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Quality Assurance Guidance for the Collection of Meteorological Data Using Passive Radiometers

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Prepared by

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Region 10 Office of Environmental Assessment

and

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PREFACE

This document augments the February 2000 guidance entitled *Meteorological Monitoring Guidance for Regulatory Modeling Applications* and the March 2008 guidance entitled *Quality Assurance Handbook for Air Pollution Measurement Systems Volume IV: Meteorological Measurements Version 2.0 (Final)* by adding passive microwave radiometers to the remote sensing discussions. Recent developments in the technology and the availability of commercial units for passive profiling of temperature, humidity and liquid water have made these instruments available and a viable option for the measurement of vertical profiles of these variables. Until such time that the above referenced documents are modified to include remote sensing using passive radiometers, this document will serve to provide guidance for the setup, operation, data processing and quality assurance and quality control to assure the data collected are of a known quality and usable for modeling and analysis of the lower boundary layer. While measurements of humidity and liquid layer density and thickness are linked to atmospheric stability and boundary layer winds, the discussions provided herein are limited to the measurement of temperature as it relates to air quality related applications.

As with the development and deployment of any new measurement technology, the incorporation of the data into models and forecast methodologies will evolve with time. Through this evolution, the advantages and limitations will become more apparent. This is a path that has been followed by radar and acoustic profiling as well as remote sensing from space based platforms. To this end, this document provides guidance for the quality assurance of passive radiometers and methods to be used to assess the operations and suitability for the generated data to be used in regulatory driven measurement programs.

This document has been prepared by the U.S. Environmental Protection Agency with the assistance of Mr. Robert Baxter of Technical & Business Systems. The EPA technical lead for the guidance development was Dr. Robert Elleman in Region 10. Peer review of the April 2011 draft of this document was provided by Kevin Durkee (SCAQMD), Michael Gravier (Alaska DEC), Phil Swartzendruber (Puget Sound Clean Air Agency), Clinton MacDonald (Sonoma Technology, Inc.) Randolph Ware (Radiometrics Corp.) and Clive Lee (Kipp and Zonen). Their review and comments are greatly appreciated.

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1. FUNDAMENTALS

Observations of atmospheric variables such as temperature, humidity and liquid water are very important in understanding the behavior of the atmosphere, all of which can be measured by radiometers. In particular, the vertical temperature structure, or lapse rate, of the atmosphere has a major influence on how the atmosphere will mix and disperse pollutants, and is the measurement this document addresses. It is recognized that moisture profiles are also important and an improved understanding of them will help improve air quality models and forecasts. Future updates to this guidance may expand on this atmospheric variable.

In the last several decades, significant progress has been made in the commercialization of passive ground based profiling radiometers that can determine the temperature structure of the lower troposphere by measuring the radiation emitted by the atmosphere. The discussion below provides a simplified summary of the passive radiometer technique whereby the measurements of the temperature profile are achieved without the use of an active transmitter. This passive technique provides the distinct advantage over active systems that emit radio and/or acoustic energy, and allows operations in regions that may be sensitive to such active systems. More details on the theory of operation can be found in references **[1]** and **[2]**.

The operation of passive radiometers is based on the principle that all matter with a temperature other than absolute zero emits microwave radiation, with a spectrum and intensity determined by its physical temperature and structure. For temperature, observations from the ground are typically taken at various elevation angles to the zenith in multiple frequency channels from 50 to 60 gigahertz (GHz) **[3]**. These frequencies correspond to wavelengths of about 5 to 6 mm. In this spectrum, the oxygen absorption complex is well established for observing the atmospheric temperature profile. The specific frequency of the channels determines the effective volume of the measurement. The measured "brightness temperatures" in this volume is determined by the measured radiation at the specific frequency. By tilting the receiver beam, these integrated temperatures can be determined over the path of the differing altitude ranges and a profile of temperature can be derived. Typically the use of a single channel radiometer limits the altitude range to about 600 to 1,000 meters. The use of multiple channels around the 60 GHz center frequency allows profiles to altitudes over 1,000 meters, with data up to 10,000 meters achievable using historical radiosonde and neural network or regression methods **[4]**. With either the single or multiple channel techniques, an established baseline for the profile is obtained by comparing the near-surface brightness temperature to a locally measured reference temperature.

The vertical resolution of the reported temperature data varies with altitude due to the geometry of the measured elevation angle and the path length of the measured volume defined by the radio frequency. An increased altitude resolution is obtained on certain units by using a narrow receiver beam and smaller increments of measured elevation angles on the antenna. However, because the receiver beam is essentially a cone, there may be an overlap, or oversampling, of levels with small elevation angle increments. Therefore, the selection of the radiometer should consider the desired application and altitude coverage and resolution needs. Figures 1-1 and 1-2 show two commercially available profiling radiometers. The operational technique for elevation scanning and the resulting effective volumes of the atmosphere through incrementing elevation angles is shown in Figure 1-3. Included in this figure is the block diagram of typical components used to generate the temperature profiles. Figure 1-4 shows the atmospheric emissions spectrum received by a multi-channel system that is used to derive temperature and moisture profiles.

The sampling technique, whether elevation scanning, multiple channels or a combination of the two, provides the unique advantage of highly time resolved profiles and a continuous "picture" of the changing atmosphere. However, along with this advantage comes the limitation of the measurement not being able to replicate the atmospheric profiles traditionally obtained from sequential radiosonde soundings. In the process of obtaining vertical "slices" with associated volume average temperatures and then rebuilding a sounding from these sampled volumes, the profiles are unavoidably smoothed. Depending on the specific application, this may affect the usability of the data sets obtained. It is up to the user to understand this limitation and its potential effect on the intended application, and to adapt as needed the measurements to the end use of the data. In many cases this limitation may be far outweighed by the advantage of having the radiometer's high time resolution to help explain the behavior of the atmosphere in between the periods when scheduled radiosonde soundings are taken and/or at locations that cannot be adequately represented by the nearest radiosonde soundings. Additionally, such a system could be an advantage for some programs where the site location and related logistics for access and operations may define the automated passive system as a logical alternative to a human-based program simply for cost-effectiveness and safety reasons.

Figure 1-1. Example single channel commercially available profiling radiometer for measuring temperature profiles (photo courtesy of Kipp and Zonen).

Figure 1-2. Example multi-channel commercially available profiling radiometer for measuring temperature, humidity and liquid water content (photo courtesy of Radiometrics Corporation).

