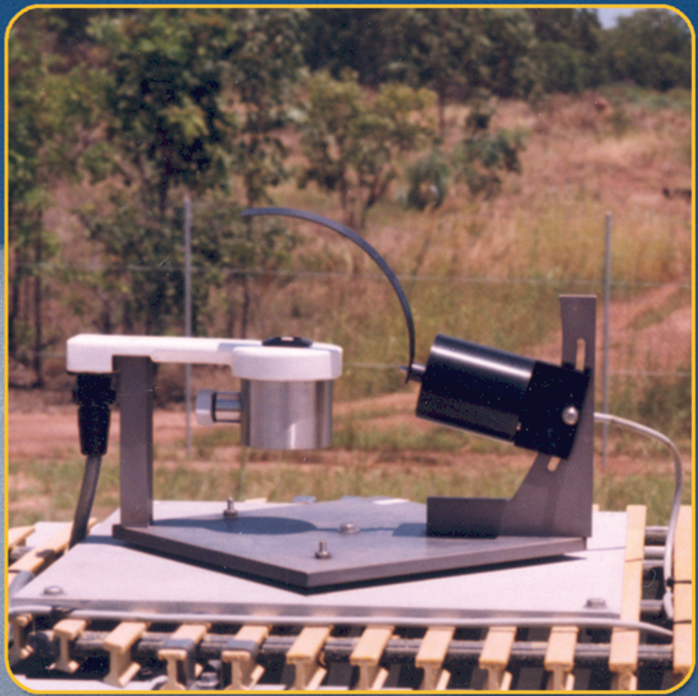
ARM TR-059

Multi-Filter Rotating Shadowband Radiometer
Handbook



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1. General Overview

The multi-filter rotating shadowband radiometer (MFRSR) takes spectral measurements of direct normal, diffuse horizontal and total horizontal solar irradiances. These measurements are at nominal wavelengths of 415, 500, 615, 673, 870, and 940 nm. The measurements are made at a user-specified time interval, usually about one minute or less. The sampling rate for the Atmospheric Radiation Measurement (ARM) Program MFRSRs is 20 seconds. From such measurements, one may infer the atmosphere's optical depth at the wavelengths mentioned above. In turn, these optical depths may be used to derive information about the column abundances of ozone and water vapor (Michalsky et al. 1995), as well as aerosol (Michalsky et al. 1994) and other atmospheric constituents.

A silicon detector is also part of the MFRSR. This detector provides a measure of the broadband direct normal, diffuse horizontal and total horizontal solar irradiances. A MFRSR head that is mounted to look vertically downward can measure upwelling spectral irradiances. In the ARM system, this instrument is called a "multi-filter radiometer (MFR)". At the Southern Great Plains (SGP) there are two MFRs; one mounted at the 10-m height and the other at 25 m. At the North Slope of Alaska (NSA) sites, the MFRs are mounted at 10 m. MFRSR heads are also used to measure "normal incidence" radiation by mounting on a solar tracking device. These are referred to as normal incidence multi-filter radiometers (NIMFRs) and are located at the SGP and NSA sites. Another specialized use for the MFRSR is the narrow field of view (NFOV) instrument located at SGP. The NFOV is a ground-based radiometer (MFRSR head) that looks straight up. Complete instrument descriptions for the MFR, NIMFR, and NFOV are available.

2. Contacts

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2.2 Instrument Developer

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3. Deployment Locations and History

