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Multifilter Rotating Shadowband Radiometer Instrument Handbook

With subsections for derivative instruments:

Multifilter Radiometer (MFR)
Normal Incidence Multifilter Radiometer (NIMFR)

GB Hodges
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ARM CLIMATE RESEARCH FACILITY

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Office of Science, Office of Biological and Environmental Research

Acronyms and Abbreviations

AMF	ARM Mobile Facility
ARM	Atmospheric Radiation Measurement Climate Research Facility
CF	Central Facility
ESRL	Earth System Research Laboratory
GMD	Global Monitoring Division
MFR	Multifilter Radiometer
MFRSR	Multifilter Rotating Shadowband Radiometer
NIMFR	Normal Incidence Multifilter Radiometer
NOAA	National Oceanic Atmospheric Administration
NSA	North Slope of Alaska
SGP	Southern Great Plains
TWP	Tropical Western Pacific

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1.0 Instrument Overview and History

The visible Multifilter Rotating Shadowband Radiometer (MFRSR) is a passive instrument that measures global and diffuse components of solar irradiance at six narrowband channels and one open, or broadband, channel (Harrison et al. 1994). Direct irradiance is not a primary measurement, but is calculated using diffuse and global measurements. To collect one data record, the MFRSR takes measurements at four different shadowband positions. The first measurement is taken with the shadowband in the nadir (home) position. The next three measurements are, in order, the first side-band, sun-blocked, and second side-band. The side-band measurements are used to correct for the portion of the sky obscured by the shadowband. The nominal wavelengths of the narrowband channels are 415, 500, 615, 673, 870, and 940 nm. From such measurements, one may infer the atmosphere's aerosol optical depth at each wavelength. 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 (Harrison and Michalsky 1994) and other atmospheric constituents.

The MFRSR was among the original instruments deployed at the first U.S. Department of Energy Atmospheric Radiation Measurement (ARM) Climate Research Facility sites. Over time, the MFRSR network degraded to the point at which a significant number of stations that were intended to have an instrument did not. Lack of spare instruments and replacement parts were the primary reasons for the slow degradation. Around 2005, it was decided to bring the network back to full capacity. After much consideration, it was decided the best way to accomplish this was to refurbish all the heads in-house and to transition to a different data-logging system. By early 2007, the first refurbished units were deployed, and by the end of 2008, every Southern Great Plains (SGP) site that was intended to have an MFRSR had a functioning unit. The new loggers provided expanded measurement capabilities over the previously used loggers. They provide researchers with the ability to tailor instrument operation for specific measurement needs. The hardware updates and changes necessitated significant changes to the data collection and ingest software. The data files available include a host of information. MFRSR Value-Added Products have been updated. For example, ARM is now producing a high-quality, Langley-calibrated data product.

Figure 1. Visible MFRSR. This particular unit is a Yankee Environmental Systems Inc. model.

2.0 Contact Information

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Website: http://www.campbellsci.com

Instrument manual available at http://www.campbellsci.com/manuals

Yankee Environmental Systems, Inc.
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Fax: (413) 863-0255
Email: info@yesinc.com
Website: http://www.yesinc.com

Instrument manual available at http://www.yesinc.com/support/index.html#SupportDocs

3.0 Deployment Locations

Current ARM deployment locations for MFRSRs are listed in Tables 1, 2, 3, and 4. During 2009 and 2010, more than 10 SGP extended facilities were shut down, and most of those facilities had MFRSRs. The stations that were decommissioned were the farthest from the Central Facility (CF). In the future, most of the closed stations will be re-established at locations closer to the CF, although they will undoubtedly have different site names.

Table 1. Current deployments of SGP MFRSRs.

