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# Microwave Radiometer Profiler (MWRP) Instrument Handbook

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ARM CLIMATE RESEARCH FACILITY

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Revision 1

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# Acronyms and Abbreviations

| | |
|---|---|
| AMF | ARM Mobile Facility |
| ARM | Atmospheric Radiation Measurement |
| DOE | U.S. Department of Energy |
| ENA | Eastern North Atlantic |
| IMMS | Instrument Mentor Monthly Summary |
| LWP | liquid water path |
| MWRP | microwave radiometer profiler |
| NSA | North Slope of Alaska |
| QC | quality control |
| PWV | precipitable water vapor |
| SGP | Southern Great Plains |
| RMSE | root-mean-square error |

# Contents

# Figures



# Tables

# 1.0 General Overview

The Microwave Radiometer Profiler (MWRP) provides time-series measurements of brightness temperatures from 12 channels between 22.235 and 58.80 GHz. These channels are sensitive to the presence of liquid water and precipitable water vapor and to the atmospheric temperature and humidity profile.

# 2.0 Contacts

## 2.1 Mentor

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## 2.2 Vendor/Instrument Developer

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info@radiometrics.com

# 3.0 Deployment Locations and History

**Table 1**. Status and location of the MWRP.

| **Serial Number** | **Property Number** | **Location** | **Date Installed** | **Date Removed** | **Status** |
|---|---|---|---|---|---|
| MP3002 | | NSA/C1 | 2004/02/19 | | Operational |
| MP3015 | | AMF1/M1 | 2005/02/11 | | Operational |
| MP3156A | | ENA/C1 | 2014/02/26 | | Operational |

# 4.0 Near-Real-Time Data Plots

Plots of near-real-time data can be viewed at the U.S. Department of Energy (DOE) Atmospheric Radiation Measurement (ARM) Climate Research Facility's DQ Explorer system accessible through the web site: http://dq.arm.gov/. Click on "QC Metrics and Plots" and select the desired site and data stream. The MWRP data stream is "sssmwrpFF.b1" where 'sss' is the site (NSA, ENA, etc.) and 'FF' is the facility (C1, M1, etc.)

# 5.0 Data Description and Examples

## 5.1 Data File Contents

Datastreams available from the ARM Archive are named: **sssmwrpFF.b1** and contain calibrated brightness temperatures and retrievals. Raw data files are available upon request; they are named sssmwrpFF.00.yyyymmdd.hhmmss.raw.yyyy-mm-dd_hh-mm-ss_lv0.csv. Data files containing the calibration results from tip curves are named sssmwrpFF.00.yyyymmdd.hhmmss.raw.yyyy-mm-dd_hh-mm-ss_tip.csv.

### 5.1.1 Primary Variables and Expected Uncertainty

The primary variables measured by the MWRP are brightness temperatures at 12 frequencies listed in the table below. By relating the observed radiances to atmospheric water vapor and liquid water it is possible to derive precipitable water vapor (PWV) and liquid water path (LWP) from the measurements. The MWRP has seven channels sensitive to emissions due to oxygen resonances (frequency band near 60 GHz). Because the mixing ratio of oxygen is invariant with altitude, the emission at each altitude depends on the local temperature; the variation of emission with frequency permits radiation from a range of altitudes to reach the instrument, thereby permitting the vertical temperature distribution to be retrieved. The emission due to water vapor varies in proportion to the water vapor density; it also depends on altitude due to the effect of pressure broadening on the line shape, thereby permitting the vertical distribution of water vapor density to be retrieved. Retrievals of integrated water vapor and liquid water path obtained from brightness temperatures as well as retrieved temperature and humidity profiles are provided in the data files together with calibrated brightness temperatures. Uncertainties in the retrieved parameters are provided in the data files as root-mean-square errors (RMSE). A more detailed analysis of retrieval uncertainties is provided here: [1]

**Table 2**. Primary variables.

| Variable Name | Quantity Measured | Unit | Uncertainty (1σ) |
|---|---|---|---|
| brightnessTemperature | sky brightness temperature at:<br>NSA/AMF1<br>22.235 23.035 23.835 26.235 30.000 51.250 52.280 53.850 54.940 56.660 57.290 58.800<br>ENA<br>22.234 23.034 23.834 26.234 30.000 51.248 52.280 53.848 54.940 56.660 57.288 58.800 | K | ~1 K |
| totalPrecipitableWater | Precipitable water vapor retrieved from 12 channels | cm | ~0.05 mm |
| totalPrecipitableWater2 | Precipitable water vapor retrieved using only 23.835 and 30.0 GHz | cm | ~0.05 cm |
| liquidWaterPath | Liquid water path retrieved from 12 channels | mm | ~0.015 mm |
| liquidWaterPath2 | Liquid water path retrieved using only 23.835 and 30.0 GHz | mm | ~0.015 cm |
| Temperature | Retrieved temperature profile | K | 1-2K through the profile |
| waterVaporDensity | Retrieved humidity profile | g/m$^3$ | ~20% through the profile |

[1] See section 7.5 for a definition of uncertainty.