Table 1. MFRSR Status as of January 1, 2005

Site	Collect Data	Ingest Data
E1 (Larned, KS)	YES	YES
E2 (Hillsboro, KS)	NO	NO
E3 (LeRoy, KS)	YES	YES
E4 (Plevna, KS)	YES	YES
E5 (Hesston, KS)	YES	YES
E6 (Towanda, KS)	YES	YES
E7 (Elk Falls, KS)	YES	YES
E8 (Coldwater, KS)	YES	YES
E9 (Ashton, KS)	YES	YES
E10 (Tyro, KS)	NO	NO
E11 (Byron, OK)	YES	YES
E12 (Pawhuska, OK)	YES	YES
E13 (Central Facility)	YES	YES
C1 (Central Facility)	YES	YES
E15 (Ringwood, OK)	YES	YES
E16 (Vici, OK)	YES	YES
E18 (Morris, OK)	YES	YES
E19 (El Reno, OK)	NO	NO
E20 (Meeker, OK)	NO	NO
E21 (Okmulgee, OK)	NA	NA
E22 (Cordell, OK)	NO	NO
E24 (Cyril, OK)	YES	YES
E25 (Seminole, OK)	NA	NA
E27 (Earlsboro, OK)	YES	YES
TWP C1 (Manus Island)	YES	YES
TWP C2 (Nauru Island)	YES	YES
TWP C3 (Darwin)	YES	YES
NSA C1 (Barrow, AK)	YES	YES
NSA C2 (Atqasuk, AK)	YES	YES

Note about the MFRSRs at the SGP Extended Facilities (EFs):

Because of limited resources, efforts to maintain operability and calibrations of MFRSRs and associated devices (MSRs, NIMFRs, and NFOVs) are concentrated on so-called "critical sites." These critical sites are the SGP Central Facility, the Tropical Western Pacific (TWP), and the NSA. Improvements and upgrades are quite limited for the MFRSRs at the SGP EFs (except E13 located at the Central Facility). Data users should use extreme caution in making assumptions about calibration stability, continuity of data, and alignments that affect the reliability of the total, diffuse, and direct irradiance components at the SGP EFs.

Many MFRSRs have been in operation going on 10 or more years and are starting to show their age. In fact, some have been removed from service pending repair (E2, E19, E20, and E22). Primarily it is the interference filters that are starting to show their age. ARM is currently in negotiations with a company to manufacture replacement filters. It is hoped this will occur in FY05. The plan is to replace the filters in every instrument when suitable filters are procured.

An engineering change request is currently in process that will replace the current MFRSR data logging system to Campbell Scientific loggers. The expectation is the Campbells will be less costly to purchase and maintain than new Yankee logger boards. Additionally, because Campbells are universally used, not only in the ARM Program but also in general, there will be more resources and support available for use with the MFRSR.

An additional motivation for the logger board change is the improved programming flexibility and sampling rate of the Campbell CR10X. Currently, the MFRSR shadowband operation mode involves aligning the instrument and several of its components very precisely and then programming the shadowband position to be set for each measurement according to solar ephemeris calculations (which are based on inputs of time, date, and latitude/longitude). If the initial instrument alignments are off or if they shift with time, the band position is then also off. This results in the diffuser not being completely shaded and consequently the measurements are erroneous. A solution to this is to allow the band position to be monitored and corrected, if necessary, based on real-time evaluation of the instrument measurements. By scanning measurements near the assumed correct shading band arm position, a jump in signal will indicate the edge of the band's proper position. This jump corresponds to when the periphery of the diffuser is seeing direct sun. Adjusting the band position several steps in the appropriate direction would ensure the diffuser is completely shaded. If the edge cannot be determined (for example, on an overcast day) the measurement is made with the band in the position that is based on the ephemeris calculation. This technique was developed and has successfully been implemented by Chuck Long for a rotating shadowband radiometer instrument he has developed. The Campbell CR10X can readily be programmed to do this and the sampling is rapid enough to permit scanning the measurements and taking the final measurement within a short period of time.

4. Near-Real-Time Data Plots

See the MFRSR General Plots.

See the MFR General Plots.

5. Data Description and Examples

5.1 Data File Contents

5.1.1 Primary Variables and Expected Uncertainty

As mentioned above, the primary quantities measured by the system are the:

1. Direct normal solar spectral irradiance (W m^{-2} nm^{-1})
2. Total horizontal solar spectral irradiance (W m^{-2} nm^{-1})
3. Diffuse horizontal solar spectral irradiance (W m^{-2} nm^{-1}).

These quantities are measured at wavelengths of 500, 615, 673, 870 and 940 nm. The measurements at each wavelength are made by a single filtered detector with a nominal 10-nm full width at half maximum) (FWHM) bandwidth.

Table 2 shows the wavelengths used in the MFRSR and the primary atmospheric constituents measured with each wavelength channel (Michalsky et al. 1995).