Serial Number	Internal ID	SGP Location	Installation Date	Status
Y440	$1050	C1/Lamont		Operational
B925	$AB95903	E4/Plevna	03/05/2008	Operational
Y370	$AB9ED6A	E6/Towanda	05/20/2008	Operational
B916	$AB9F0D0	E7/Elk Falls	09/24/2008	Operational
B924	$ABC5195	E9/Ashton	03/04/2008	Operational
Y344	$ABCA176	E11/Byron	07/22/2008	Operational
B902	$AB9E17D	E12/Pawhuska	08/21/2008	Operational
Y322	$ABC9CC1	E13/Lamont	02/08/2007	Operational
Y436	$AB8D992	E15/Ringwood	03/06/2008	Operational
Y346	$AB9E987	E16/Vici	03/12/2008	Operational
Y345	$ABB7202	E19/El Reno	03/13/2008	Operational
Y227	$ABD3A2B	E20/Meeker	08/01/2008	Operational

Table 2. Current deployments of the North Slope of Alaska (NSA) MFRSR.

Serial Number	Internal ID	Location NSA	Installation Date	Status
240	$AB9F142	C1/Barrow		

Table 3. Current deployments of Tropical Western Pacific (TWP) MFRSRs.

Serial Number	Internal ID	Locations TWP	Installation Date	Status
347	$AB8E068	C1/Manus	02/19/2010	Operational
	$ABBFAC4	C2/Nauru	03/16/2010	Operational
	$ABC9F8E	C3/Darwin	01/08/2010	Operational

Table 4. Current deployments of ARM Mobile Facility (AMF) MFRSRs.

Serial Number	Internal ID	Locations AMF	Installation Date	Status
B914	$F460	GRW/M1		Operational
B917	$0DB7	GRW/S1		Operational
	$ABBF984	SBS/M1	11/03/2010	Operational
	$BB5D	SBS/S1	12/02/2010	Operational

4.0 Near-Real-Time Data Plots

Near-real-time data plots can be accessed via the ARM Data Quality Health and Status (DQ HandS) plot browser at http://plot.dmf.arm.gov/plotbrowser/.

5.0 Data File Contents

The MFRSR currently produces data at the .00, .b1, .c1, and .s1 data levels. Below is a very brief summary of the different data levels.

- .00 – Raw data, straight from the instrument
- .b1 – Lamp-calibrated data
- .c1 – Langley-calibrated data and aerosol optical depth information
- .s1 – A subset of the .c1 level data. Most users should find this sufficient.

For a detailed listing of the file contents at each data level, go to https://engineering.arm.gov/tool/dod/showdod.php?Inst=mfrsr&View=user

6.0 Links to Definitions and Relevant Information

6.1 Datastream

http://www.arm.gov/data/datastreams/mfrsr

6.2 Data Object Description

https://engineering.arm.gov/tool/dod/showdod.php?Inst=mfrsr&View=user

6.3 Data Plots

http://www.archive.arm.gov/arm/armql.jsp?id=mfrsr

6.4 Data Quality

The following link goes to current data quality health and status results: http://dq.arm.gov/.

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

6.5 Instrument Mentor Monthly Summary

http://www.db.arm.gov/IMMS/IMMSView.php?inst=mfrsr

7.0 Instrument Technical Specification

7.1 MFRSR Head Refurbishment

With one exception, all the MFRSRs deployed by ARM have been completely refurbished. The only original parts are the aluminum case, and in a few instances the original diffuser is still used. The refurbishment of each includes:

- New filter detectors and electronics
- Relocated internal thermistors
- New connectors
- Gain resistors moved to head
- Improved insulation
- New Spectralon® diffuser.

Perkin-Elmer is the vendor ARM contracted with to produce the filters and assemble the filter detectors. The printed circuit boards that are assembled into a cube, which in turn house the detectors, were manufactured by Douglas Electronics, Inc. The assembly of the cubes with filter detectors was performed by a shop in Richland, Washington. Final assembly of the heads was performed by John Schmelzer at Pacific Northwest National Laboratory. Currently, heads are still being refurbished, though on a much smaller scale. Refurbishment is performed as needed by Mark Klassen at the SGP CF.