### 5.1.2 Secondary/Underlying Variables

**Table 3**. Secondary variables.

| Variable Name | Quantity Measured | Unit | Uncertainty (1σ) |
|---|---|---|---|
| time | Time offset from midnight | s | |
| surfaceTemperature | Ambient temperature | K | 0.5 |
| surfacePressure | Pressure | hPa | 0.5 |
| surfaceRelativeHumidity | Relative humidity | % | 5 |
| surfaceWaterVaporDensity | Water vapor density | $g/m^3$ | - |
| liquidWaterContent | Retrieved liquid water content | $g/m^3$ | - |
| virtualTemperature | Derived virtual temperature | K | - |
| dewpointTemperature | Derived dewpoint temperature | K | - |
| waterVaporMixingRatio | Derived water vapor mixing ratio | g/kg | - |
| relativeHumidity | Derived relative humidity | % | - |
| liftingCondensationLevel | Derived lifting condensation level | m | - |
| levelFreeConvection | Derived level of free convection | m | - |
| equilibriumLevelPres | Derived equilibrium level pressure | hPa | - |
| equilibriumLevel | Derived equilibrium level | m | - |
| liftingCondensationLevelPres | Derived Lifting condensation level pressure | hPa | - |
| levelFreeConvectionPres | Derived level of free convection pressure | hPa | - |
| cape | Convective available potential energy | J/kg | - |
| infraredTemperature | Zenith-pointing infrared temperature at 10um | K | ~0.5 K |
| cloudBaseHeight | Derived cloud base height | m | - |
| wetWindowFlag | Presence of rain 1=yes 0=no | - | - |

### 5.1.3 Diagnostic Variables

The following diagnostic variables are in the sssmwrpFF.00.yyyymmdd.hhmmss.raw.yyyy-mm-dd_hh-mm-ss_tip.csv files associated with the raw datastream.

**Table 4**. Diagnostic variables.

| Variable Name | Quantity Measured | Unit | Uncertainty (1σ) |
|---|---|---|---|
| TKBB | Black body physical temperature | K | 0.2 K |
| Tnd | Instantaneous Tnd from tip curves (K-band channels) | K | 5 K |
| R | Regression coefficient (K-band channels) | - | - |
| alpha | Receiver non-linearity coefficient | - | - |
| dTdG | Receiver hardware parameter | - | - |
| K1 | First temperature correction coefficient | - | - |
| K2 | Second temperature correction coefficient | - | - |
| K3 | Third temperature correction coefficient | - | - |
| K4 | Fourth temperature correction coefficient | - | - |

### 5.1.4 Data Quality Flags

Data quality flags are named qc_'fieldname' (i.e. qc_temperature). Possible values for qc_flags are: 0 (value is within the specified range), 1 (missing value), 2 (value is less than the specified minimum), 4 (value is greater than the specified maximum), and 8 (value failed the valid "delta" check). Specified maximum and minimum values for retrieved variables are shown in Table 5.

**Table 5**. Data quality thresholds.

| Field Name | Min | Max |
|---|---|---|
| brightnessTemperature | 0 | 305 |
| temperature | 180 | 300 |
| waterVaporDensity | 0 | 18 |
| surface_temperature | 220 | 300 |
| surface_pressure | 965 | 1050 |
| surface_relative_humidity | 20 | 110 |
| surfaceWaterVaporDensity | 0 | 18 |
| totalPrecipitableWater | 0 | 4 |
| liquidWaterPath | 0 | 0.5 |

### 5.1.5 Dimension Variables

**Table 6**. Dimension variables.

| Field Name | Quantity | Unit |
|---|---|---|
| base_time | Base time in Epoch | seconds since 1970-1-1 0:00:00 0:00 |
| time_offset | Time offset from base_time | s |
| lat | north latitude | degrees |
| lon | east longitude | degrees |
| alt | altitude | meters above Mean Sea Level |

## 5.2 Annotated Examples

N/A

## 5.3 User Notes and Known Problems

A detailed evaluation of the instrument performance and capabilities is provided in [3] and is available upon request.

