with computer interfaces so that the data can be logged and the necessary calculations performed in a timely manner. Under good conditions, wind profiles can be obtained up to an altitude of 3 000 m. However, the technique fails in adverse conditions such as precipitation, low cloud or fog.

It is, of course, possible to obtain additional wind data in the lower atmosphere using conventional radiosondes by taking more frequent tracking measurements in the first few minutes of a normal full sounding, for example, between 2 and 10 per minute.

5.3.2 Boundary layer radiosondes

Conventional radiosonde systems are described in detail in Part I, Chapter 12. Special radiosondes have been designed specifically to make detailed observations of the boundary layer and lower troposphere. They differ from conventional radiosondes in that the sensors have greater sensitivity and faster response rates. Such radiosondes are used to measure temperature, humidity and wind profiles in the layer from the surface to elevations of typically 3 to 5 km.

The vertical ascent rate of these radiosondes is usually arranged to be between 150 and 200 m min–1, which is rather slower than conventional radiosondes. The slower rate of ascent allows more detailed vertical profiles to be produced. The rate of ascent is normally determined by selecting an appropriately sized balloon, but may be modified by the use of a trailing brake parachute.

Because these instruments are required only to reach a limited height, they can normally be carried by a pilot balloon. In other respects, the sounding procedures and data processing are similar to those employed by standard radiosondes.

For soundings to an altitude of no more than 2 000 m, the pressure sensor is sometimes dispensed with, which results in a simpler and less expensive radiosonde. Even simpler systems are available which measure temperature only.

The basic requirements for boundary layer radiosondes are as follows:

|  |  |  |
| --- | --- | --- |
| Variable | Operating range | Resolution |
| Pressure | 1 050 to 500 hPa | ±0.5 hPa |
| Temperature | +40 °C to –40 °C | ±0.1 K |
| Humidity | 100% to 20 (or 10)% | ±2% |
| Wind speed | 0.5 to 60 m s–1 | ±0.5 m s–1 |
| Wind direction | 0° to 360° | ±5° |

Measurements are typically taken at least every 30 s to give a vertical resolution of 50 to 100 m.

5.3.3 Instrumented towers and masts

Special instrumented towers and masts are used for many purposes, especially for the estimation of the diffusion of atmospheric pollution. A discussion is provided by Panofsky (1973).

For some purposes, the height of the tower must be up to 100 m, and for air-pollution monitoring and control projects it should exceed the height of the important sources of pollution by at least 50 m.

Measurements of temperature, humidity and wind should be made at several (at least two or three) levels, the lowest of which should be at the level of standard meteorological screen, close to the tower or mast. The number of measuring levels depends upon both the task and the height of the tower or mast. The use of just two levels provides no information on the shape of the vertical profile of meteorological variables and is, thus, very limiting. The number of measuring levels is usually greater for research projects than for routine use.

Usually, the data are processed and presented automatically together with differences between the levels that are provided to characterize the meteorological conditions. If the data are to be used directly by non-meteorological staff – such as those concerned with keeping concentrations of air pollutants within safe limits – they are often processed further by computer to provide derived data which are easily applied to the task in hand.

The sensors most commonly used for measurements on towers or masts are as follows:

(a) Temperature: electrical resistance or thermocouple thermometers in screens, with or without aspiration;

(b) Humidity: psychrometers, electrochemical or electromechanical sensors in screens;

(c) Wind: cup and vane, propeller, sonic or hot-wire devices.

All sensors should have linear or linearized characteristics and their time constants should be small enough to ensure that the data gathered will adequately reflect local changes in the meteorological variables.

It is important that the structure of the tower or mast should not affect the sensors and their measurements appreciably. For open structures, booms – whether stationary or retractable – should be at least 2 m long, and preferably long enough to keep the sensors at least 10 tower diameters removed from the tower or mast. For solid structures, or where the required booms would not be practicable, a double system is required at each level, with booms on opposite sides of the tower or mast extending for at least three times the structure diameter. Measurements at a given time are then taken from the sensors exposed to the undisturbed wind.

Sometimes, in special situations, towers can be used to gather meteorological profile data without the direct mounting of fixed sensors; rather, a simplified method of sounding is used. A pulley is fastened at the highest possible point and a closed loop of rope extending to ground level is used to carry a radiosonde up and down the levels required by means of a hand- or motor-operated winch. The radiosonde, which is modified to include wind sensors, transmits its data to an appropriate receiving system at ground level. Much more vertical detail is possible than that provided by a boom installation, and the altitudes of significant features can be determined. However, sustained observation is possible at only a single level.