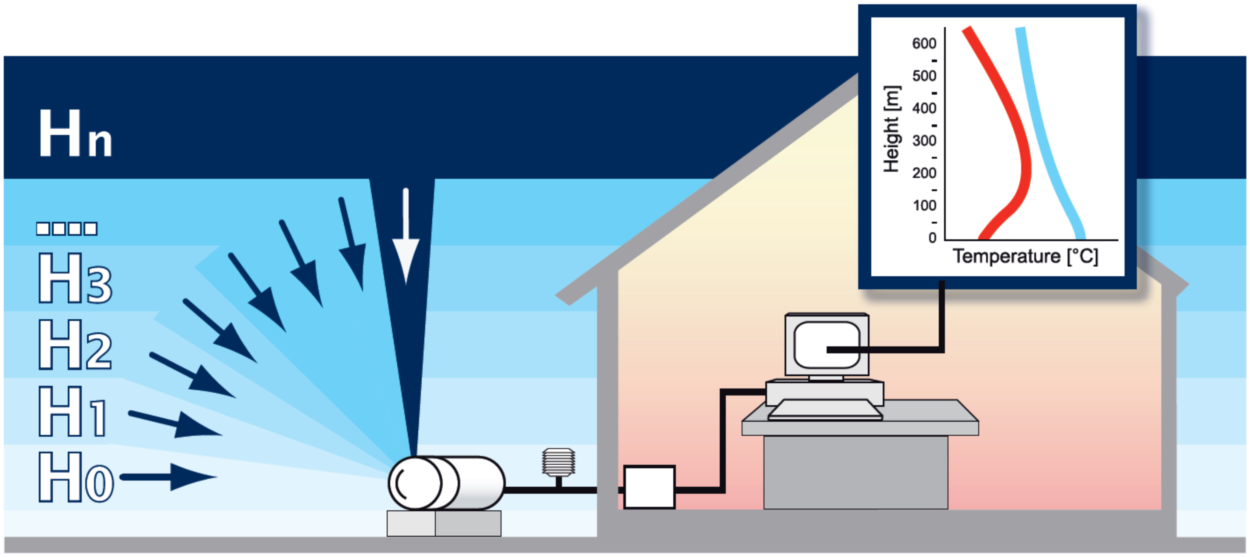

Figure 1-3. Operational technique to obtain a vertical temperature profile (at altitudes H_0, H_1 . . . H_n) using the scanning technique. The resulting temperatures represent a volume average at the reported levels (graphic courtesy of Kipp and Zonen).

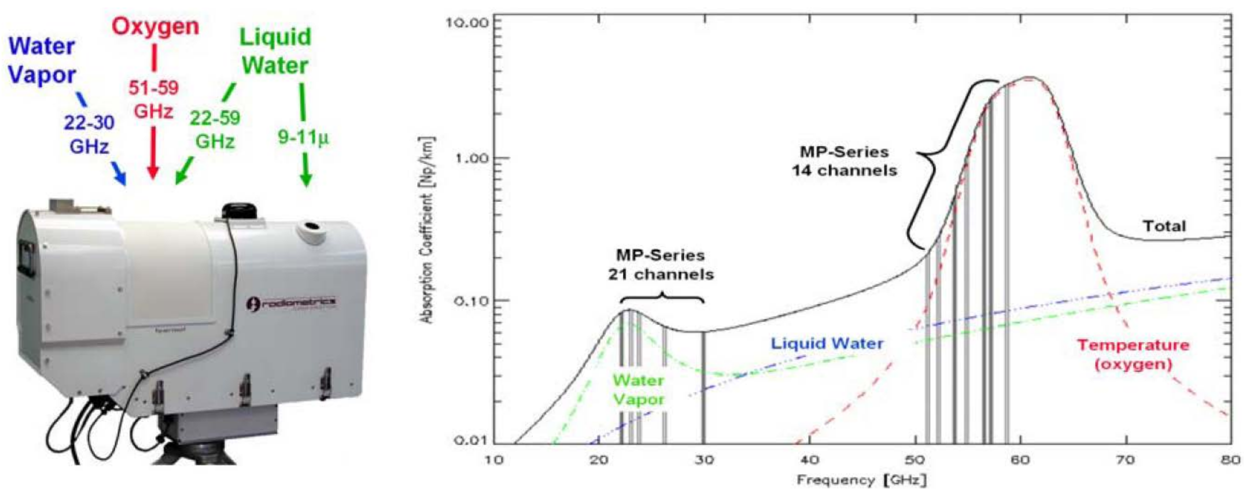

Figure 1-4. The atmospheric emissions spectrum received by a multi-channel radiometer. The microwave spectra are received by various sensors in the radiometer (graphic courtesy of Radiometrics Corporation).

2. PERFORMANCE CHARACTERISTICS

Performance characteristics for remotely sensed variables are based in large part on the theoretical basis and limitations of the observations. For temperature measurements using a five to ten channel radiometer, the root mean square (RMS) accuracy of this method is about 0.6°C close to the surface and degrades to 1.5 to 2 °C in the middle troposphere **[3]**. This accuracy is defined as the closeness of agreement between a test result and an accepted reference value **[5]**. Determining the absolute accuracy of an upper-air, remote sensing instrument through an inter-comparison study is difficult because there is no "reference" instrument that can provide a known or true value of the atmospheric conditions. This is due in part to system uncertainties and inherent uncertainties caused by meteorological variability, spatial and temporal separation of the measurements, external and internal interference, and random noise. The only absolute accuracy check that can be performed is on the system electronics, by processing a simulated signal. Similarly, a true precision, or standard deviation of a series of measured values about a mean measured reference value, can only be calculated using the system responses to repeated inputs of the same simulated signal.

The performance specifications provided by manufacturers for accuracy, precision, and other data quality objectives (DQOs) are derived in a number of ways, and it is prudent to understand the basis behind the published specifications. Manufacturers' specifications may be derived from the results of inter-comparison studies, from what the instrument system can resolve through the system electronics and processing algorithms, or a combination of these methods. It may not be practical for a user to verify the exact specifications by the manufacturers. What is needed instead is a means of verifying that the data obtained from an upper-air system compare reasonably to observations obtained from another commonly used and commonly accepted measurement system. This reasonableness comparison should evaluate both the accuracy of the temperature measurement as well as the ability of the radiometer to construct an accurate vertical profile of stability in the lowest layers. This includes depiction of both the lapse rate and the altitudes of significant changes in the lapse rate.

Quantifying the ability of the radiometer to accurately represent the vertical structure of the atmosphere requires the user to define the specific purpose and goals for the data set. As the radiometer measures the thermodynamics of the atmosphere, the air quality community most commonly uses it to define the mixed layer depth and the temperature structure of the mixed layer. To this end, the ability of the radiometer to detect the transition points in the atmosphere that will define changes in mixing properties should be assessed. As mixed layer depths of interest will vary from a few 10s of meters in cold and well-sheltered environments to several kilometers in hot desert regions, a maximum altitude of interest should be established based on the intended use of the data, and the evaluation performed to determine if the radiometer performs acceptably to this defined altitude of interest. It should be noted that the defined altitude may be different from the radiometer's maximum reported altitude. Thus, the evaluation will be performed on the altitude range of interest and not the full reporting altitude. Additionally, this altitude of interest may differ with season so the range specification may be different for different seasons.

