NOAA Technical Memorandum OAR GMD-16

A REVIEW OF REFERENCE RADIATION SCALE TRANSFER TO BROADBAND GLOBAL SW PYRANOMETERS IN USE BY THE NOAA/GMD SOLAR RADIATION PROGRAM AND ITS PREDECESSORS

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A Review of Reference Radiation Scale Transfer to Broadband Global SW Pyranometers In Use by the NOAA/GMD Solar Radiation Program and its Predecessors 1977-2004

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1.0 Introduction

This report reviews the history of nineteen broadband solar shortwave (2π steradian field-of-view) sensors (pyranometers) used for measurements of downwelling short wave solar irradiance by the NOAA/Global Monitoring Division (GMD) and its predecessors, the CMDL (Climate Monitoring and Diagnostics Laboratory) and the GMCC (Geophysical Monitoring for Climatic Change), for the period 1977 through 2004, as presented in Dutton et al., 2006. Monitoring locations discussed in Dutton et al., 2006 include the four NOAA baseline observatories: Pt. Barrow Alaska; Mauna Loa Observatory on the island of Hawaii, the Samoa Observatory located in American Samoa on the island of Tutuila, the CAF (Clean Air Facility) at Amundson-Scott Station Antarctica, plus the NOAA /Solar Radiation Facility (SRF) in Boulder, Colorado. For the duration of the time series (1977-2004) each sensor was regularly compared with calibrated standards traceable to a consistent internationally adopted radiometric reference scale, either via side-by-side on-site comparisons with a calibrated traveling standard pyranometer or exchanged with a calibrated sensor and returned to Boulder for recalibration at the NOAA/SRF.

A data archive on magnetic media of all historical SRF data collected for calibration purposes at the NOAA/SRF since 1977 was used in the preparation of this report with the intention of documenting the stability and precision of NOAA radiometric reference(s), and verifying the historical radiometric scale transfers to NOAA/GMD pyranometers.

2.0 Pyranometer Description

The serial numbers of the nineteen pyranometers used at NOAA/GMD field sites and the SRF for downwelling solar irradiance measurements during the period (1977-2004) are listed in Table 1. The pyranometers in Table 1 are representative of sensor designs from the early 1970s. All sensors except one were manufactured by EPLAB and differ only in exterior appearance and

minor detector design. All are thermopile based detectors of optical radiation. The F3 type pyranometers were originally purchased for the NOAA/GMCC program in 1973 and initial responsivity values assigned to these pyranometers were provided by the manufacturer, EPLAB, or via side-by-side comparisons with other standards. For example, a few of the pyranometers in Table 1 were also part of a group of fifteen new pyranometers purchased in early 1973 for the NOAA/GMCC program and participated in an intercomparison of radiometers during April 1973 in Miami, Florida in preparation for the Global Atlantic Tropical Experiment (GATE) project. Results of this intercomparison (Hanson and Latimer, 1973) were also used in preparation of this report. The GATE comparison results for the group of GMCC pyranometers are also documented in the 1973 GMCC Annual Report. Another group of pyranometers, the Eppley Model II D1 series were acquired by the SRF in 1990. These sensors incorporated an extended temperature compensation range plus a slightly different thermopile design and were well suited for high latitude measurement locations such as Barrow and Antarctica. Responsivities assigned to these sensors all originated via calibrations at the SRF. Two Eppley Model PSP radiometers and the Spectro Lab serial number 73-36 were originally part of the SRF instrument inventory added to the GMCC sensor inventory in 1985.

Pyranometer Serial Numbers	
Model	**Serial Number**
Eppley Model II	8029D1
Eppley Model II	8038D1
Eppley Model II	8045D1
Eppley Model II	8046D1
Eppley Model II	8047D1
Eppley Model II	8048D1
Eppley Model II	11050F3
Eppley Model II	12263F3
Eppley Model II	12269F3
Eppley Model II	12270F3
Eppley Model II	12271F3
Eppley Model II	12272F3
Eppley Model II	12273F3
Eppley Model II	12274F3

Pyranometer Serial Numbers	
Eppley Model II	12276F3
Eppley Model II	12616F3
Eppley Model PSP	14861F3
Eppley Model PSP	15952F3
Spectro Lab Model 15	73-36

Table 1. Serial numbers of pyranometers used for downwelling solar irradiance measurements at GMD baseline stations and the SRF during the period 1977-2004.