Table 2. Wavelengths of Narrowband (10-nm) Filters Used in the MFRSR, and Main Trace Species Measured (Michalsky et al. 1995).

Wavelength (nm)	Trace Species
415	aerosol
500	aerosol, ozone
615	aerosol, ozone
673	aerosol, ozone
870	aerosol
940	water vapor

Ozone abundances may be inferred by measurements made by the 500-, 615-, and 673-nm channels. These wavelengths, particularly 615 and 673 nm, are influenced by the Chappuis band of ozone (Goody and Yung 1989). Water vapor primarily affects the 940-nm channel. Rayleigh scattering most strongly affects the lower wavelength channels. This phenomenon is well understood and, therefore, can be removed from an analysis of the optical depth measurements made at all wavelengths.

The uncalibrated silicon detector provides a measure of the:

1. Direct normal solar broadband irradiance (counts)
2. Total horizontal solar broadband irradiance (counts)
3. Diffuse horizontal solar broadband irradiance (counts).

These quantities are uncalibrated and reported as counts. Note that the actual output of the instrument is millivolts, and the use of "counts" is historical and has been attached to the MFRSR since it was developed. The counts are linearly scaled using broadband radiometers to be roughly equivalent to W/m^2. Zhou et al. (1995) discusses the proportionality between the MFRSR broadband channels and broadband irradiances measured by the World Meteorological Organization (WMO) first-class thermopile radiometers.

5.1.1.1 Definition of Uncertainty

Note about MFRSR calibration as of May 30, 2000:

We have long suspected that the amplitude of measured irradiances from the MFRSR is sensitive to the ambient temperature. For example, if one examines a year-long time series of so-called "Ios" derived from Langley regressions a sinusoidal pattern in the time series will be seen. The period of this pattern is exactly one year and the peak of the sine wave corresponds to the warmest times of the year while the valley corresponds to the coldest times of the year.

This pattern, in itself, is not sufficient evidence to implicate sensitivity to temperature. However, we retrieved the MFRSR head associated with these data, and we put the head and logger board in an "environmental chamber" and measured the temperature responsiveness of the system. The responsiveness can be characterized by temperature coefficients for each wavelength channel; these coefficients indicate about a 1 to 2% change in MFRSR output for each 1-degree change in head temperature. Typically, the MFRSR head temperature changes about 2 degrees over a diurnal period and about 5 degrees over the year. Therefore, the potential for output fluctuations over the course of a year may be as high as -+ 5%. If we consider the atmosphere to be gray, the temperature sensitivity errors induce an equivalent broadband error of about +- 50 w/m^2 error (by contrast, a drifting filter may contribute errors on the order of 500w/m^2!!). In short, the temperature sensitivity errors may be significant.

After measuring the temperature sensitivity we devised a way to correct the data based on the measured temperature coefficients. When these corrections were applied, the sinusoidal pattern in the MFRSR Ios disappeared, and the calibration stability of the MFRSR was essentially flat over the entire year. Furthermore, the temperature-corrected MFRSR data was used to drive a broadband model and the output of this model was compared with broadband measurements. In many cases, the use of temperature-corrected MFRSR data (as opposed to the uncorrected data) caused the agreement between the model and the broadband data to improve significantly. (Note: these calculations are not yet finished, so we can't be sure this conclusion will hold). All this evidence taken together strongly suggests that the temperature sensitivity is real.

Independent evidence of the temperature sensitivity comes from MFRSR data collected as part of old, defunct, non-ARM programs in which the sinusoidal wave had been observed but not explained until now. Again, in these old data sets the peak of the sine wave occurs during the warm times of the year and the valley into coldest times of the year.

We (Pacific Northwest National Laboratory [PNNL], Yankee Environmental Systems, and Atmospheric Sciences Research Center [ASRC]) don't know what's causing this problem, and we don't know if the magnitude of the problem is different from head to head. The analysis and temperature chamber operation is costly, and we don't have the time or budget needed to get to the bottom of this problem. The data can be partially corrected by using monitoring the Ios from Langley regressions, but this is at best, an imperfect solution.