For an accurate definition of the extent of pollution dispersion in certain weather conditions, the tower height may be too limited. In such circumstances, unless a radiosonde station is within about 50 km, a special radiosonde is provided at the site of the tower or mast for making local soundings up to an altitude of about 3 000 m. In addition to their main purpose, the data obtained can be treated as complementary to those of the basic aerological network, and can also be used in more detailed investigations of local weather phenomena.

Tower measuring equipment requires periodical checking by highly qualified instrument maintenance staff who should pay special attention to the state and performance of sensors and recorders and the connecting cables, sockets and plugs exposed to outdoor weather conditions.

5.3.4 Instrumented tethered balloons

Typical applications of instrumented tethered balloons include the measurement of temperature, humidity and wind profiles (and their short-period changes) from the surface to an altitude of about 1 500 m, and longer-period investigation of the meteorological conditions at one or more selected levels. The sensors are suspended in one or more packages beneath the balloon, or clamped to the tethering cable. The sensor’s response is normally telemetered to the ground either by radio, or by conductors incorporated into the tethering cable. The techniques are discussed by Thompson (1980).

Tethered-balloon systems tend to use either large (~600 m3) or small (~10 to 100 m3) balloons. The small balloons are normally used to obtain profiles, and the larger ones to obtain measurements at multiple levels. Tethered balloons should be designed for low drag and to ride steadily. They are usually inflated with helium. Larger balloons should be able to carry a load of up to 50 kg (in addition to the tethering cable) to an altitude of 1 500 m. The balloon should be capable of operation at wind speeds of up to 5 m s–1 at the surface and 15 m s–1 at altitudes within the operational range. The tethering cable of a large balloon should be able to withstand a force of 2 000 to 3 000 kg to avoid a breakaway (200 to 300 kg for smaller balloons).

Tethered-balloon flying is subject to national rules concerning aviation safety. For this reason and for the convenience of the operating staff, the use of balloons which have distinct colours and night-warning lights is highly recommended. An automatic device for the rapid deflation of the balloon is mandatory, while a metallized radar target suspended below the balloon is optional.

The main factors limiting tethered-balloon operation are strong wind speed aloft, turbulence near the surface and lightning risk.

The winch used to control the balloon may be operated electrically or by hand. At least two speeds (e.g. 1 and 2 m s–1) should be provided for the cable run. In addition, the winch should be equipped with a hand-brake, a cable-length counter and a tension gauge. The winch should be electrically earthed, whether electrically operated or not, as protection against atmospheric discharges.

The use of conductors to convey the sensor signals back to the ground is undesirable for a number of reasons. In general, it is preferable to use special radiosondes. Such radiosondes will have better resolution than those normally employed for free flights. The temperature and humidity sensors must have a horizontal shield to provide protection against solar radiation and rainfall, while allowing for adequate ventilation. Extra sensors are needed for wind speed and direction.

The basic requirements are the following:

| Variable | Operating range | Resolution |
| --- | --- | --- |
| Pressure | 1 050 to 850 hPa | ±0.5 hPa |
| Temperature | +40 °C to –20 °C | ±0.1 K |
| Humidity | 100% to 20 (or 10)% | ±2% |
| Wind speed | 0.5 to 15 m s–1 | ±0.5 m s–1 |
| Wind direction | 0° to 360° | ±1° |

For telemetry, one of the standard radiosonde frequencies may be used; the 400 MHz allocation is a frequent choice. The maximum weight, including the battery, should be within the load capability of the balloon; a limit of 5 kg is reasonable. The radiosonde should be suspended at least three balloon diameters below the balloon in a stable condition so that adequate shielding and ventilation are maintained.

A major problem encountered in the measurement of turbulent, rather than mean, quantities is the effect of cable vibration and balloon motion on the measurements. Special techniques have to be used for such measurements.

The ground-based equipment must include a receiver and recorder. The data are usually processed with the aid of a small computer.