Once the maximum altitude of interest is established, then the ability of the radiometer to detect the significant inflections in the lapse rate can be evaluated using a quantitative evaluation criterion. This criterion is best defined by the specific application, but a starting point for the evaluation can be a value of ±10% of the maximum altitude of interest. Thus, if the defined maximum altitude of interest is 600 meters, then the evaluation criterion would be ±60 meters for the detection of significant inflections, such as the inversion base or top.

To quantify the reasonableness of the data for comparison or audit purposes, one compares observations from the upper-air system being evaluated to data provided by another commonly accepted sensor that is known to be operating properly. In assessing how well the sensors compare with respect to data accuracy, two metrics are typically used. The first involves calculating the "systematic difference" between the observed variables measured by the two methods. The second involves calculating a measure of the uncertainty between the measurements, which is referred to as the "operational comparability", (or simply "comparability"), as described in reference **[6]**. Comparability, for these purposes, is the root-mean-square (RMS) of a series of differences between the two instruments measuring nearly the same population. The calculation of comparability also provides an indicator of how well the lapse rate has been estimated by the radiometer. While systematic differences may show a good overall estimation of the average accuracy, the scatter between the measurements due to differences in lapse rate will be reflected in the comparability value. Higher RMS values will indicate more uncertainty in the measurements. The importance of how well the radiometer estimates the lapse rate depends on the intended use of the data. This is discussed further in Section 3.

Using the ASTM notation **[6]**, the systematic difference (d) is defined as:

$$d = \frac{1}{N}\sum_{i=1}^{N}(X_{ai} - X_{bi})$$

where

X_{ai} = ith measurement made by one system (the instrument being evaluated),

X_{bi} = ith simultaneous measurement made by another system (the "reference" instrument), and

N = number of samples used.

Operational comparability (C, or root-mean-square error) is defined as

$$C = \pm\sqrt{\frac{1}{N}\sum_{i=1}^{N}(X_{ai} - X_{bi})^2}$$

Another important performance specification for the radiometer is data recovery rate. For standard surface measurements, the data recovery rate is calculated as the ratio of the number of valid observations divided by the total number of possible observations during the reporting period. For the radiometer, as with other remote sensing instrumentation, this specification should be reported as a function of altitude as well.

Some of the studies that have been performed to estimate the accuracy and precision of radiometers have been based on inter-comparisons to tower-based measurements. These comparisons have generally assumed that the tower measurements provide the known standard and are representative of the same environment measured by remote sensors. However, differences between point measurements from *in situ* sensors located on the tower and volume-averaged measurements from the remote sensors located near the tower are expected to lead to differences in the results, even though conditions for these inter-comparisons are likely as close to "ideal" as one could expect.

Similarly, because of the altitude range of the radiometers, comparisons are frequently made to radiosondes as opposed to towers. In these instances, the comparisons are made between volume averages from the radiometer to a "snapshot" profile from the radiosonde. Using this method, the data from the radiosondes are altitude averaged into the radiometer range gates to obtain as close a comparison in altitude as possible. Nevertheless, there are still spatial differences as the radiosonde moves away from the radiometer beam and, depending on the wind profile, potentially far from the radiometer site.

Another consideration in comparing the data relates to the sampling technique used by the radiometer and how it differs from an in-situ measurement. The radiometer uses a vertical volume averaging technique and obtains temperatures in the atmosphere through different volumes. These volume-averaged temperatures are then used to build a vertical profile of temperature (or humidity) through an iterative process, with interpretation algorithms calculating the temperatures through these different volumes. This process has an inherent smoothing that makes fine scale temperature changes more difficult to discern, especially at higher altitudes. Thus, elevated temperature inversions and other thermal structures will tend to be smoothed and may not even be apparent in the profiles. This limitation of the radiometric measurement technique will affect the statistical calculations and must be considered in the evaluation of the results and implications on the usability of the data.

Given the above potential uncertainties, it is critical that those tasked with interpreting comparison data must clearly understand both the instrumentation limitations of both the radiometer, and the radiosonde (or other comparison sensor), as well as the effect of the local meteorological conditions on the comparison.

3. MONITORING GOALS AND OBJECTIVES

When the primary use of upper-air data is for analysis and modeling of meteorological and air quality conditions in the boundary layer and lower troposphere, the focus of the upper-air program should be to maximize the temporal and spatial resolution of the data collected in this portion of the atmosphere, i.e. the first one to three kilometers. This is especially true if the conditions of interest are limited to lowest few hundred meters. Each modeling and analysis application will have its own unique objectives and scales of interest that have a large bearing on the type of upper-air measurement system chosen, the manner in which it is operated, and data processing and archival procedures. These characteristics include the duration of the measurement program and the required spatial and temporal resolution. The measurements can be part of a long-term monitoring program of seasonal to yearly extent, or a shorter-term intensive field campaign characterized by a greater number of measurements. Modeling requirements dictate the spatial and temporal resolution and will also affect the choice of measurement systems, as will the need in many cases to make comparable measurements with surface-based meteorological systems.

The options associated with radiometer measurements provide a variety of available configurations to measure just temperature or both temperature and moisture, and either with higher vertical resolution close to the ground or with lower vertical resolution across a larger altitude range. With that choice comes the need to carefully consider the requirements of the application and to choose and configure the appropriate systems. Specific items to consider in defining the monitoring goals and objectives include:

- The intended use of the vertical structure data as it relates to estimated lapse rates, or stability calculations
- The minimum and maximum altitude to which data are needed
- The altitude reporting resolution, and to what extent the levels may be oversampled or smoothed
- The temporal reporting intervals to match the expected use of the data
- Ambient meteorological conditions and the potential of adverse weather to affect the instrument operation therefore affecting data quality and recoverability
- Routine maintenance required for the expected local conditions
- Manufacturer provided or otherwise available software for the data processing and validation

Inherent in any measurement program is the need to establish DQOs. These relate the quality of the measurements obtained to the level of uncertainty decision makers are willing to accept in the data and results derived from the data. DQOs state how “good” the data need to be to satisfy the program objectives. The stated objectives generally include completeness, systematic difference, and comparability. Operators of the instruments should let the objectives be determined based on instrument performance specifications, and modeling and analysis needs. Data quality objectives should be specified for all of the primary variables measured by the instrument.

To check whether or not the data meet the DQOs from an instrument performance perspective, a comparison to another sensor that is known to be operating properly is recommended. In assessing how well the sensors compare, the systematic difference and operational comparability, as described in Section 2, can be computed and compared to performance criteria. As the radiometric technique derives the temperature profile from a series of volumetric averages and is not a direct measurement of the temperature, a two-tiered approach is recommended to help account for inherent smoothing in the radiometer profiles. Simple profiles within the altitude range of interest that have only one inflection point should have a recommended systematic difference of ±1.0°C and operational comparability of 1.5°C. These criteria are consistent with guidance provided for the Radio Acoustic Acoustic Sounding System (RASS) in references **[7]** and **[8]**. More complex profiles, as measured by an in-situ measurement such as a high resolution radiosonde, with multiple significant inflection points that clearly identify changes in stability in the atmosphere will inherently not be as accurately reproduced by the radiometer, and the criteria is recommended to be relaxed to ±2.0°C for the systematic difference and 3.0°C for the operational comparability. This will evaluate the performance of the radiometer recognizing the limitations in resolving a more complex vertical structure.