## 5.4 Frequently Asked Questions

This section is not yet available.

# 6.0 Data Quality

## 6.1 Data Quality Health and Status

A daily quality check on this datastream can be found at the DQ Explorer page: http://dq.arm.gov/. Click on "QC Metrics and Plots" and select the desired site and datastream. For example, for the MWRP located at the site "NSA", the datastream is "nsamwrpC1.b1" and the facility is "C1".

## 6.2 Data Reviews by Instrument Mentor

The instrument mentor submits a monthly summary report (IMMS) accessible from the instrument web page. Some of the general checks performed by the instrument mentor are shown below.

1. In general, the brightness temperature time series should be smooth and with low noise levels.
2. Brightness temperatures should be greater than 2.75 K and less than approximately 330 K.
3. External temperature readings can be compared to tower measurements. The agreement should be +/- 2 K.
4. External pressure readings can be compared to tower measurements. The agreement should be +/- 5 KPa.
5. External relative humidity readings can be compared to tower measurements. The agreement should be +/- 5%
6. Measured brightness temperatures are also compared with model computations as a general quality check.
7. Data from the rain detection system are routinely checked against other similar measurements depending on their availability at a given site.

## 6.3 Data Assessment by Site Scientist/Data Quality Office

The Data Quality Office daily data assessment can be view at the DQ Hands web page.

## 6.4 Value-Added Procedures

N/A

# 7.0 Instrument Details

## 7.1 Detailed Description

The MWRP measures sky radiances at 12 frequencies. Radiance measurements are converted to "equivalent brightness temperatures" through the calibration procedure. A complete description of the instrument can be found in [2]. Below is detailed description of the instrument components.

### 7.1.1 List of Components

- RF section: microwave radiometer MP3002, MP3015, MP3156A
- Dewblower
- Radiometer stand
- Heitronix KT15II infrared thermometer

### 7.1.2 System Configuration and Measurement Methods

In this section we give a brief description of the MWRP hardware configuration. The MWRP is composed of two heterodyne, direct double-sideband receivers. Both receivers are similar in architecture and construction, except for the frequency range covered. The channels have a bandwidth of 300 MHz and the receivers are thermally stabilized to within 0.5 C. Residual temperature dependences are corrected in the calibration procedure with the use of additional temperature coefficients. The Gaussian Optical Lens focuses the radiation into a pair of corrugated feedhorns. The Full Width Half Power beam width varies from 6.3 to 4.9 degrees for the K-band and from 2.5 to 2.4 for the V-band. The gain is monitored by periodically injecting a calibrated noise through a noise diode. In normal operation mode the radiometers observe the sky in zenith position. Zenith measurements are interrupted to collect scanning measurements used to perform the absolute calibration (tip curve). The radome is kept free of dew and water drops in drizzle conditions by a dewblower. For a complete description of the radiometer hardware, refer to the radiometer user manual [2].

### 7.1.3 Specifications

**Table 7**. Instrument specifications.

| Parameter | Value |
|---|---|
| Receiver noise temperature K-band | < 500 K |
| Receiver noise temperature V-band | < 500 K |
| Channel bandwidth K band | 300 MHz |
| Channel bandwidth V band | 300 MHz |
| Radiometric resolution | 0.1-1 K |
| HPBW K band channels | ~4.9°-6.3° |
| HPBW W band channel | ~2.4°-2.5° |
| Integration time | >=1 s |
| Operating temperature range | -50 to +50 C (Environmental Chamber tested) |
| Operating altitude range | 0 to +3000 m |