Soundings can be performed during the ascent and descent of the balloon, either continuously or with pauses at selected levels. For the lower levels, height can be estimated from the length of the cable paid out, but at higher levels this method is no more than an approximation and an alternative is necessary. This takes the form of a calculation by means of the hydrostatic equation, using the observed distribution of pressure, temperature and humidity. Thus, the increment in geopotential metres from level n to level n+1 is given by:

 (5.12)

where Tv is the mean of the virtual temperatures at levels n and n+1; and pn and pn+1 are the two associated pressures. If conversion from geopotential to geometric height is required, this is readily done by using the Smithsonian meteorological tables; however, this is unlikely to be necessary. The height of the station barometer is taken as the datum for these calculations.

If the meteorological variables are observed using the level-by-level method, a few measuring cycles should be taken at each level, with the time required for stabilization being 2 to 3 min. In this way, the whole sounding sequence could take from a half to one whole hour. As for all radiosondes, a baseline check in a control screen should be made just before use, to establish the differences with a barometer and an aspirated psychrometer. A similar check should also be made just after the sounding is completed. Again, as for regular radiosonde ascents, the station-level data should be obtained not from the radiosonde data, but from conventional instruments in a standard station screen.

For the sounding data, pressure, temperature and humidity should be averaged at each level. For wind speed, the average should be calculated for a period of 100 or 120 s. If wind direction is not measured directly, it can be roughly estimated from the orientation of the balloon’s longitudinal axis with respect to the north. The uncertainty of this method is ±30°.

It should be stressed that operators must advise air traffic authorities of their plans and obtain permission for each sounding or series of soundings using tethered balloons.

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**APPENDIX II**

# Site Selection Specification for New Generation Doppler Weather Radar in China

(Abridged Edition)

## Introduction

To guide the site selection of new generation Doppler weather radar in China (CINRAD for short) and give full play to the benefits of the construction of the new generation weather radar, this specification is formulated. The new generation weather radar refers to the S-band (2700 MHz to 3100 MHz) and C-band (5250 MHz to 5650 MHz) Doppler weather radar system, which can quantitatively estimate the information such as echo intensity, radial velocity and spectral width using the full phase-coherent and Doppler technology.

## General principles

The site selection of new generation weather radar should be in line with the development plan of the new generation Doppler weather radar in China (CINRAD), be helpful to monitor the disastrous weather, give full play to the radar detection function, and have a good clearance environment and a good electromagnetic environment so that the weather radar can continuously monitor weather systems in all directions and obtain information on the weather systems at different altitudes to the maximum extent.

When selecting a radar site, 3-5 candidate sites should be pre-selected, and the site spacing, geographical environment, clearance environment, electromagnetic environment, communication environment, construction investment scale, operation management and technical support of the candidate sites should be comprehensively evaluated. At the same time, local urban construction planning should also be taken into account. If other conditions are similar, priority should be given to the sites where the working conditions, living conditions and construction conditions are relatively convenient. Among the candidate sites that meet the requirements of radar station location, determine a proposed site.

## Basic requirements for site selection

### 3.1 Site spacing

According to the maximum unambiguous distance, velocity range and minimum height of the detected target of CINRAD as well as the influence of atmospheric attenuation and the curvature of the Earth, the distance between radar stations should meet the following requirements:

The distance between the proposed radar site and the adjacent radar location should be 250 – 200 km.

The distance between the radar sites in the areas that tend to be frequently hit by disastrous weather, key monitoring areas, economically developed areas, mountainous hilly areas or areas with annual precipitation above 800 mm can be properly shortened to 150-100 km.

To cope with sudden and extreme weather events and enhance the security of radar nets, the density of radar sites in individual areas can be about 100 km.

The straight-line distance between the proposed radar site and the local meteorological observatory (station) should be less than 50 km.

### 3.2 Geographical conditions

The geographic location of the proposed radar site shall be determined by the geographical surveying and mapping department with related qualifications. The accuracy of latitude and longitude measurements is less than 3′′, and the accuracy of altitude measurement is less than 5 m.

The proposed radar sites should avoid the areas with frequent natural disasters such as floods, mudslides, landslides etc., and also avoid the geology of sandy soil and wetland.

The proposed radar site should avoid the places prone to suffering from high incidence of corrosive gas, industrial pollution and water pollution.

The proposed radar site should avoid damages to the existing meteorological detection environment and local landscape.

### Clearance environment

The proposed radar site should be open all around, avoiding obstacles such as high mountains, iron towers, tall trees and tall buildings to block radar electromagnetic waves.