To determine how well the radiometer detects significant thermodynamic changes in the atmosphere, the inflection points in the lapse rate that limit mixing can be compared to the independent sounding to determine if the radiometer detected inflections occur at the correct altitude. While this comparison is somewhat qualitative, the reported inflection point altitude can be compared against the actual inflection point altitude using a criterion based on the maximum altitude of interest from the radiometer measurements. As indicated in Section 2, a starting point for this criterion should be a value of ±10% of the maximum altitude of interest of the reporting system.

If the intended use of the radiometric data includes the estimation of stability within layers based on calculated lapse rates (changes in temperature with altitude), then an evaluation of how well the radiometer data compares to a traditional means of calculating lapse rates should be performed. As calculated lapse rates are strongly influenced by the vertical altitude resolution and averaging of the measurements, there are no set criteria at this time on how well the lapse rates should compare. However, to document the estimation of lapse rate, comparisons of lapse rates should be made with vertical sounding data collected as part of quality control or quality assurance audit soundings that are performed. The reported data should include identified layers and lapse rates (°C/100 meters) within the layers measured by both the radiometer and the comparison system, with noted differences between the data sets. The intent of this information is to aid in the understanding of the measurements and how it may influence the expected uses of the data.

The data completeness goal for radiometric data is 90% calculated on a quarterly basis, similar to the goal from in-situ sensors. However, environmental factors can have a significant effect on the rate of data capture for remote sensing systems **[8]**, so it is recommended that deviations from the 90% goal may be acceptable providing the goals of the modeling and analysis can still be achieved. The monitoring and quality assurance project plan should identify any ambient conditions that may prevent the radiometric technology from retrieving valid data, and present a plan for how the periods of affected data would be treated in the data completeness calculation.

4. SITING AND EXPOSURE

Careful planning should accompany the siting of radiometers, since siting, exposure and the ambient environment will directly affect the quality of the data. The complexities of ground-based remote sensing devices provide a challenge for the user to balance the conditions favorable for the technology with the availability of sites and the overall data collection goals of the program. Site selection will benefit from the experience of vendors or users of the type of radiometer to be installed. Additional information on the siting of surface temperature instruments can be found in references **[7]** and **[8]**. Listed below are some key issues to consider in siting radiometers.

- **Representative location.** Sites should be located where upper-air data are needed and in the appropriate terrain such that the meteorological features important to meeting the program objectives are characterized. Panoramic photographs should be taken of the site in at least the four cardinal directions to aid in the evaluation of the data and preparation of the Quality Assurance Project Plan (QAPP). Data collected at sites in regions with local geographic features such as canyons, deep valleys, etc., may be unrepresentative of the surrounding area and should be avoided, unless such data are needed to resolve the local meteorological conditions. Measurements made in complex terrain may be representative of a much smaller geographical area than those made in simple homogeneous terrain. Care should be taken to choose a site that has the radiometer reference temperature sited in a manner that is consistent with surface temperature measurements to meet the program monitoring goals. As the radiometer reference temperature is used to establish the baseline temperature at the elevation of the radiometer, it is key to make sure it is representative of the surrounding environment and not influenced by unrepresentative terrain, local heat sources or improper aspiration. Additionally, terrain features or structures in the field of view of the radiometer beam can affect the accuracy of the data. The site should be selected in consultation with the instrument manufacturer or other knowledgeable operators to assure a minimum of interference with the intended measurements. For the surface sensors, references **[7]** and **[8]** provide guidance on the proper siting.

- **Site Logistics.**

    - Adequate power, both capacity and reliability, should be available for the instrument system as well as an environmentally controlled shelter that houses the system electronics, control computer, data storage and communication devices. Consideration should be given to a backup power system to keep the system running during short power outages.

    - The site should be in a safe, well lit, secure area with level terrain, sufficient drainage and clear of obstacles. The site should allow adequate room for additional equipment that may be required for calibrations, audits, or supplementary measurements. In addition, the site should be generally accessible to the operator seven days a week.

- A fence should be installed around the equipment and shelter to provide security, and appropriate contact information conspicuously posted in the event that issues arise at the site and the operator needs to be notified.

- A remote data communications link should be installed to provide the ability to transfer data and access the instrument. A site in a remote location with no communications capabilities may collect valid data, but if the system goes down it may not be discovered until the next time the site is visited. This down time may compromise the ability to meet the data capture goals.

- In the event that the radiometer needs to be elevated well above ground level then an adequately designed platform must be provided to be both secure and of sufficient height to meet the operational requirements of the radiometer. If the measurement program requires surface temperature at a standard 2 m height and the mounting of the radiometer surface temperature sensor is unrepresentative of this height then consideration should be given to having an additional surface temperature sensor installed at the standard 2 m collection height. References **[7]** and **[8]** provides the siting and operational criteria for this type of sensor.

- **Collocation with surface meteorological measurements.** Several advantages can be gained by locating an upper-air radiometer site with or near an existing meteorological monitoring station. For instance, collocated data can be used for data validation purposes and for performing reasonableness checks (e.g. agreement of temperature and/or humidity measurements with the radiometer). Existing shelter, power, communications, cameras and personnel could also assist in site operations and visual observations.

- **Passive interference/noise sources**. While a passive microwave radiometer does not transmit any signal, it is susceptible to interfering objects that may be in the field of view. Some radiometers require an unobstructed view along the horizon in a north or near-north direction in order to obtain a surface temperature correlation. Obstructions in this field of view will bias the measurements and create an offset in the resulting temperature profile. The manufacturer should be consulted as to the proper pointing direction and limitations on the field of view, and the installation should follow the recommendations for the instrument pointing direction, height above ground and limits on blockage to the field of view.

- **Active interference/noise sources**. The radiometer is effectively a very sensitive radio receiver that may be susceptible to nearby strong radio frequency (RF) sources. While the radiometer receiver frequency is high, in the GHz range, users should be aware that radio-transmitting equipment may produce harmonics in multiples of the base frequency that could fall into the receiver range of the radiometer. While well-designed transmitting equipment suppresses these harmonics, some interference may still be present if the radiometer is close to the RF source. Additionally, beam directions that may pass through active power lines should be avoided to minimize potential RF and temperature interference.

Surveying candidate locations. Prior to final site selection, a survey is recommended to identify potential RF sources that may degrade the system performance. Additionally, panoramic photographs should be taken to aid in the evaluation of the candidate site and for preparation of the monitoring plan. As part of the survey, appropriate topographic or other maps should be used to identify other potential sources of interference such as terrain features or buildings that may be in the radiometer field of view.