## 7.2 Theory of Operations

Absorption and emission of microwave radiation in the range 10-80 GHz are dominated by molecular water vapor and oxygen, as well as cloud liquid water. In Figure 1 [3], the absorption due to the water vapor resonance at 22.235 GHz and the band of oxygen resonances near 60 GHz is shown near the surface (solid lines) and at 2 km (dashed lines) based on the mean vertical profiles of temperature and water vapor during the summer at the U.S. Department of Energy (DOE) ARM Southern Great Plains (SGP) observatory. The absorption due to cloud liquid water at 283 K (dot-dashed line) is also presented. Because the mixing ratio of oxygen is invariant with altitude, the emission at each altitude depends on the local temperature; the variation of emission with frequency permits radiation from a range of altitudes to reach the instrument, thereby permitting the vertical temperature distribution to be retrieved. The emission due to water vapor varies in proportion to the water vapor density; it also depends on altitude due to the effect of pressure broadening on the line shape, thereby permitting the vertical distribution of water vapor density to be retrieved. The variation of liquid water absorption approximately as the square of frequency permits a coarsely resolved vertical distribution of liquid water retrieval to be attempted. The MWRP measures the microwave radiance, expressed as brightness temperature, at five frequencies near the water vapor resonance centered at 22.235 GHz and seven frequencies in the band of oxygen resonances between 51 and 59 GHz. These were selected based on an eigenvalue analysis by Solheim et al. [4] and are indicated in Figure 1 by the vertical grey lines.

Retrievals of physical variables such as integrated water vapor, cloud liquid water path, temperature and humidity profiles are derived using a statistical algorithm and are provided to the users.

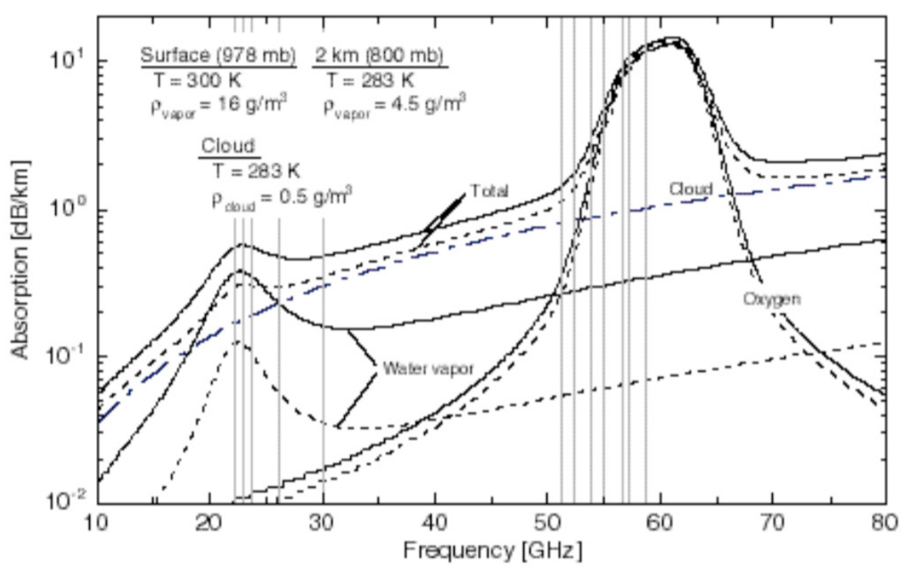


**Figure 1**. The microwave absorption spectrum for water vapor and oxygen calculated for mean summer conditions at the surface (solid) and at 2 km (broken). The cloud liquid water absorption (dot-dashed) is also given for a liquid water content of 0.5 g/m$^3$ and 283 K.

## 7.3 Calibration

### 7.3.1 Theory

The frequency-dependent microwave radiance, reported as a brightness temperature $T_B$ is the fundamental quantity measured by the radiometer. The accuracy of the brightness temperature measurements is critical to obtaining accurate retrievals of atmospheric state parameters. The measurement accuracy depends on the quality and stability of the hardware as well as on the accuracy and precision of the calibration, which can be difficult to separate.

The tipping curve method is used to provide the cold reference temperatures in the 10-90 K range necessary to calibrate the K-band channels. The tipping curve method exploits the linear relationship between optical thickness and atmospheric path length that holds when the sky is free of liquid water clouds and strong horizontal water vapor gradients to derive the zenith brightness temperature. The MWRP acquires tipping curve measurements continuously, at about 15-minute intervals. These are screened for valid sky conditions based on the linearity of the regression of optical thickness on path length (“air mass”) by requiring that the correlation coefficient exceed 0.99.