The proposed radar site should be selected in the direction of major weather processes and key service areas. The blocking elevation angle of its obstruction to the radar electromagnetic wave must not exceed 0.5°, and the blocking elevation in other directions should not exceed 1.0°. The isolated occlusion azimuth should not exceed 1.0°, and the total occlusion azimuth should not exceed 5°. However, if the neighboring radar can cover the shielding area, the requirement can be reduced appropriately.

Detection environment of the proposed site should be protected by local government and ensure long-term stability.

### 3.4 Electromagnetic environment

The proposed radar site should avoid high-voltage lines, power stations, radio stations, industrial interference sources, and avoid areas in conflict with national defense facilities.

According to the classification of weather radar frequency resources by the International Telecommunication Union (ITU) and the State Radio Regulatory Commission of China, the S-band weather radar has a frequency range of 2700-3100 MHz, and the C-band weather radar has a frequency range of 5250-5650 MHz.

The radio monitoring institution with monitoring qualification shall test the electromagnetic environment of the proposed radar site in full frequency band and issue a formal electromagnetic environment test report.

Based on the test report of the radio monitoring institution, select the operating frequency or bandwidth for the proposed radar station. The occupied bandwidth of the S-band weather radar is (f0±15) MHz, and the occupied bandwidth of the C-band weather radar is (f0±15) MHz.

The impact of the proposed radar site on public radiation should meet the relevant requirements ofthe *GB9175-88 Environmental Electromagnetic Wave Sanitary Standard*, the *GB8702-88 Electromagnetic Radiation Protection Regulation*, and the *GB10436-89 Sanitary Standard for Microwave Radiation in Workplaces*.

If the proposed radar site is near radar stations of other departments or airports, the same-frequency interference of adjacent radars must be taken into account and the requirements of aviation flight safety must be satisfied.

### 3.5 Communication environment

The proposed radar site should facilitate the establishment of broadband communication links with local meteorological stations to ensure the real-time and reliable transmission of detection data and remote control information.

Weather radar adopts the radial flow transmission mode, so independent broadband communication links should be used, and the communication bandwidth should not be less than 10 M.

### 3.6 Lightning protection requirements

The proposed radar site should be selected in the geographical environment where the probability of lightning is low and the soil resistivity is relatively low. The grounding resistance of the site is preferably ≤ 4Ω. The construction of a CINRAD station should meet the requirements of the *QX2-2016 New Generation Weather Radar Station Lightning Protection Technical Specifications*.

### 3.7 Operating environment requirements of equipment room

The radar equipment room should be equipped with air-conditioning facilities to ensure proper temperature and humidity for radar operation. The ambient temperature of the transceiver is generally kept at 22°C or below, and the relative humidity is generally lower than 80% to ensure the normal operation of the radar.

Enough space should be kept between each extension and wall in the radar equipment room to satisfy the needs of installation, maintenance and repair of the equipment. The connection of cables and wires should meet the requirements of the technical specifications for installation of the manufacturer.

The floor of the radar equipment room should be laid with the electrostatic floor to prevent the static electricity or the leakage of electricity from causing damage to the equipment and people; the design and construction should be carried out in accordance with the weather radar lightning protection specification (QX/T 2-2016).

The radar equipment room must be equipped with fire alarm system and fire protection facilities. It should have good sealing performance and be waterproof, windproof, dustproof, salt spray-proof and corrosion-proof to prevent the intrusion of rodents and all kinds of insects. All personnel entering the equipment room should take anti-radiation measures and there should be guard bars around the radome to prevent people from falling.

The radar equipment room should be equipped with environment and equipment monitoring system and security system. The design of each system shall be implemented in accordance with the requirements of the Grade B Data Center Standard of *Data Center Design Standard* (GB50174-2017), the *Technical Code for Safety Prevention Engineering* (GB50348) and the *Intelligent Building Design Standards* (GB/T50314). The environment and equipment monitoring system should adopt collecting and distributing structure or distributed network structure. The system should be easy to expand and maintain, and should have the functions of display, record, control, alarm, analysis and prompt. The environment and equipment monitoring system and security system can be set in the same monitoring center. The power supply of each system should be reliable, and the independent uninterruptible power supply system should be used. When a centralized uninterruptible power supply system is used, a separate circuit should be used for distribution.

Corresponding fire extinguishing systems should be installed in weather radar towers and equipment rooms according to the current national standards, such as *Code for Fire Protection Design of Buildings* (GB50016) *Code for Fire Protection Design of High-rise Civil Buildings* (GB50045) and *Code for the Design of Gas Extinguishing Systems* (GB50370). The radar equipment room shall meet the requirements of the Grade B Data Center Standard of *Data Center Design Standard* (GB50174-2017).