7.2 Campbell Scientific Data Logger

Along with the refurbishment of the instrument heads, ARM decided to replace the original data logger with Campbell Scientific data loggers. The model chosen is the CR1000. The new logging system provides programming flexibility that was not possible in the past. The original logger, which also doubles as an instrument controller, is constrained in a few ways. Primarily, its programming flexibility is limited. While sampling rates and averaging periods can be changed, the fundamental instrument operation is locked. Additionally, there are some measurements that are collected, but only used internally, and that cannot be captured for analysis.

The incorporation of the CR1000 opens up the operational possibilities of the MFRSR, either for innovative research or merely to improve the accuracy of the principal measurements. To date, ARM has focused primarily on replicating the function of the original logger, rather than moving into innovative operations. While focusing on the operational basics, ARM has taken advantage of the ability to log all the data produced by the instrument. In particular, with the CR1000 we are now able to record the data from the side-band measurements, the sun-blocked measurement, and both head thermistors. The side-band measurements (the measurements taken just before and after the sun-blocked measurement) have proven interesting. With those data we can see the impact that rapidly changing sky conditions have on the final values.

A convenient benefit of the CR1000 that was not initially considered is its ability to hold a program in non-volatile memory. This means a system can be set up and a program loaded while still in the laboratory. Then, when the instrument is put in its operational position and the data logger is turned on, it will start functioning. Furthermore, in the event of power loss the program is preserved, and the instrument will begin functioning once power is re-established. This has proven beneficial over the original logger that must be initialized, either with a local computer or remotely, after every power loss.

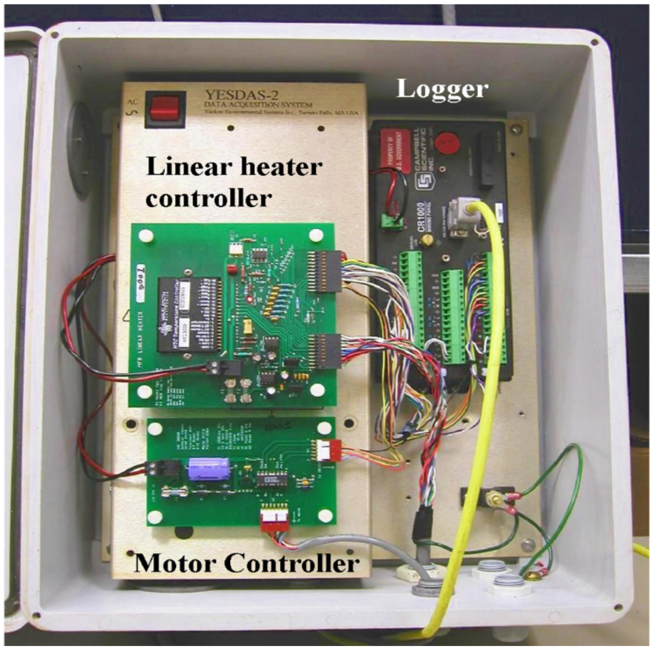

Figure 2. Logger and system controller boards that comprise the new logging system for ARM MFRSRs. Shown in this picture are the CR1000 data logger, the proportional (linear) heater controller, and the motor controller.

7.3 Linear Heater Controller

The original MFRSR logger is also the instrument controller responsible for the shadowband movement and regulation of the head temperature. (The term "logger" refers to both the logging and instrument controller functionality). The MFRSR head is designed to be operated near 40°C. The original logger uses the "bang-on/bang-off" method for regulating the head temperature. That is, when the temperature drops below 40°C, it turns on and heats at 100% effort until 40°C is reached, then the heat shuts completely off. This style of heat regulation has the unfortunate aspect of creating electromagnetic frequency interference with the irradiance measurements. To overcome this problem, the original logger is designed to give the irradiance measurements priority, and thus will stop the heater regardless of the head temperature when a measurement is made. The result of the bang-on/bang-off heating of the head is the creation of a "saw tooth" trace of head temperature.