5. INSTALLATION AND ACCEPTANCE TESTING

The installation period is the optimal time to receive appropriate training in instrument principles, operations, maintenance, and troubleshooting, as well as data interpretation and validation. Meteorological consultants as well as some manufacturers and vendors of meteorological instruments provide these services.

Installation procedures specific to radiometer monitoring systems include the following:

- The latitude, longitude, and elevation of the site should be determined using U.S. Geological Survey (USGS) topographical maps, other detailed maps, or a Global Positioning System (GPS) instrument.

- The orientation of the instrument should be defined with respect to true north. One method is to use the GPS alignment method described in reference **[7]**. In May 2000, the Department of Defense removed the Selective Availability (SA) encoding on the GPS satellite constellation, which increased the position accuracy of 12-channel GPS receivers to within 5 m to 10 m. This degree of accuracy is capable of measuring the direction of travel, or bearing, over short distances. The method uses a simple GPS receiver to "walk off" the pointing direction of an instrument. An alternative method is to use the solar siting technique, also described in reference **[7]**. This technique enables determination of true north at any location using a compass (or other pointing device suitable for measuring the azimuth angle to the sun), a computer program, the site latitude and longitude, and accurate local time. Because some locations may not have a clear view of the sun due to cloud cover or the particular locale, the GPS method is the preferred method. Using either of these methods should result in a measurement accuracy of about ±1°. The manufacturer of the radiometer should be contacted regarding specific requirements for orientation of the instrument.

- The site should be documented as follows:

    - Photographs in sufficient increments to create a documented 360° panorama around the receiver should be taken. Additionally, pictures of the receiver installation, shelter and any obstacles that could influence the data should be obtained.

    - Photographs of the instrument, site, shelter, and equipment and computers inside of the shelter should be obtained.

    - A detailed site layout diagram that identifies true north and includes the locations of the instrument, shelter, other equipment, etc. should be prepared. Additionally, it is recommended that the site layout diagram include the electrical signal cable layout, and the field of view of the radiometer pointing direction. References **[7]** and **[8]** show an example site layout. Note that for the example site layout, the radiometer should be located on the north end of the site compound to allow an unobstructed view of the horizon to the north.

- A vista table that documents the topographic features and objects surrounding the site in 30° increments should be prepared. The table should identify any potential passive and active noise sources in each direction, and the approximate distance and elevation angle above the horizon to the objects. References **[7]** and **[8]** show an example vista table.

An acceptance test is used to determine if an instrument performs according to the manufacturer's specifications. Manufacturer's procedures for unpacking, inspection, installation, and system diagnostics should be followed to assure that all components are functioning appropriately. All acceptance-testing activities should be documented in the station log.

Once the system is installed, a final field check is needed to assure that the data are reasonable. This is best performed using collocated meteorological information from towers or other upper-air sensors that overlap the operating range of the radiometer. In the absence of these data sources, nearby upper-air data from the National Weather Service radiosonde network, the National Oceanic and Atmospheric Administration profiler network, aircraft reports, National Center for Environmental Prediction high resolution mesoscale analyses, or other upper-air data may be a reasonable substitute. It is important to have an individual trained in the interpretation of the data perform a thorough review of at least several days of data. This check is not meant to evaluate whether or not the data meet the manufacturer's data specifications, but is intended to identify problems such as:

- Component failures
- Incorrect or improper operating/sampling parameters
- Antenna azimuth or level angles improperly specified or incorrectly measured
- Siting problems (active and passive interfering noise sources)

Shortly after the installation and startup of the instrument, a system and performance audit should be performed. These audits will provide information for the qualitative and quantitative assessment of the performance of the system, as well as the adequacy of the standard operating procedures (SOPs) used for the collection, processing and validation of the data. To best assure that the data collected is of known quality, and that potential problems are identified early, it is recommended the initial audit be performed within 30 days of the start-up date.

6. QUALITY ASSURANCE AND QUALITY CONTROL

The discussions provided below provide information on Quality Assurance/Quality Control (QAQC) procedures unique to radiometer systems. Section 8 of reference **[8]** provides more general materials related to QAQC procedures and definitions of terms used in this section.

With the exception of the surface temperature measurement used as a reference, radiometers provide indirect measurements of the meteorological variables used in dispersion modeling and forecasting. This presents a unique challenge to the QAQC of these systems; for example, there is no radiometer counterpart to the multiple temperature water baths for standard temperature sensors. The alternative to the bench-top calibration is a calibration using a collocated transfer standard. This involves locating an accepted standard instrument as close as practical to the instrument being calibrated – again, as with the bench-top procedure, there is no upper-air counterpart to the collocated transfer standard for temperature. Similarly, there is no upper-air counterpart to the performance audit of a temperature probe (as the difference has to do with the independence of the person conducting the audit). Given the inability to conduct a true performance audit, the onus for claims of data validity for radiometer measurements, as it is for most upper-air measurements, falls on the system audit and is essentially a challenge to the QAPP and provides an overall assessment of the commitment to data validity. Alternative procedures for calibrations and performance audits of radiometers are based on inter-comparisons with other measurement systems, which are discussed below.

6.1 Calibration Methods

A calibration involves measuring the conformance to or discrepancy from a specification for an instrument and an adjustment of the instrument to conform to the specification. In this sense, other than directional alignment or level checks, a true calibration of the radiometer response is difficult. Due to differences in measurement techniques and sources of meteorological variability, direct comparison with data from other measurement platforms in itself is not adequate for calibration. Instead, a calibration of these instruments also relies on other reference methods and internal noise sources to provide some measure of calibration. These other methods may include external blackbody reference targets, a tipping curve calibration method, brightness temperature calculations from radiosondes, or blackbody targets immersed in cryogenic fluids **[2]**. Combined with the manufacturer recommended electronic calibrations or calibrations of the external sensors used for reference, these methods form the calibration of the radiometer unit.

The system calibration and diagnostic checks should be performed at six month intervals, or in accordance with the manufacturer's recommendations, whichever is more frequent. The alignment, referenced to true north, and level of the system should be verified at six month intervals.

6.2 System and Performance Audits

Audits of upper-air instrumentation to verify their proper operation pose some interesting challenges. While system audits can be performed using traditional system checks and alignment and orientation techniques, performance audits of some instruments require unique, and sometimes expensive procedures. In particular, with the exception of the surface reference temperature, the radiometers cannot be challenged using known inputs from temperature baths. Recommended techniques for both system and performance audits of the radiometers are described below. These techniques should form the basis of operational procedures for the conduct of the audit. These procedures will then become part of, or referenced in, the QAPP for the measurement program. The audits are conducted by a group or organization that is completely independent of the radiometer operations and associated data processing and validation.

6.2.1 Systems Audit

The systems audit should include a complete review of the QAPP, any monitoring plan for the station, and the station's SOPs. The system audit will determine if the procedures identified in these plans are followed during the station operation. Deviations from the plans should be noted and an assessment made as to what effect the deviation may have on data quality. To ensure consistency in the system audits, a checklist should be used. System audits should be conducted at the beginning of the monitoring program and annually thereafter.