### 3.8 Power supply requirement

The radar site should be selected in the place where the local power supply condition accords with the relevant national standards, the power supply voltage can meet the requirements of radar equipment, and the load of power supply system should have sufficient redundancy. At the same time, the area with large electricity users shall be avoided to ensure the voltage stability and good quality of power supply.

### 3.9 Other requirements

The proposed radar site should be selected in the place where basic environmental conditions such as power supply, roads and water are basically available and the social environment is safe, or that is convenient for the maintenance and development of radar station so as to facilitate the construction and maintenance of the new generation Doppler weather radar.

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**APPENDIX III**

**Unified Standards of Key Technology for China New Generation Radar (CINRAD)**

**（Equipment working group）**

**Meteorological Observation Center of CMA**

**November 2017**

1. OVERVIEW

In order to maximize the benefit of the CINRAD network in China and improve the quality of weather radar in the national network, since August 2016, China Meteorological Administration (CMA) has carried out special quality control work for CINRAD throughout the nation. In view of the fact that the technical status of calibration, observation mode and key adaptation parameters of the operational radars are not uniform, there are some differences in radar observation quality and data assimilation. At the same time, the performance degradation of radar key components results in the increase of maintenance cost. To deal with these issues, the working group of radar equipment management will manage to improve the performance of radar equipment by unifying the key technical standards of the radar.

# UNIFIED STANDARD OF TECHNICAL STATE

According to the radar rectification task and work requirements, through this rectification, a unified technology status should be achieved, including 7 aspects such as unified calibration and monitoring system, unified scanning mode and so on. Seven technology unified state standards as follows:

## Unified calibration and monitoring system

The technical standards of radar calibration and monitoring system mainly include on-line monitoring parameters, test signals, timing and real-time calibration techniques and procedures, etc. After the rectification, the basic parameters of the online automatic testing and uploading monitoring of various types of radar will be unified into 66 items in 5 categories, which are detailed in the attached table. At the same time, the calibration of radar echo intensity will be achieved in all types of radar, such as calibration method, online calibration and correction test signal, online calibration and check test signal, online echo intensity measurement error correction method, online real-time detection of radar state parameters and so on.

The calibration system of SA/SB/CB type radar is relatively complete and basically meets the operational requirement, but the calibration system of CC/SC/CD type radar is relatively simple，in the rectification, the online test function of the phase noise is included to further improve the SA/SB/CB radar calibration system. By including the phase noise, noise figure, clutter suppression parameter online testing, online speed check function, etc, CC/SC/CD model radar calibration system is established.

In addition to including the basic parameters of calibration system, all types of radars add additional calibration parameters on the basis of 66 basic parameters. The number of calibration and monitoring points for each type of radar are shown in Table 1.

Table 1. The number of calibration and monitoring points for each type of radar

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Type | SA | SB | CB | CC | SC | CD |
| Number | 128 | 128 | 128 | 159 | 112 | 99 |

## Basically unified scanning mode

Through rectification, we have optimized the working parameter design of CC/SC/CD radar scanning mode, basically unified VCP11, VCP21, VCP31 and other scanning strategies, and improved the coverage of multiple radar networked mosaic image. At the same time, we added a high mountain observation mode VCP41 on various radars.

The unified parameters are mainly elevation angle, layer number, VCP cycle, pulse processing mode and detection range, in which VCP11 includes 14 elevation layers observed under common precipitation conditions, VCP21 includes 9 elevation layers observed under heavy rainfall conditions, VCP31 includes 5 elevation layers observed under clear air conditions, VCP41 includes 10 elevation layers observed on the mountainous radar. The detection range of the S/C band radar after unifying VCP mode is shown in Table 2.

Table 2. Intensity and velocity detection range after unified radar scanning mode

|  |  |  |
| --- | --- | --- |
| Band | Intensity detection range | Velocity detection range |
| S | ≥460km | ≥230km |
| C | ≥300km | ≥200km |

## Unified key adaptation parameters

Through rectification, the same type radar adaptation parameters are standardized, including meteorological parameters, signal processing parameters, calibration parameters, test channel parameters, quality control parameters, etc. According to the regional climate characteristics, the fixed parameters (such as signal processing parameters, quality threshold, clutter filtering) are configured unifiedly, while individual parameters (such as antenna gain, test signal power, pulse width etc.) are managed differently, to ensure consistency in radar observation data for the same type of radar.