When the new logging system was designed, the bang-on/bang-off method of head temperature control was dropped in favor of proportional heating. As the name implies, the proportional heater operates continuously, regardless of the timing of irradiance measurements. The new controller is able to control the heating based on the difference between the temperature and the set point, and the result is a much more stable head temperature. There is no longer a saw tooth pattern in the temperature trace, and the variation of head temperature through the day is miniscule. Electromagnetic frequency interference is not an issue when the head is at operating temperature, as there is no surge associated with the heater turning off and on.

7.4 Motor Controller

As has been stated, the original MFRSR logger is responsible for logging data and instrument control. When designing the Campbell-based MFRSR logger and instrument controlling system, it was necessary to build a controller for the shadowband motor. In general, a stepper motor controller is a basic device, so minimal explanation is required. However, there are two points worth mentioning. First, the new motor controller has proven very robust. To date there have been no failures of this part. Second, the current system moves the motor in half-step increments, just as the original logger did. While sufficient, this relatively coarse stepping increment can make for a frustrating experience when adjusting the shadowband. Each half-step increment moves the band 0.45 degrees. It takes the sun about 108 seconds to move that amount. This means that the shadowband only moves to a new position every five or six sampling intervals, which are started at 20-second intervals. If the shadowband is adjusted either right after or just before the shadowband moves to a new position, a shading issue can occur in the morning or afternoon. With the new Campbell systems, it is possible to build a motor controller that will move the current MFRSR shadowband motor in one-eighth steps (i.e., 0.225 degrees). Even finer stepping is possible, but stepping at 0.225 degrees would all but eliminate the shadowband adjusting issue just described.

8.0 Technical Specifications

8.1 Units

The fundamental measurements are made in millivolts.

8.2 Range

± 250 millivolts

8.3 Accuracy

0.06% of 250 millivolts, i.e., 0.15 millivolts

8.4 Repeatability

33.3 µvolts (if differential measurement)

8.5 Uncertainty

0.06% of 250 millivolts

8.6 Input Voltage

Excitation voltage for thermistors is 5 volts

8.7 Input Current

1 nano-ampere (typical)

9.0 Instrument System Functional Diagram

Figures 3 and 4 are functional and cut-out diagrams of a visible MFRSR. The main components are the head that houses the filter detectors and amplification circuitry; the stepper motor with shadowband; and the mounting frame. The instrument is set up with the motor aligned toward the Equator. The stepper motor and shadowband alternately cover and uncover the diffuser, allowing measurements of global (sometimes called total) and diffuse irradiance at six narrowband channels and one open channel to be made. Direct irradiance is calculated from the global and diffuse measurements.

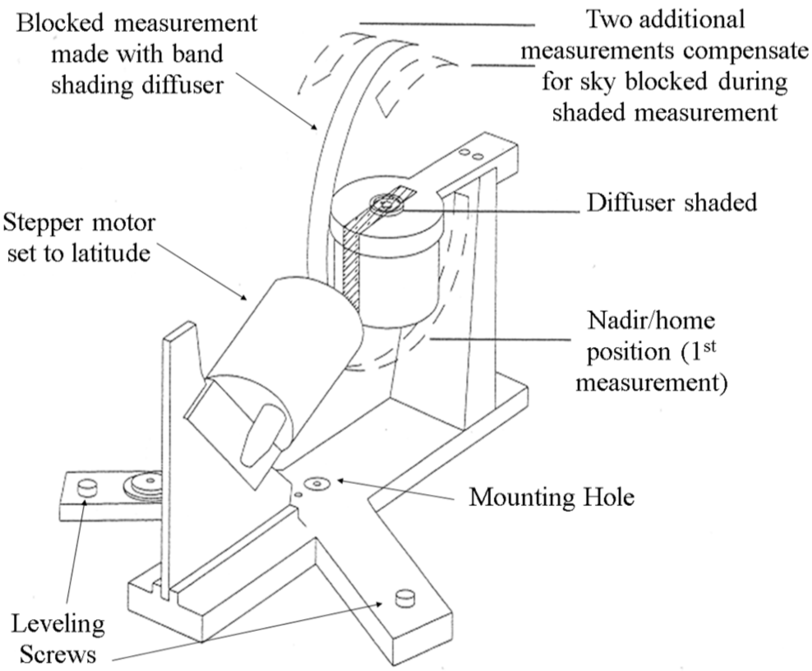

Figure 3. Functional diagram of a visible MFRSR.