3.0 NOAA Radiometric Scale Maintenance and Traceability 1975-2005

All responsivities assigned to sensors discussed in this report are referenced to the absolute radiometric scale, realized through a methodology set forth (Brusa and Fröhlich, 1974) and adopted by the WMO/CIMO (World Meteorological Organization/Committee on Instruments and Methods of Observation) (CIMO VII, 1978). As a result of the CIMO document, a World Standard Group of cavity radiometers was established. The averaged value of irradiances measured with the standard group of radiometers is the designated international reference, the WRR (World Radiometric Reference). Historical information and documentation regarding the origin, implementation and maintenance of the absolute scale, the World Standard Group (WSG) of radiometers and the World Radiometric Reference (WRR), can be found in the following list of references, which is intended to be informative and not a comprehensive history (Kendall and Berdahl, 1970; Fröhlich et al., 1970; Willson, 1972, 1973; Fröhlich, 1973; Brusa and Fröhlich, 1974; Fröhlich, 1977; Fröhlich, 1984; Fröhlich, 1991; Philipona, 2000).

The WSG is maintained at the PMOD/WRC (Physikalisch-Meteorologisches Observatorium Davos /World Radiation Center) in Davos Switzerland and is the primary means for realizing the absolute irradiance scale designated by the WMO as the international reference for solar irradiance measurements. Although some of the original WSG cavity radiometers are no longer in the original group and new additions to the group have been made during the past thirty years, historical relationships to the absolute scale and the original WSG group have been continuously documented and systematically updated to establish and preserve the long term stability of the WRR (Fröhlich, 1977, 1984, 1991).

Performance history for the NOAA reference radiometer with the longest historical

traceability to the WSG is shown in Table 3. The historical departures and the standard deviations for TMI67502 from the WRR for the past seven IPCs beginning with IPC IV in 1975 through IPC X in 2005 are also summarized in Table 2. (WRCD Reports #58, #94, #137, #162, #188, #197, IOM 91,WMO/TD 1320). As evidenced in the table, the averaged differences between the WRR and NOAA cavity TMI67502 during the past thirty years after more than 3500 irradiance measurements recorded during seven IPCs, is on the order of 0.09 percent, with an averaged standard deviation of 0.19 percent. Stability of the absolute scale as realized by the WSG over multi-decade time scales has been established and accepted. The precision demonstrated by an individual NOAA absolute radiometer compared with the WSG during the past thirty years has consistently exceeded the stated absolute uncertainty of the radiometers themselves (Kendall and Burdahl, 1970; Willson, 1973).

Ratios of NOAA/ESRL/GMD Reference Cavity TMI Model MKVI 67502 to WRR 1975-2005				
IPC Year	**TMI67502 Ratio to WRR**	**Standard Deviation in %**	**Departure from WRR in %**	**Number of Observations**
IV 1975	1.000400	0.210	0.034	1678
V 1980	1.002786	0.600	0.278	96
VI 1985	1.001530	0.140	0.153	434
VII 1990	0.999610	0.130	-0.039	373
VIII 1995	1.001340	0.130	0.134	239
IX 2000	1.000340	0.090	0.034	219
X 2005	1.000530	0.090	0.053	255
30 Year Averages:	**1.000934**	**Avg: 0.190%**	**Avg: 0.092%**	**Total: 3591 Comparisons to WRR during 30 years**

Table 2. Results from seven IPCs summarizing the performance of NOAA cavity radiometer serial number 67502

4. NOAA/GMD Pyranometer History

Using original data from the historical SRF archive but employing current methods of assigning responsivities, an examination of the GMD pyranometers used for broadband downwelling solar irradiance monitoring from 1977-2004 was undertaken to reveal any scale transfer artifacts, to verify the originally assigned responsivities and, if necessary, to retroactively adjust responsivity values based on current SRF practice as of 2005.