## Unified software testing platform

Through rectification, all types of radar have special parameter testing platform, and realize automatic test function. Each type of radar automatically completes the test and storage of radar parameters based on pre-set test procedures through software controlling external instruments. The main interface of the radar software testing platform of each type is required to be consistent, and the specific test items are shown in the attached table 3.

Table 3. Test items in software testing platform

|  |  |  |
| --- | --- | --- |
| No. | Test parameter item | Notes |
| 1 | Setting of related test parameters | Include control and communication parameters, etc of external instrument |
| 2 | Transmitter trigger pulse control | Control / numerical control attenuator control /PRF switching / pulse width switching with each module of a test channel |
| 3 | System noise figure test | Cold and hot group data display |
| 4 | Receiver dynamic range test | Internal / external |
| 5 | Receiver sensitivity | Long pulse / short pulse |
| 6 | Reflectivity calibration test | Internal / external, using external signal source needs to provide connection interface settings |
| 7 | External velocity check | Include PRF switch |
| 8 | System phase noise and ground clutter suppression test | Include PRF switch |
| 9 | Antenna control test | Velocity setting / positioning accuracy /PPI/RHI |
| 10 | Measurement of beam direction by solar method | Latitude and longitude setting |
| 11 | Virtual digital spectrum analysis | Single bin spectrum analysis, limit improvement factor measurement |
| 12 | Measurement of antenna parameters by solar method |  |
| 13 | ASCOPE function |  |
| 14 | Receiver test signal control | Attenuator control, switch selection, automatic control of external instrument and so on |
| 15 | Other related control such as waveguide switch |  |

## Unified supplement of radar standard output controller

Through rectification, each type of radar will be equipped with radar standard output controller (WRSOC), which has complete remote control, online performance analysis, operational process (maintenance activity, adaptation parameters change, software upgrade) monitoring and running environment online monitoring and control functions, to improve the level of intelligent applications for operational radar, and to dynamically detect the change of radar performance.

The remote control can realize that the radar maintenance personnel with different privileges can control radar remotely through internal network, and remote control items and functions are basically the same as the local radar, mainly including the control of the radar working state, remote control of the radar subsystem power on / off, etc to realize automatic unattended radar operation.

## Improved performance of key devices

Through rectification, we set up the unified requirements of the main technical specifications of radar key components (fixing specifications), and enhance the technical performance of key components of each radar type, so as to improve radar detection performance and reliability, reduce the use cost of radar and the failure rate. Table 4 is a summary of the performance enhancement of the main key parts for each radar type.

Table 4. Summary of the performance enhancement of the main key parts for each radar type

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| No. | Key device | Technical parameters or items | Before rectification | After rectification | Radar type |
| 1 | Frequency synthesizer | Output limit improvement factor | ≥52dB（S-band） | ≥55dB | all types |
| ≥49dB（C-band） |
| Phase noise | -133dBc/Hz@10KHz  （S-band） | -138dBc/Hz@10kHz  （S-band） |
| -105dBc/Hz@1kHz（C-band） | -110dBc/Hz@1kHz （C-band） |
| 2 | Network version of digital IF receiver | Receiver dynamic range | ≥85dB | ≥90dB | SA、SB、CB |
| Mixer calibration channel | N/A | Yes |
| 3 | Slip ring | Warranty life | ≥4 million rotation | ≥5 million rotation | all types |
| Maintainability | Needs regular maintainance | Maintenance free |
| 4 | Power probe | Internal power fluctuation detection | ≤0.5dB | ≤0.2dB | SB |
| 5 | Klystron | Warranty life | ≥5000h | ≥10000h | all types |

## Unified signal processor

Through rectification, unified technical scheme and standard of signal processor is formed, and gradually unified content includes: IQ data format, the signal processor hardware requirements, signal processor output data format compatibility with ROSE, signal processor external data interface format, basic signal processing algorithm, signal processor server, general test and evaluation methods. According to the schedule, currently planned unified IQ data format, signal processor hardware requirements, output data format, external data interface format, have been implemented in the rectification prototype, which is to lay a good foundation for the later complete test and evaluation as well as finally unified signal processor.