The strongly absorbing oxygen resonances in the 51-59 GHz range cause the relationship between optical thickness and absorber amount or atmospheric path length to be non-linear, which precludes the use of the tipping curve method for calibration. Instead, because the lowest brightness temperature measured at the least absorbing frequency (51.25 GHz) is about 100 K, a liquid-nitrogen-filled external target is used to provide the ~77 K cold temperature reference needed to determine $T_{nd}$. As shown in Figure 2, the external target is comprised of a very low-absorption, thick-walled StyrofoamTM container with a blackbody target placed inside on the bottom and filled with 25-30 liters of LN2. Alternating measurements of the near ambient internal and cold external targets are performed for up to an hour, or until condensation forms on the bottom of the Styrofoam container. The blower normally used to prevent dew from condensing on the polycarbonate foam window of the radiometer is activated to delay the formation of condensation on the bottom of the container. The brightness temperature measured by the MWRP when viewing the LN2 target is elevated ~2K above the boiling point of LN2, which depends on atmospheric pressure, due to a number of effects, principally reflection at the interface between the Styrofoam and LN2 (~1.7 K), the absorption of the Styrofoam (~0.2K), and the elevation of the boiling point of LN2 due to the hydrostatic pressure of the 20-cm column of LN2 above the bottom of the container (~0.2K) as discussed by Solheim [5]. Corrections for these effects are included in the calibration process.

**Figure** 2. The microwave Radiometer Profiler (MWRP) at Barrow, Alaska with the LN2-filled Styrofoam target in place during calibration of the V-band channels in September 2000.

### 7.3.2 Procedures

The calibration algorithm is based on the assumption that, although noise diodes are known to be stable over time, the effective noise diode injection temperature as determined from tip curves will eventually show some drift over a period of a few months. The radiometer equations used to calibrate the brightness temperatures are the following [2]:

$$Tsky = (Vsky/gain\_sky)^{1/\alpha} - Trcv\_sky \qquad (1)$$

*Where measured values are:*

Vsky = integrated receiver output from a sky observation with Noise Diode off

Vsky_nd = integrated receiver output from a sky observation with Noise Diode on

Vbb = integrated receiver output from an ambient Black Body target observation with Noise Diode off

Vbb_nd = integrated receiver output from an ambient Black Body target observation with Noise Diode on

TkBB = Black Body target effective radiation temperature

*Where calibrated parameters are:*

$\alpha$= non-linearity correction exponent

Tnd290 = Noise Diode temperature @ TkBB = 290K

K1-K4 = factory calibrated temperature coefficients receiver

dTdG = hardware-specific parameter

*Where calculated values are:*

gain_sky=gain during sky observation=$[(Vsky\_nd^{1/\alpha} – Vsky^{1/\alpha})/(Tnd290 + TC)]^{\alpha}$

Trcv_sky = Receiver temperature during sky observation = Trcv_bb + dTdG*(gain_sky – gain_bb)

gain_bb = gain during ambient Black Body Target observation = $[(Vbb\_nd^{1/\alpha} – Vbb^{1/\alpha})/(Tnd290 + TC)]^{\alpha}$

Trcv_bb = Receiver temperature during ambient Black Body Target observation = $(Vbb/gain\_bb)^{1/\alpha}$ – TkBB

$TC = K1 + K2*TkBB + K3*TkBB^2 + K4*TkBB^3$

### 7.3.3 History

N/A

## 7.4 Operation and Maintenance

### 7.4.1 User Manual

User manuals are provided to the site operators during the deployment stage.

### 7.4.2 Routine and Corrective Maintenance Documentation

N/A

### 7.4.3 Software Documentation

Available through the Data Management Facility or instrument mentor.

### 7.4.4 Additional Documentation

N/A

## 7.5 Glossary

**Uncertainty:** We define uncertainty as the range of probable maximum deviation of a measured value from the true value within a 95% confidence interval. Given a bias (mean) error *B* and uncorrelated random errors characterized by a variance $\sigma^2$, the root-mean-square error (RMSE) is defined as the vector sum of these,

$$RMSE = \left(B^2 + \sigma^2\right)^{1/2}.$$

(*B* may be generalized to be the sum of the various contributors to the bias and $\sigma^2$ the sum of the variances of the contributors to the random errors). To determine the 95% confidence interval we use the Student's *t* distribution: $t_{n;0.025} \approx 2$, assuming the RMSE was computed for a reasonably large ensemble. Then the *uncertainty* is calculated as twice the RMSE.

## 7.6 Acronyms

See Acronyms and Abbreviations, p. iii.

## 7.7 References

[1] Cadeddu, MP, JC Liljegren, and DD Turner. 2013. "The atmospheric radiation measurement (ARM) program network of microwave radiometers: Instrumentation, data, and retrievals," *Atmospheric Measurement Techniques* 6(9): 2359-2372, doi:10.5194/amt-6-2359-2013.

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[5] Solheim, FS. 1993. User of pointed water vapor radiometer observations to improve vertical GPS surveying accuracy. Ph.D. Thesis, University of Colorado, 128 pp.

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