Yankee knows about this problem, and they may try to fix it (this could take a very long time).

Note about MFRSR calibration as of November 1, 1999:

Installation of new interference filters has significantly reduced the calibration drift. To date, the calibrations (for MFRSRs that contain the new filters) appear to be very stable. The new units have been installed at the E13 and C1 sites at the SGP, and at all TWP and NSA sites.

Note about MFRSR calibration as of March 11, 1998:

As of 11 March 1998, the calibration of the MFRSR is problematic. For some channels (i.e., wavelengths), the calibration drifts significantly with time. For other channels the calibration is stable but not very accurate; in some cases, the error in the spectral fluxes may be as much as 50%. The poor calibrations affect some of the flux measurements but do not affect any of the optical depths derived from the MFRSR.

5.1.2 Secondary/Underlying Variables

This section is not applicable to this instrument.

5.1.3 Diagnostic Variables

This section is not applicable to this instrument.

5.1.4 Data Quality Flags

-9999.0 signifies missing data.

See MFRSR, MFR10M, and MFR25M Data Object Design files for ARM netCDF file header descriptions.

5.1.5 Dimension Variables

This section is not applicable to this instrument.

5.2 Annotated Examples

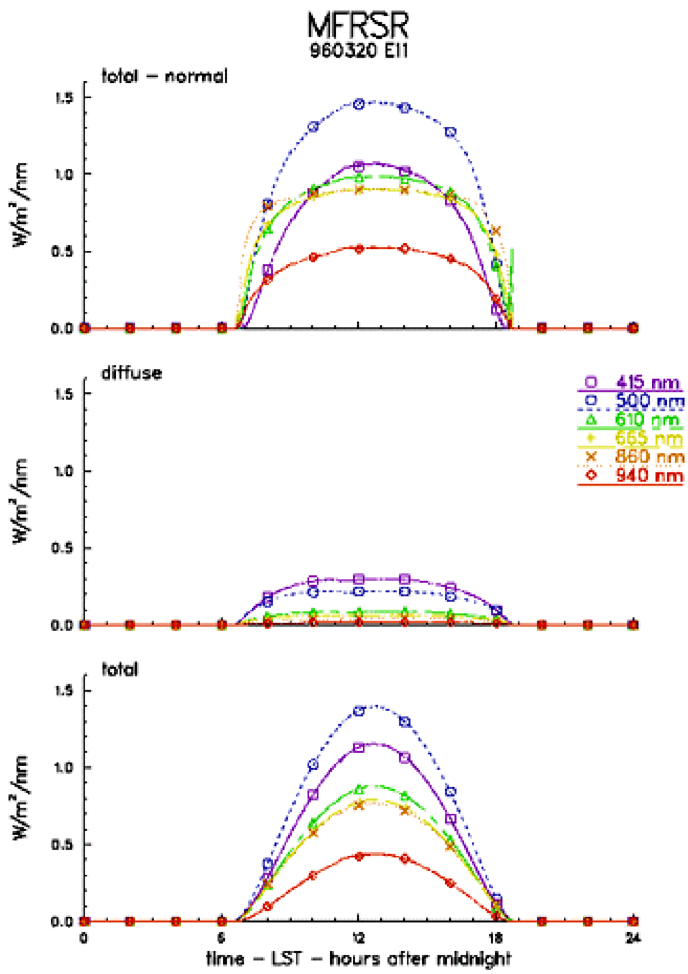

Figure 1.

5.3 User Notes and Known Problems

The MFRSR used to be part of the solar and infrared observing system (SIROS) datastream. This data-stream consisted of the MFRSR data as well as data from the broadband radiometers. Around 1997, the SIROS datastream was split in two: one stream became the "Solar Infrared Station (SIRS)," consisting of broadband data only, while the other became "MFRSR," containing only MFRSR data. For MFRSR data including 1997 and before, you will need to retrieve SIROS data from the ARM archive. These SIROS data contain a label that follows the pattern of "sgpsirosE12.a1".

5.4 Frequently Asked Questions

Currently there are no FAQs for this instrument.