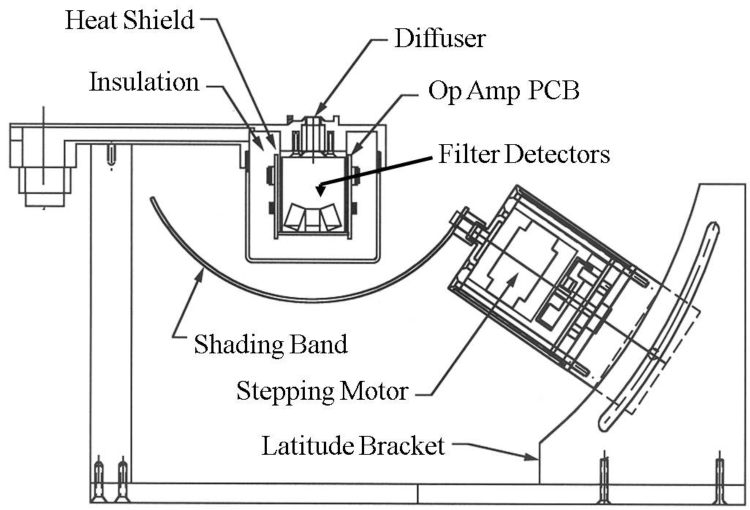

Figure 4. Cut-out view of the MFRSR.

10.0 Instrument/Measurement Theory

The MFRSR is often thought of as a sun photometer, but that is an incorrect characterization. The reason for the confusion is that the most commonly considered datastream produced by the MFRSR is direct beam irradiance. With a sun photometer, the direct beam is a principal measurement. The MFRSR, however, derives the direct beam from its principal measurements. It is a passive radiometer that measures solar energy in six narrowband channels and one broadband channel. For each sample, the following four measurements are taken.

1. The initial measurement taken while the shadowband is in the home position out of the 180° field of view. Sometimes called the nadir, or unblocked, measurement.
2. Next, the first of two side-band measurements is taken. The two side-band measurements are used to correct for the signal lost due to the portion of the sky obscured by the shadowband during the following measurement.
3. Then, the sun-blocked measurement is taken. This is the measurement taken while the shadowband's shadow is cast over the diffuser.
4. Finally, the second side-band measurement is taken. When this last measurement is completed, the shadowband then returns to the home position.

With the core measurements described, we now turn to the corrections that are applied. They are the cosine, diffuse, and offset corrections. Each of these corrections is described below:

- The cosine correction is necessary because the instrument has a varying response to the irradiance incident depending on the direction of the solar disc. When the sun is directly overhead, the theoretical cosine correction is one. The cosine correction is determined in the laboratory with a cosine bench. Briefly, the cosine bench consists of a lamp, a collimating tube, and an indexing plate to which the MFRSR head is mounted. Instrument output is measured at 1° intervals between -90° and 90° in both the south-north direction and the west-east directions. The results are used to build a cosine response correction file.

- When considering the diffuse correction, we can think about the cosine correction for the direct beam. The diffuse irradiance has the same cosine issue, but the energy arrives at the diffuser from all directions, not from a single point like the direct beam. The correction is found by modeling a Rayleigh sky with input from the SolarInfo (cosine response) file. It has been found that using an isotropic sky for the determination produces a value within one percent of actual sky conditions. As the diffuse correction is small, it is not worth the effort to determine a correction for each data point based on current sky conditions.
- The offset correction is necessary to correct for inherent bias in each sensor. While under normal operations, nighttime data are averaged to produce the offset correction for the following day. It is expected the offset will vary with time; therefore it was decided to calculate the offset on an ongoing basis rather than relying on a single value determined during the standard lamp calibration. Using nighttime data also accounts for the offset of the entire system, not just the head. It should be noted that, for the total and diffuse irradiance measurements, it is important to account for the offsets. For the calculation of the direct beam, it is possible to ignore the offset because it cancels out in the calculation.