A routine check of the monitoring station should be performed to ensure that the local technician is following all SOPs. In addition, the following items should be checked:

- The radiometer power and controller interface cables should be inspected for proper connection.

- Supporting measurement equipment such as reference temperature sensors are inspected for appropriate shielding, exposure and representativeness of the measurement environment. The siting and accuracy specifications should be consistent with reference **[8]**.

- The orientation and level of the radiometer should be measured. If the manufacturer states a specific instrument orientation, then that value should be within ±5° of the audit measured orientation. Additionally, the level of the radiometer unit should be within ±0.5° of the manufacturer recommended value. In most cases this is 0°. The level of the system is the most critical as calculations in the system have assumed the instrument is level.

- A general survey of the surrounding environment should be made to assess the potential for RF interfering sources. Antennas can be a good indicator of potentially active RF sources, as well as a query of nearby operations that may have technology that use RF transmissions. A more quantitative survey may be accomplished using a RF scanner. The radiometer manufacturer should be contacted to determine what specific frequencies could interfere, and a scan of those general bands can be performed.

- The vista table for the site should be reviewed. If a table is not available then the auditor should prepare one.

- The electronic systems and data acquisition software should be checked to ensure that the instruments are operating in the proper mode and that the data being collected are those specified in the SOPs.

- Station logbooks, checklists, and calibration forms should be reviewed for completeness and content to assure that the entries are commensurate with expectations in the procedures for the site. Manuals and other documentation should be present at the site.

- The site operator should be interviewed to determine his/her knowledge of system operation, maintenance, and proficiency in the performance of quality control checks.

- The support platforms and radiometer enclosure should be inspected for structural integrity that could allow undesired movement in high winds.

- Methods for water or snow removal from the radome (the antenna cover) or antenna through either manual removal or operational blowers should be inspected for proper implementation and operation.

- Preventive maintenance procedures should be reviewed for adequacy and implementation.

- Time clocks on the data acquisition systems should be checked and compared to a standard of ±2 minutes.

- The data processing procedures and the methods for processing the data from sub-hourly to hourly intervals should be reviewed for appropriateness.

- Data collected over a multi-day period (e.g., 2-3 days) should be reviewed for reasonableness and consistency. The review should include vertical consistency within given profiles and temporal consistency from period to period.

6.2.2 Performance Audit and Comparison Procedures

Performance audits should be conducted at the beginning of the monitoring program and annually thereafter. A final audit should be conducted at the conclusion of the monitoring program. In the event that the there are significant seasonal changes during the period of the monitoring program the final audit may be performed during an alternate season in order to verify the operation under different conditions from the first audit. Thus, an annual monitoring program may have the “final” audit performed prior to the end of the monitoring period. The decision of when the audits will be conducted will be made in consultation with the governing regulatory agency to assure the performance of the radiometer is properly understood during the periods of interest.

As radiometers have historically had limited use in regulatory monitoring programs, the performance audit methods have only recently been implemented. A different method of measuring temperature profiles, the RASS has been used now for over a decade. For auditing the RASS, typically multiple radiosonde launches are used, as the radiosondes provide a high-resolution profile of the boundary layer measured by the RASS. For these systems, the radiosonde audit method has worked well provided the auditor understands the limitations of both the audit and site systems. The same holds true for the use of radiosondes in auditing a radiometer. Radiosondes provide a snapshot of the atmosphere at the time the balloon ascends, while the radiometer will provide a form of integrated profile. Additionally, depending on the local winds, the radiosonde can travel some distance from the launch point making the comparison differ in space as well as well as time. Recognizing these differences and properly interpreting the results is the responsibility of a knowledgeable auditor. If circumstances permit, alternative methods of performance auditing may include other remote sensors, such as a RASS. However, any selected method must include an appropriate traceability of the selected audit device and, as with the radiosonde, the auditor must be knowledgeable in the advantages and limitations of such instruments.

Given the above understanding of the systems, and assuming the use of a radiosonde type audit device, a performance audit will consist of a sufficient number of soundings (typically 4 to 6) over the course of a day in order to cover a variety of meteorological conditions. Typical radiometer data has a variable altitude reporting interval with range gates in the lowest levels being spaced closer together and those at higher levels spaced further apart. In order to prevent a skewing of statistical results to the levels with a higher range gate density, the radiometer data set needs to be converted to reporting altitudes with the same increment, i.e., 10m, 25m, 50m, etc. It is recommended that the finest altitude resolution reported from the radiometer profile be selected as the altitude reporting increment for the converted data set and that all data be interpolated to this resolution before statistical comparisons are made. For example, if the lowest levels in the profile are reported at 10 m increments, then data from the converted set will have an altitude reporting interval of 10 m through the entire profile. The data collected from each sonde should then be altitude averaged into intervals consistent with the radiometer averaging volumes, and the values compared on a level-by-level and overall basis. The comparisons performed will include both systematic and RMS differences determined by each sounding and for the entire data set as a whole. The results should be compared to a criteria of ±1.0°C for systematic and 1.5°C for RMS differences for a simple profile with a maximum of one significant inflection point in the sounding, and ±2.0°C for systematic and 3.0°C for RMS differences in a complex profile with more than one inflection point that clearly shows changes in stability in the profile. For differences that fall in the latter category, a further discussion of the complexity of the sounding should be provided to support the greater differences that likely occurred due to the volume averaging by the radiometer.

Each of the comparison soundings evaluated for the systematic and RMS differences should then be evaluated for how well the radiometer profile represents the lapse rate structure observed from the audit soundings. The altitude of the inflection points in the lapse rates of the comparison pairs should be tabulated and the differences in the heights evaluated using a criterion of ±10% of the altitude range of interest.

Results outside of the above criteria do not necessarily mean a failure of the system. Reasons for greater differences may be due to radiosonde offsets, fundamental differences in technologies, radiometer offsets, or spatial or temporal differences between the two measurements. It is the responsibility of the auditor to understand the instrumentation and to assess any differences found and the reasonableness of the reported radiometer data. This assessment should include a comparison of the fine structure observed by the radiosonde to the potentially smoothed structure reported by the radiometer, and should include implications for the intended use of the data.

If the intended use of the radiometric data includes the estimation of stability within layers based on calculated lapse rates (changes in temperature with altitude), then an evaluation of how well the radiometer data compares to a traditional means of calculating lapse rates should be performed. Using the audit sounding data collected above (as well as other available comparison data), lapse rates within significant layers should be calculated and a comparison made of audit and site calculated values. The results should provide the individual calculated lapse rates and differences noted. As the significance of the differences depends on the intended use of the data, and instrument and audit sensor capabilities, there are no defined comparison criteria. However, it is important for analysts to have the calculated differences to help understand how the data may influence models and analyses that will use the radiometer data collected.