6. Data Quality

6.1 Data Quality Health and Status

The following links go to current data quality (DQ) health and status results:

- DQ HandS (Data Quality Health and Status)
- NCVweb for interactive data plotting using.

The tables and graphs shown contain the techniques used by the ARM Program's DQ analysts, instrument mentors, and site scientists to monitor and diagnose DQ.

6.2 Data Reviews by Instrument Mentor

- **QC frequency**: Weekly
- **QC delay**: Up to one week
- **QC type**: Graphical plots
- **Inputs**: Raw and Processed data
- **Outputs**: Summary reports
- **Reference**:

Once a week the instrument mentor downloads both the raw and processed (NetCDF) files from the ARM Data Archive. Time series plots of the NetCDF files for each instrument (every channel) are produced and examined. In addition, the raw data files are processed independent of the ARM Archive and compared to the NetCDF files from the archive for inconsistencies. Any problems found are reported so technicians can make the appropriate repairs. Once a month the mentor submits a report summarizing the general health and status of all the MFRSRs.

6.3 Data Assessments by Site Scientist/Data Quality Office

All DQ Office and most Site Scientist techniques for checking have been incorporated within DQ HandS and can be viewed there.

6.4 Value-Added Procedures and Quality Measurement Experiments

Many of the scientific needs of the ARM Program are met through the analysis and processing of existing data products into "value-added" products or VAPs. Despite extensive instrumentation deployed at the ARM sites, there will always be quantities of interest that are either impractical or impossible to measure directly or routinely. Physical models using ARM instrument data as inputs are implemented as VAPs and can help fill some of the unmet measurement needs of the program. Conversely, ARM produces some VAPs not to fill unmet measurement needs, but to improve the quality of existing measurements. In addition, when more than one measurement is available, ARM also produces "best estimate" VAPs. A special class of VAP, called a Quality Measurement Experiment (QME), does not output geophysical parameters of scientific interest. Rather, a QME adds value to the input datastreams by providing for continuous assessment of the quality of the input data based on internal consistency checks, comparisons between independent similar measurements, or comparisons between measurement with modeled results, and so forth. For more information see, see the VAPs and QMEs web page.

An important value-added product for the MFRSR is optical depth. If the sky is sufficiently clear, an automated Langley analysis (Harrison and Michalsky 1994b) applied to each day's data provides optical depths for all spectral channels except the 940 nm channel. (This channel requires a modified Langley analysis [see Michalsky et al. 1995] that is not done as part of the routine data processing).

7. Instrument Details

7.1 Detailed Description

7.1.1 List of Components

Many of the MFRSRs deployed at the SGP site have been manufactured by PNNL. The other MFRSRs are manufactured by Yankee Environmental Systems (Model MFR-6).

7.1.2 System Configuration and Measurement Methods

The sensors associated with each wavelength are all located in a small canister capped by a level, upward looking, Lambertian diffuser. Radiation that strikes the diffuser is directed towards the sensors. These sensors consist of a single silicon photodetector for measuring broadband radiation, and a set of interference-filter-photodiode detectors for measuring spectral irradiances. The diffuser is shaded at periodic intervals by a rotating shadowband. During these intervals, the total horizontal diffuse radiation is measured for each wavelength (as well as the broadband channel). The shadowband is then moved so the diffuser is fully exposed to the sky. The total horizontal downward radiation is then measured. The difference between the total horizontal and diffuse radiation gives the downward component of the direct beam solar irradiance. From this quantity, the direct beam solar irradiance is easily calculated. The measurements are corrected for the cosine response of the diffuser/sensor assembly as well as the "excess sky" obscured by the shadowband during the diffuse radiation measurement. A detailed discussion of the instrument's measurement methods is contained in Harrison and Michalsky (1994a).

7.1.3 Specifications

The spectral irradiances are measured at or close to, the following wavelengths: 415, 500, 615, 673, 870 and 940 nm. These measurements are made over a passband of nominally 10 nm. A silicon photodiode measures broadband irradiances. These irradiances are reported in "counts" and are not calibrated per se, but rather linearly scaled to broadband instruments.