Two primary techniques used for directly transferring a radiometric scale to a pyranometer are

the sun/shade method and the component summation method. A report summarizing these two calibration techniques as practiced at the NOAA/SRF has been published (Nelson, 2000). Component summation and the sun/shade procedures are still used but advances in instrumentation and methodology have been implemented since the report was published. Two significant advances have been addition of zero-offset corrections for single-black-detector type pyranometers (Michalsky et al., 1999; Dutton et.al., 2001; Haeffelin et al., 2001) and the use of pyranometers with black-and-white detector design for measurement of diffuse sky radiation (Dutton et. al., 2001)

With respect to GMD downwelling solar irradiance measurements, the period 1977 through 2004 consists of two operational modes. During the period 1977 through 1986, individual field sensors were compared on site with a traveling-standard pyranometer (Eppley Model II Ser. 12617F3) that was sent to the GMCC field sites on an approximately annual schedule. Ratios of the in-situ field sensors to the traveling standard were used to detect evidence of drifts in field sensor responsivity relative to the traveling standard. These ratio changes were then linearly interpolated over time to adjust the irradiance time series. Beginning in 1985, field sensors were exchanged with sensors calibrated at the NOAA/SRF in Boulder. The exchanges were scheduled biennially, and have continued to date. In each case, any changes in responsivities evident after a post-calibration were assumed to vary linearly with time-in-field and thus pre- and post-deployment responsivities were linearly interpolated over the time-in-field for scaling sensor signals into irradiances. A chronological deployment history for the nineteen sensors used at the five sites mentioned earlier in this report is summarized in Table 3. The table contains starting and ending times at respective sites for each sensor by serial number, and the pre-deployment and post-deployment responsivity values assigned to the sensor.

5. Results

The NOAA/SRF cavity radiometer reference examined in this report has demonstrated stable and repeatable precision and accuracy relative to the absolute radiation scale for over thirty years. Data confirming this performance has accumulated through participation in the past seven International Pyrheliometer Comparisons (IPCs), conducted every five years since 1975 at the

Table 3. (see label at the end of the table for explanation)

		Station ID				
		BRW	BLD	MLO	SMO	SPO
Exchanges 1977-2004		12	2	7	13	6
Start yr0		1976	1977	1976	1976	1976
Start doy0		1	159	1	1	1
Start hr0		0	0	0	0	0
	X					
Ser.# on	1	12263	73-36	12616	12273	12271
Start rspnv	1	9.32	7.84	7.74	9.04	10.45
Start rspnvB	1	9.32	8.01	7.74	9.04	10.45
End yr	1	1984	1978	1986	1982	1988
End doy	1	340	208	171	33	20
End hr	1	0	0	0	0	5
End rspnv	1	8.87	8.03	7.09	8.31	10.25
Ser # on	2	12263	73-36	12616	12276	12272
Start rspnv	2	9.32	8.03	7.09	9.95	9.32
Start rspnvB	2	8.87	8.03	7.09	9.80	9.32
End yr	2	1986	1983	1989	1986	1990
End doy	2	160	365	152	160	336
End hr	2	0	0	2	21	22
End rspnv	2	8.84	8.02	7.04	9.20	9.21
Ser. # on	3	12263	73-36	12271	12276	12269
Start rspnv	3	8.84	8.02	10.25	8.81	9.85
Start_rspnvB	3	8.84	8.02	10.25	9.20	9.85
End yr	3	1989	1988	1992	1986	1994
End doy	3	19	181	301	330	341
End hr	3	22	0	21	1	2
End rspnv	3	8.68	7.83	9.85	9.14	9.57
Ser. # on	4	12263	73-36	8038	12276	12270
Start rspnv	4	9.32	7.83	6.38	9.95	8.55
Start rspnvB	4	8.68	7.83	6.38	9.14	8.55
End yr	4	1989	1994	1994	1989	1999
End doy	4	54	237	102	164	19
End hr	4	22	0	19	0	14
End rspnvB	4	8.68	7.74	6.43	8.79	8.82
Ser # on	5	12263	73-36	12271	12274	8046
Start rspnv	5	8.68	7.74	9.85	9.12	6.63
Start rspnvB	5	8.68	7.74	9.85	9.12	6.63
End yr	5	1991	1999	1996	1989	2002
End doy	5	32	244	317	182	315
End hr	5	1	0	21	1	21
End rspnv	5	8.63	7.64	9.66	9.12	6.48