In addition to the performance audit of the radiometer reported data, any surface measurements that are integral to the accuracy of the radiometer reported values will have an appropriate performance audit conducted. This may include surface or reference temperature, relative humidity, or pressure sensors. Audit methods for these surface sensors are provided in reference **[7]**. Table 6-1 summarizes the audit criteria.

Table 6-1. Summary of Audit Criteria

VARIABLE	CRITERIA	QUALIFICATIONS
Instrument Level	±0.5° in all directions	
Instrument Orientation	±5° referenced to true north	Orientation is only critical if the elevation scanning includes data that may be affected by a scan that looks into the sun. The manufacturer should be contacted regarding the system susceptibility to this condition.
Temperature Simple profile with one inflection point Complex profile with 2 or more inflection points	 ±1.0°C Systematic Difference 1.5°C RMS Difference ±2.0°C Systematic Difference 3.0°C RMS Difference	 Comparison made for each sounding and the average as a whole. If any of the individual sounding comparisons are outside criteria an explanation should be provided.
Sounding Structure (as indicated from inflection points)	±10% of the altitude range of interest	The inflection points in each sounding pair should be evaluated.
Lapse Rate	Non specified	If stability is being calculated from the radiometer data then this lapse rate calculation assessment should be performed and reported.

6.3 Standard Operating Procedures

SOPs should be developed that are specific to the operations at a given site. The purpose of an SOP is to spell out operating and QC procedures with the ultimate goal of maximizing data quality and data capture rates. Operations should be performed according to a set of well defined, written SOPs with all actions documented in logs and on prepared forms. SOPs should be written in such a way that if problems are encountered, instructions are provided on actions to be taken. At a minimum they should address the following issues:

- Installation, setup, and checkout
- Site operations and calibrations
- Operational checks and preventive maintenance (both on-site and remote)
- Audit methods and procedures
- Data collection protocols
- Data validation steps
- Data archiving

6.4 Operational Checks and Preventive Maintenance

Like all monitoring equipment, radiometers require various operational checks and routine preventive maintenance. The instrument maintenance manuals should be consulted to determine which checks to perform and their recommended frequency. The quality and quantity of data obtained will be directly proportional to the care taken in ensuring that the system is routinely and adequately maintained. The site technicians who will perform preventive and emergency maintenance should be identified. The site technicians serve a crucial role in producing high quality data and thus should receive sufficient training and instruction on how to maintain the equipment. Some general issues related to operational checks and preventive maintenance should be addressed in the QAPP, including:

- Identification of the components to be checked, cleaned or replaced
- Development of procedures and checklists to conduct preventive maintenance
- Establishment of a schedule for checks and preventive maintenance
- Identification of persons (and alternates) who will perform the checks and maintenance
- Development of procedures for maintaining spare components that need frequent replacement

- Documentation of all activities at the site and any instrument maintenance performed

Listed below are some key items to be included in the operational checklists. This list is by no means complete, but should serve as a starting point for developing a more thorough set of instrumentation checks.

- Safety equipment (first aid kit, fire extinguisher) should be inventoried and checked.

- After severe or inclement weather, the site should be visited and shelter and equipment inspected. Consideration should be given to installation of a real-time camera to help document the site conditions and assessment of the site visit need.

- Computers should be routinely monitored to assure adequate disk space is available, and diagnosed to ensure integrity of the disk(s).

- A visual inspection of the site, shelter, instrument and its components should be made.

- Data should be backed up on a routine basis.

- If the system is operated in cold environments, procedures for snow and ice removal should be developed and implemented as needed.

- The clock time of the instrument should be monitored and a schedule for updating the clocks established based on the timekeeping ability of the instrument.

- The radiometer level and orientation should be verified periodically.

- The inside of any shelters or equipment that is accessible by leaves, dust, animals, insects, snow or ice should be inspected and cleaned. This includes any air filters that may be present on the radiometer.

- Cables, guy wires and supporting structures should be checked to ensure structural integrity.

- Power and signal cables as well as connectors should be inspected for signs of wear, damage or animal activity.

- Changes in the surrounding environment such as additional fences, buildings or obstacles to the field of view of the radiometer should be noted.

All operational checks and preventive maintenance activities should be recorded in on-site logs and/or on appropriate checklists (electronic and/or paper), which will become part of the documentation that describes and defends the overall quality of the data produced.

6.5 Corrective Action and Reporting

A corrective action program must have the capability to discern errors or defects at any point in the monitoring program. It is an essential management tool for coordination, QC, and QA activities. A workable corrective action program must enable identification of problems, and establish procedures for reporting problems to the responsible parties, tracing the problems to the source, planning and implementing measures to correct the problems, maintaining documentation of the results of the corrective process, and resolution of each problem. The overall documentation associated with the corrective action and reporting process will become part of the documentation that describes and defends the overall quality of the data produced.

7. DATA PROCESSING AND MANAGEMENT

An important component of any upper-air meteorological monitoring program is the processing, quality assurance, management, and archival of the data. Each of these components is briefly discussed below. Further guidance is provided in reference **[8]**.

7.1 Overview of Data Products

For radiometers, the final data products usually consist of one or more ASCII files containing the averaged profiles of temperature and possibly other products, as a function of altitude. Supporting information provided with the reduced data products may include other information that can be used to regenerate profiles or document the operations. These metadata become an integral part of the dataset and to the extent possible are "attached" to it so that any future user has the needed documentation to decode and understand the data. All data collected should be archived for backup purposes and to support post-processing, validation and analyses of periods of interest.

7.2 Steps in Data Processing and Management

Data processing, validation and management procedures for a radiometer data set would typically include the following steps, which should be described in the QAPP:

- Collection and storage on-site (as appropriate) of the "raw" signals from the radiometer, followed by real-time processing of the "raw" data by the radiometer computer to produce reduced, averaged profiles of the temperature and possibly other data. The reduced data are stored on the system computer, usually in one or more data files.

- Transfer of the reduced data to a central data processing facility at regular intervals (e.g. daily). Once the data are received at the central facility, they should be reviewed by an experienced data technician as soon as possible to verify the operational readiness of the radiometer. Backup electronic copies of the data should be prepared and maintained both on-site and off-site.

Data collected by the radiometer should be obtained by polling the data system at a site from the central facility, or pushing the data from the site to the central facility. Many options are available for site communications, and the real-time or near real-time access to the data is considered a high priority in maintaining acceptable data recovery.

A rapid on-going review of the incoming data is not very time consuming, but is considered an extremely important component of a successful monitoring program. It is at this stage that most problems affecting the data quality or data recovery will be detected. If the data are reviewed frequently, then problems can be detected and corrected quickly, often the same day, thereby minimizing losses. At a minimum, the operational readiness of a radiometer site should be checked daily from the start of monitoring using both automated screening and manual review. As the reliability of the instrumentation is assessed and automated methods to screen the data are fine tuned, the schedule for manual review may be extended if the instrument reliability is appropriately demonstrated. However, one is cautioned that to maintain a high rate of data recovery, frequent checks should be the norm. Likewise, maintaining backup copies of the data at each stage of processing is extremely important. Backup copies should be kept at the central data processing facility and at a separate, off-site location(s) to ensure that no data are damaged or lost.