Below we go through a few of the equations used for processing raw MFRSR data to show how the corrections described above are implemented.

10.1 Definitions

blk = sun-blocked measurement[1]

cordif = cosine-corrected diffuse measurement

cordirhor = cosine-corrected direct horizontal

corth = corrected total horizontal calculated using cordirhor and cordif

dif = sideband-corrected sun-blocked measurement

dirhor = vertical component of the direct beam on a horizontal surface

fsb = first side-band1

ssb = second side-band1

th = total horizontal

10.2 Equations

Dif = blk + [th -(fsb + ssb)/2]

Dirhor = (th - offset) - (dif - offset) = th - dif = th - blk - [th - (fsb + ssb)/2] = (fsb + ssb)/2 - blk

Cordif = dif/(diffuse cosine correction derived from SolarInfo file)

Cordirhor = dirhor/(cosine correction from SolarInfo file)

[1] Note that these are not available as output values from the previously used data loggers. These quantities can be and are captured with the Campbell data logging systems.

Corth = cordif + cordirhor

Offsets are an inherent part of the measurements. Because the direct is calculated and the offsets for the th, fsb, ssb, and blk are the same, the offsets cancel out. Cosine corrections used in the calculation of corrected direct horizontal (cordirhor) are found by running the instrument in the laboratory on a cosine bench.

11.0 Setup and Operation of Instrument

The instrument should be mounted on a stable post or platform in a location with as few obstructions as possible. Perfect sites are not usually found, so a compromise is almost always required that takes into account instrument access and obstructions such as trees and buildings. Ideally, there will be no site obstructions that cast a shadow over the instrument at any time during the day.

Once a suitable location is found, the instrument is mounted, usually on a metal plate. The instrument must be mounted with the motor toward the Equator and aligned north-south. The shadowband motor is adjusted so that its angle is set to the local latitude. These alignments are necessary for the ephemeris calculation to work properly. Setting the motor to the site latitude dispenses with the need for a coordinate transformation in the ephemeris calculation. Finally, the shadowband is adjusted, ideally at solar noon, so that it is shading the diffuser squarely at the sun-blocked shadowband stop.

It should be noted that more recent versions of the MFRSR available from Yankee Environmental Systems employ a different method for mounting the motor and adjusting the shadowband. For these instruments, identified by three motor mounting holes on the vertical motor bracket, please consult the Yankee manual. The ARM Facility does not currently operate any of these newer versions.

12.0 Software

All the software used by ARM for the MFRSR data collection and processing was produced within the ARM organization. The one exception is the AMF2, which uses LoggerNet from Campbell Scientific for the data collection.

13.0 Calibration and Characterization

Before being deployed, each instrument head is run through the SGP calibration facility. This includes a standard lamp calibration, cosine response determination, and a mapping of the spectral response function of each filter detector (i.e., the filter function). The lamp calibration is considered to be a nominal calibration because it is less accurate than the Langley calibration, but it provides a good laboratory estimate. Once deployed in the field, and with enough data collected, the instrument is Langley-calibrated. The nominal calibration data are found in the .b1 data files, and Langley-calibrated data are contained in the .c1 data files.

While Langley calibrations are superior to lamp calibrations, they cannot be performed for the 940 channel because of the highly variable nature of water vapor in the atmosphere. Because of this, each head is returned to the SGP calibration facility annually for lamp calibration. When the heads are brought back for standard lamp calibrations, they also are run through the cosine and spectral benches.