Appendix

Table 1. Automatic testing and basic parameters uploading of weather radarcalibration system

|  |  |  |
| --- | --- | --- |
| **Radar static parameters** | | |
| **No.** | **Upload parameter** | **Notes** |
| 1 | Radar station number |  |
| 2 | Site name |  |
| 3 | Latitude |  |
| 4 | Longitude |  |
| 5 | Antenna height | feed height, unit: meter |
| 6 | Ground height | unit: meter |
| 7 | Radar type | SA/SB/SC/CA/CB/CC/CD |
| 8 | RDA version number | monitoring software |
| 9 | Working frequency | unit: MHz |
| 10 | Antenna gain | unit: dB |
| 11 | Horizontal beamwidth | unit: degree |
| 12 | Vertical beamwidth | unit: degree |
| 13 | Transmitting feedline loss | unit: dB |
| 14 | Receiving feedline loss | unit: dB |
| 15 | Other losses | unit: dB |
| **Radar operating mode parameters** | | |
| 16 | Date |  |
| 17 | Time |  |
| 18 | VCP mode | VCP11、21、31、41 |
| 19 | Sign of control | Local control, remote control |
| 20 | System status | normal, available, maintenance, malfunction, and shutdown |
| 21 | Version number of the uploaded status data format | Old format is 0, new format is 1 |
| 22 | Dual polarization radar mark | Doppler, dual polarization |
| **Radar operating environment parameters** | | |
| 23 | Room temperature | unit: ℃ |
| 24 | Transmitter temperature | unit: ℃ |
| 25 | Radome temperature | unit: ℃ |
| 26 | Room humidity | unit: % |
| 27 | Transmitter humidity | unit: % |
| 28 | Radome humidity | unit: % |
| **Radar online fixed time calibration parameters** | | |
| 29 | KD calibration expected value | unit: dBZ |
| 30 | KD calibration measured value | unit: dBZ |
| 31 | Horizontal channel phase noise | unit: degree |
| 32 | Vertical channel phase noise | Reserved for dual polarization，unit: degree |
| 33 | Horizontal channel unfiltered power | unit: dBZ |
| 34 | Horizontal channel filtered power | unit: dBZ |
| 35 | Vertical channel unfiltered power | Reserved for dual polarization，unit: dBZ |
| 36 | Vertical channel filtered power | Reserved for dual polarization，unit: dBZ |
| **Radar online real time calibration parameters** | | |
| 37 | Transmitter peak power | unit: kW |
| 38 | Transmitter average power | unit: W |
| 39 | Antenna peak power in horizontal channel | unit: kW |
| 40 | Antenna average power in horizontal channel | unit: W |
| 41 | Antenna peak power in vertical channel | Reserved for dual polarization，unit: kW |
| 42 | Antenna average power in vertical channel | Reserved for dual polarization，unit: W |
| 43 | Transmitter power zero adjustment |  |
| 44 | Antenna power zero adjustment in horizontal channel |  |
| 45 | Antenna power zero adjustment in vertical channel | Reserved for dual polarization |
| 46 | Power ratio of transmitter and antenna | unit: dB |
| 47 | Short pulse noise level | unit: dB |
| 48 | Long pulse noise level | unit: dB |
| 49 | Noise level for different pulse widths in horizontal channel | unit: dB |
| 50 | Noise level for different pulse widths in vertical channel | Reserved for dual polarization，unit: dB |
| 51 | Current noise level in vertical channel | Reserved for dual polarization，unit: dB |
| 52 | Current noise level in horizontal channel | unit: dB |
| 53 | Noise temperature/figure in horizontal channel | unit: K/dB |
| 54 | Noise temperature/figure in vertical channel | Reserved for dual polarization, unit: K/dB |
| 55 | System calibration constant for short pulse |  |
| 56 | System calibration constant for long pulse |  |
| 57 | System calibration constant for different pulse widths |  |
| 58 | Reflectivity expected value | unit: dBZ |
| 59 | Reflectivity measured value | unit: dBZ |
| 60 | Velocity expected value | unit: m/s |
| 61 | Velocity measured value | unit: m/s |
| 62 | Spectrum width expected value | unit: m/s |
| 63 | Spectrum width measured value | unit: m/s |
| 64 | ZDR calibrated value | Reserved for dual polarization, unit: dB |
| 65 | PDP calibrated value | Reserved for dual polarization, unit: degree |
| 66 | Pulse width | unit: µs |