Table 3. Con't

Ser# on	6	12263	73-36	8047	12274	8045
Start rspnv	6	8.63	7.64	6.42	9.95	5.73
Start rspnvB	6	8.63	7.64	6.42	9.95	5.73
End yr	6	1993	2004	2002	1989	
End doy	6	25	208	355	318	
End hr	6	0	0	21	0	
End rspnv	6	8.47	7.58	6.07	9.12	
Ser# on	7	12263	73-36	11050	12274	
Start rspnv	7	8.47	7.58	6.74	9.12	
Start rspnvB	7	8.47	7.58	6.74	9.12	
End yr	7	1993			1992	
End doy	7	182			266	
End hr	7	0			2	
End rspnv	7	8.45			8.50	
Ser# on	8	12263			8029	
Start rspnv	8	8.47			6.70	
Start rspnvB	8	8.45			6.70	
End yr	8	1996			1995	
End doy	8	15			223	
End hr	8	0			2	
End rspnv	8	8.12			6.42	
Ser.# on	9	12263			8048	
Start rspnv	9	8.12			6.05	
Start rspnvB	9	8.12			6.05	
End yr	9	1998			1996	
End doy	9	9			183	
End hr	9	0			1	
End rspnv	9	8.29			6.01	
Ser# on	10	12263			14861	
Start rspnv	10	8.29			8.74	
Start rspnvB	10	8.29			8.74	
End yr	10	2001			1999	
End doy	10	27			218	
End hr	10	0			2	
End rspnv	10	7.90			8.06	
Ser# on	11	12263			8029	
Start rspnv	11	7.90			6.40	
Start rspnvB	11	7.90			6.40	
End yr	11	2003			2002	
End doy	11	5			46	
End hr	11	0			3	
End rspnv	11	7.65			6.22	
Ser. # on	12	12263			15952	

Table 3. Con't

Start rspnv	12	7.65			9.07	
Start rspnvB	12	7.65			9.07	
End yr	12				2004	
End doy	12				238	
End hr	12				1	
End rspnv	12				9.07	
Ser #on	13				21408	
Start rspnv	13				8.35	
Start rspnvB	13				8.35	

Table 3. Chronology of deployment and responsivity determinations for pyranometers used at the five sites of the NOAA/GMD downwelling solar radiation program, 1977-2004. The first six rows in the table give column heading and time series starting date information. The following seven rows contain relevant information for each indexed instrument deployment at a given site. Included are some redeployments of the same instrument due to in-situ recalibrations, or in the case of Barrow, cycling of the sensors back to the SRF during the annual winter dark period. The first row of the group of seven is identified as "Ser. # on" and is the serial number of the instrument for which information in the following six rows applies while online at the station named in the column heading. The second row in the group, labeled "Start rspnv" is the pyranometer responsivity value that was initially applied to the data when first processed, in near-real-time, from raw voltages into engineering units of watts per square meter. These scaled irradiance values constitute the long-term GMD initial archive of solar irradiance data and served as a starting point for the results reported by Dutton et al., 2006. The third row of the group is labeled "start rspnB" and is the re-determined value of irradiance that should have been used in the initial data scaling. Differences occur because the wrong responsivity had been entered into field data systems or that other adjustments had occurred in the responsivity assigned to an instrument at the time of its field deployment. The ratio of "Start_rspnv" to "Start_rspnB" provides a correction to the initial archived data. The three rows labeled "End_yr, Doy, and Hr" give the date (year and day of year) and time (GMT) that the instrument for a given deployment was removed from field service or when the succeeding information in the table is no longer valid. The last row of each group, labeled "End_rspn", contains the post-deployment responsivity value assigned to the instrument after a respective deployment. The column labeled "X" is a counting index for the number of deployments at that field site, initialized to one for each site. The irradiances in the initial data archive were corrected by interpolation between "Start_rspnB" and "End_rspn" after being adjusted for the ratio of "Start rspn" to "Start rspnB." The next line in the table is for the subsequent instrument deployment at that site, and the index X, is incremented accordingly. This file is maintained and updated as recalibrated instruments are deployed and as post-deployment calibrations are completed and adjustments to previously applied responsivities are determined. The responsivity values in this table are those used to process the time series of solar irradiances presented in Dutton et al., 2006.

World Radiation Center in Davos, Switzerland (WRCD, 1976, 1981, 1986, 1991, 1996, 2001, 2006). Transfer of the absolute scale from NOAA reference radiometers to field instruments at the NOAA/SRF was examined for nineteen pyranometers used during the past thirty three years for continuous monitoring of downwelling solar irradiance at five GMD sites. A SRF data archive beginning in 1977 was used to re-evaluate responsivities for this group using current SRF methods, measurement systems, and analysis systems to compare with historical sensor records. Table 4 contains a listing of the pre- and post- deployment responsivity values originally assigned to each pyranometer and pre- and post- deployment responsivity values obtained by reprocessing archived SRF data using present SRF methods.