14.0 Maintenance

The MFRSR is a low-maintenance instrument. Although its setup is challenging, once properly deployed, the only regular maintenance required is cleaning the Spectralon diffuser, which should be performed as frequently as reasonably possible. Depending on the site location, ARM MFRSRs are cleaned from once daily to once every two weeks. In heads that include desiccant holders, the desiccant should be checked monthly and replaced as necessary.

15.0 Safety

The MFRSR is a passive instrument, and as such does not have any unusual safety issues. It is powered by 120 VAC, and as such, field technicians need to be aware of basic electrical safety procedures when performing maintenance. When replacing parts, the power should be shut off first.

16.0 Derivative Instruments

The instruments described in this section are all derivatives of the MFRSR. The information in each subsection is intended to describe the differences between that instrument and the MFRSR. Otherwise, the information provided above for the MFRSR also applies.

16.1 Normal Incidence Multifilter Radiometer (NIMFR)

The NIMFR is a sun photometer in the strict sense. It uses the same electronics cube and sensors as found in a MFRSR, but mounted in a collimating tube instead. The NIMFR must be mounted on a solar tracking device so that it can be pointed at the sun throughout the day. All ARM NIMFRs currently use the older-style data loggers for data collection and temperature control. Currently ARM only fields NIMFRs at two sites: the SGP CF in Oklahoma and the North Slope of Alaska (NSA) Barrow site. Before being shut down in December 2010, the NSA Atqasuk site also operated a NIMFR.

Pros:

- Because it points at the sun, there is no need to determine and correct for instrument cosine errors.
- There is no shadowband associated with the NIMFR; therefore, it never has “shading issues” that are relatively common with MFRSRs.
- It produces “cleaner” data at high solar zenith angles because it points at the sun.

Cons:

- It must be mounted on a solar tracking device. This adds to the expense and effort to deploy a NIMFR.
- The NIMFR does provide total or diffuse irradiance.
- It is a custom-built instrument, and its availability is currently very limited.

16.2 Multifilter Radiometer (MFR)

In its most basic sense, the MFR is simply the head of a MFRSR mounted on a tower and pointed at the surface. It measures the reflected irradiance at the same nominal wavelengths as the MFRSR. ARM currently operates several MFRs. Two are located at the SGP CF: one located at the 25-meter level of the 60-meter tower and the other mounted at 10 meters on the same tower as the E13 instruments. The NSA Barrow site operates an MFR. Before the NSA Atqasuk site was decommissioned in December 2010, an MFR operated there. The new sites in Alaska and the Azores (Oliktok Point and Graciosa Island) each run an MFR. The MFR located at Barrow (as well as the unit that was at Atqasuk) are slightly different than the units at SGP. The internal electronics and sensors are the same, but are contained in a custom housing that provides more substantial insulation and facilitates mounting on a tower.

ARM also has an MFR mounted on the Cessna that flies out of the Ponca City, Oklahoma, airport. Mounting on the aircraft required no additional modifications to the sensor. All the specifications for the MFRSR/MFR will hold true for the Cessna instrument as well. The datastream for this instrument includes parameters that are not included with stationary instruments. These parameters are associated with the aircraft,—that is, elevation, direction, speed, etc.

17.0 Citable References

Harrison, L, J Michalsky, and J Berndt. 1994. “Automated multifilter rotating shadow-band radiometer: An instrument for optical depth and radiation measurements.” *Applied Optics* 33(22):5118-5125, doi:10.1364/AO.33.005118.

Harrison, L, and J Michalsky. 1994. “Objective algorithms for the retrieval of optical depths from ground-based measurements.” *Applied Optics* 33(22):5126-5132, doi:10.1364/AO.33.005126.

Michalsky, JJ, JC Liljegren, and LC Harrison. 1995. “A comparison of sun photometer derivations of total column water vapor and ozone to standard measures of same at the Southern Great Plains Atmospheric Radiation Measurement site.” *Journal of Geophysical Research* 100(D12):25,995-26,003, doi:10.1029/95JD02706.

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