Once data are at the central data processing facility there are four general "levels" of data validation, as described in reference **[7]**. When a data set has undergone a level of review, it passes on to the next level. The process is used to determine the validity of the data.

- Level 0 validated data are essentially raw data obtained directly from the instrument in the field. Level 0 data have been reduced and possibly reformatted, but are unedited and not reviewed. These data have not been adjusted for known biases or problems that may have been identified during preventive maintenance checks or audits. These data may be used to monitor instrument operations on a frequent basis, but should not be used for regulatory purposes.

- Level 1 data validation involves quantitative and qualitative reviews for accuracy, completeness, and internal consistency. Quantitative checks are performed by screening programs and qualitative checks are performed by meteorologists or field staff who manually review the data for outliers and problems. If the data are to be used in stability calculations then the quantitative checks should include a calculation of lapse rates through the profile to identify levels that do not conform to known meteorological and physical principles. For example, lapse rates above the surface layer should not be superadiabatic except under unusual circumstances and those identified as such should be flagged. These quality control flags are assigned, as necessary, to indicate the data quality. Data are only considered validated at Level 1 after final audit reports have been issued and any adjustments, changes, or modifications to the data have been made.

- Level 2 data validation involves comparisons with independent data sets. This function includes, for example, making comparisons to other meteorological or upper-air measurement systems.

- Level 3 data validation involves a more detailed analysis and final screening of the data. The purpose of the final step is to verify that there are no inconsistencies among the related data. Graphics programs may be run to examine the overall consistency among related data (i.e., checking diurnal patterns against other parameters).

Some final processing may be necessary to convert the data to the format that will be used to submit the information to the final archive. Final documentation should be prepared that summarizes sampling strategies and conditions, describes the results of audits and any actions taken to address issues raised by the audits, identifies any problems that adversely affected data quality and/or completeness, and fully documents the contents and formats of the database. Typically, a copy (electronic and/or paper) of this documentation accompanies the submittal of the data to the final data archive.

7.3 Data Archiving

Maintaining a complete and reliable data archive is an important component of a QAPP. Radiometers produce a large amount of data consisting of raw and processed data. A protocol for routinely archiving the data should be established.

Raw data are the most basic data elements from which the final data are produced. Archiving these data is important because at a later date the raw data may need to be reprocessed to account for problems that are identified following the original validation. In addition, future processing algorithms may become available to extract more information from the raw data. Raw data are generally stored on-site and should be archived as part of the operational checks. Data should be stored on multiple convenient and reliable archive media such as optical disks. The primary archive should be stored in a central repository with backup stored off-site.

Reduced data, which are created from the raw data by averaging, interpolating, or other processing methods, should also be archived. Reduced data include hourly averaged values or other quantities derived from the raw data. Data validation is performed on the reduced data to identify and flag erroneous and questionable data. Both the reduced and validated data should be routinely (e.g. weekly or monthly) archived onto digital media, with one copy stored on-site and second copy stored off-site.

Other supporting information that should be archived along with the data may include, but not be limited to:

- Site and maintenance logs
- Audit and calibration reports
- Site information
- Log of changes made to the data and the data quality control codes
- Information that future users would need to decode, understand, and use the data
- Surface measurements and other relevant weather data

Data should be retained indefinitely because they are often used for modeling and analysis many years following their collection. Periodically, the integrity of the archive media should be checked to ensure that data will be readable and have not become corrupted. Data should be recycled by transfer from old to new media approximately every 5 to 10 years. If an archive is scheduled to be eliminated, potential users should be notified beforehand so that any important or useful information can be extracted or saved. To this end and as funding and contracts allow, consideration should be given to options such as submission to the National Climatic Data Center where the archive, maintenance and availability of data would be centralized.

8. RECOMMENDATIONS FOR DATA COLLECTION

A summary of recommendations for collection of data using radiometers is as follows:

- Key to the collection of a usable data set of known quality is a comprehensive QAPP. The QAPP should define the expected use of the data and all of the steps that will be taken to select a site, install and operate the instrumentation, and process, validate and report the data.

- Suggested DQOs for temperature profiling radiometers are provided in Section 3. For accuracy, they should be based on systematic differences; DQOs for precision should be based on the "comparability" (RMS) statistic; for completeness they should be based on percent data recovery by altitude with any qualifications for conditions or data that would not be included in the data completeness calculation explicitly identified. DQOs for the ability of the radiometer to detect significant changes in the lapse rate that affect atmospheric mixing should be based on the maximum altitude of interest, which may vary by location and season. The development and specification of the DQOs for lapse rate are project specific and should be based on the modeling needs of the program.

- Site selection for radiometer systems is best accomplished in consultation with vendors, regulators and/or users with expertise in such systems. Operators and site technicians of systems should receive appropriate training prior to or during system shakedown. Training should include instruction in instrument principles, operations, maintenance, troubleshooting, data interpretation and validation.

- System calibration and diagnostic checks should be performed at six-month intervals, or in accordance with the manufacturer's recommendations, whichever is more frequent.

- Collected data should be reviewed at least weekly and preferably daily to assess the operational status of the system and to ensure that data are valid and reasonable.

- System and performance audits should be conducted annually. If the site experiences extreme seasonal meteorological variability then consideration should be given to performing one of the annual audits during a different season (e.g. one summer and one winter).

- It is the responsibility of the auditor to understand the technologies of both the radiometer and the instrument used to audit it in order to appropriately interpret the quantitative results of the performance audit. Guidelines for the audit criteria used in the performance audit are provided in Section 6 and are based on the modeling needs of the program.

- Performance audits of the radiometer should include any of the supporting measurements made by the system that are used in the calculation of the reported data (e.g. reference temperature measurements).

- Supporting reference measurements integral to the radiometer operations and used in the calculation of radiometer profiles should be made using sensors meeting the performance and exposure requirements for the intended application.

General recommendations for the processing, management, and archival of radiometer derived meteorological data include:

- A consistent/standardized database format should be established and maintained, at a minimum for each individual monitoring program.

- The data archive should include raw, reduced, and validated data as well as other (low-level) data products (as appropriate to allow future reprocessing if necessary) and calibration results.

- If the intended use of the data includes quantitative stability calculations then the screening of the data set during the level 1 validation should include comparisons of the radiometer calculated lapse rates to known physical and meteorological properties of the atmosphere in order to flag suspect data.

- The database should be validated to Level 2, and preferably to Level 3 before distribution.

- The data archive should be routinely backed up and checked for integrity.

- A secondary backup of the data should be kept at an alternate location, routinely checked for integrity, and periodically recycled onto new storage media.

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