Original and verified responsivities for the group of pyranometers discussed in this report are summarized in Table 4 for each documented exchange of sensors at the respective field sites. It should be noted that in some cases an exchange did not involve a physical exchange of sensors. In these instances, clerical errors involving sensor data were corrected and documented as an apparent exchange since responsivity values were altered. It is also important to note that in the early decades of the irradiance record, sensor responsivity values were entered manually into site data acquisition systems by site personnel. This procedure became a potential source for data entry errors, and when these errors were discovered, methods to correct the irradiance data records were performed. As data acquisition systems as well as digital data processing and archiving hardware and software improved, only raw sensor voltages were recorded and all scaling of field data into engineering units was performed in Boulder instead of at field sites. These advances coupled with web based near real time access to data streams from each field site have contributed to improved long term data quality.

As stated earlier in this report, historical SRF data were used to re-evaluate responsivity values assigned to the group of pyranometers listed in Table 2. This process is summarized in Table 4. If the instances where data entry errors resulted in apparent sensor exchanges are ignored, and discussion is restricted to deployments that were correctly initiated and concluded, the recomputed responsivities can be compared with original values assigned.

Serial #	Orig_Pre_Cal	Orig_Post_Cal	Verified_Pre_Cal	Verified_Post_Cal
8029	6.70	6.42	6.74	6.51
8029	6.40	6.22	6.44	6.19
8038	6.38	6.43	6.40	6.35
8045	5.73	(on site)	5.77	(on site)
8046	6.63	6.48	6.74	6.63
8047	6.42	6.07	6.37	6.08
8048	6.05	6.01	5.95	5.94
11050	6.74	(on site)	6.74	
12263	9.32	8.87	9.32	8.90
12263	8.87	8.84	8.90	8.88
12263	8.84	8.68	8.88	8.86
12263	8.68	8.68	8.86	8.86
12263	8.68	8.63	8.86	8.75
12263	8.63	8.47	8.75	8.75
12263	8.47	8.45	8.75	8.67
12263	8.45	8.12	8.67	8.50
12263	8.12	8.29	8.50	8.46
12263	8.29	7.90	8.46	8.41
12263	7.90	7.65	8.41	8.35
12263	7.65	(on site)	8.35	(on site)
12269	9.85	9.57	10.02	9.57
12270	8.55	8.82	8.40	8.80
12271	10.45	10.25	10.45	10.25
12271	10.25	9.85	10.15	10.02
12271	9.85	9.66	9.75	9.66
12272	9.32	9.21	9.72	9.66
12273	9.04	8.31	9.27	8.31
12616	7.74	7.09	7.74	7.09
12616	7.09	7.04	7.09	7.02
14861	8.74	8.06	8.74	8.05
15952	9.07	9.07	9.04	8.60
21408	8.35	(on site)	8.63	(on site)
73-36	8.01	8.03	8.05	8.03
73-36	8.03	8.02	8.03	8.02
73-36	8.02	7.83	8.02	7.83
73-36	7.83	7.74	7.83	7.74
73-36	7.74	7.64	7.74	7.64
73-36	7.64	7.58	7.64	7.58
73-36	7.58	(on site)	7.58	(on site)

Table 4. A listing of responsivities for pyranometers used for collection of GMD downwelling solar irradiance record, 1977-2004.

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List of Acronyms and Abbreviations

ARL Air Resources Laboratory

BRW Barrow GMD Observatory

BSRN Baseline Surface Radiation Network

CIMO Commission for Instruments and Methods of Observation

CMDL Climate Monitoring and Diagnostics Laboratory

DOC Department of Commerce

EPLAB Eppley Laboratory

ERL Environmental Research Laboratories

GMCC Geophysical Monitoring for Climatic Change

IPS International Pyrheliometric Scale

MLO Mauna Loa Observatory, Hawaii

Mv millivolt

NOAA National Oceanic and Atmospheric Administration

NRIP New River Intercomparison of Pyrheliometers

OAR Office of Oceanic and Atmospheric Research

SMO Samoa CMDL Observatory

SPO South Pole CMDL Observatory

sr steradian

SRF Solar Radiation Facility

STAR Solar and Thermal Atmospheric Radiation

TMI Technical Measurements Incorporated

WMO World Meteorological Organization

WMO/TD WMO/Technical Directive

WRCD World Radiation Center Davos

WRR World Radiometric Reference

WSG World Standard Group