7.2 Theory of Operation

The MFRSR is an instrument that directly measures global and diffuse components of spectral solar irradiance. The direct normal component is calculated from the difference of the global and diffuse measurements. At the start of a measurement series, a global measurement is first taken. The shadowband is then rotated from the home position and stops in three positions before returning home. The first and third stops are just before and after shading the diffuser. At the second stop the diffuser is completely shaded. Measurements at the first and third stops are used to correct the error introduced by the shadowband shading a portion of the sky.

7.3 Calibration

7.3.1 Theory

ARM employs two methods for calibrating MFRSRs. Primarily a standard lamp is used to produce calibration factors for the six narrowband channels. A secondary method, often used as a check of the lamp calibrations, is a set of Langley plots. Langley plots are used to extrapolate the values that would be read if the instrument was at the top of the atmosphere (TOA). The extrapolated value I_0, representing the irradiance at the TOA, is divided by the extraterrestrial spectrum to give a calibration factor for each channel.

7.3.2 Procedures

To perform a standard lamp calibration, the MFRSR is placed in a calibration chamber and a lamp with a known spectral output is used. The known spectral distribution in (W m^{-2} nm^{-1}) is convolved with the output of each channel to produce calibration factors in (V W^{-1} m^{-2}). Langley plots can also be done for channels 415, 500, 615, 673 and 870 nm. (Channel 940 nm is a special case). On a clear day a Langley plot will give a stable I_0 for each channel when the data are extrapolated to the top-of-atmosphere (TOA). With several I_0s from clear days, an average I_0 for each channel is obtained. The average I_0 for each channel is divided by the extraterrestrial spectrum to give a calibration factor. Because water vapor is highly variable, the Langley method of calibrating is impractical for the 940-nm channel, so only lamp calibrations are performed.

7.3.3 History

A detailed calibration history of all the ARM MFRSRs is too lengthy to be given here. To date, the instrument's calibration has been driven by instrument failure; that is, when either an instrument head or board fails, the offending component is replaced with a new one that has been freshly calibrated. This constitutes a "calibration" of the instrument. (This "calibration" procedure may change in the future.)

7.4 Operation and Maintenance

7.4.1 User Manual

Not available in electronic format at this time.

7.4.2 Routine and Corrective Maintenance Documentation

Time series plots are monitored to ensure the shadowband is shading properly. If it is not shading properly, the instrument is adjusted and/or the time is set properly. Careful monitoring of the data can also reveal interference filters that are failing.

7.4.3 Software Documentation

ARM NetCDF file header descriptions may be found at MFRSR, MFR10M, and MFR25M Data Object Design Changes.

7.4.4 Additional Documentation

March 1998: The laboratory calibration of the instruments is problematic. By comparing the laboratory calibrations to an estimate of the calibrations obtained by a Langley analysis, it appears that some calibration factors can be in error by as much as 50%. The user of the MFRSR flux data should be aware that some of these data might not be very accurate.
November 1999: The lab calibrations of the MFRSR heads have significantly improved and are now being checked before field deployment by calibrations performed using the Langley method. This "pre-deployment" checking has resulted in a significant improvement in initial calibration accuracy; an estimate of this accuracy is plus or minus 4% (or maybe even a little better).

The maintenance procedures seem adequate, although some of the instruments are "out of alignment"; this lack of alignment can corrupt data taken during certain times of day.

7.5 Glossary

See the ARM Glossary.

7.6 Acronyms

ARM	Atmospheric Radiation Measurement (Program)
ASRC	Atmospheric Sciences Research Center
EF	Extended Facility
FWHM	full width at half maximum
MFR	multi-filter radiometer
MFRSR	multi filter rotating shadowband radiometer
NFOV	narrow field of view
NIMFR	normal incidence multi-filter radiometer
NSA	North Slope of Alaska
PNNL	Pacific Northwest National Laboratory
QME	Quality Measurement Experiment
SGP	Southern Great Plains
SIROS	solar and infrared observing system
SIRS	Solar Infrared Station
TOA	top of the atmosphere
TWP	Tropical Western Pacific
VAP	value-added product
WMO	World Meteorological Organization

Also see the ARM Acronyms and Abbreviations.

7.7 Citable References

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