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Preface

This report describes procedures developed at the National Renewable Energy Laboratory to assess broadband solar radiation data that were employed in the analyses of Integrated Surface Irradiance Study (ISIS), Surface Radiation Budget Network (SURFRAD), and Solar Radiation Research Laboratory Baseline Measurement System (SRRL-BMS) irradiance from 2002 through 2013. Data in each network's native resolution and hourly averages of the data were tested. The percentage of the data that passed quality tests was calculated for each site and month and is illustrated for each network and year. These plots are used to compare the overall data quality between the ISIS and SURFRAD networks. Statistics for the SRRL-BMS, which is recognized as a high-quality site, are used in each plot as a standard for comparison.

Acknowledgments

The Integrated Surface Irradiance Study and Surface Radiation Budget Network solar radiation data used in this study were provided by the National Oceanic and Atmospheric Administration's Earth System Research Laboratory through its Global Monitoring Division website,[1] from which information about these networks and links to download the data are available.

[1] See http://www.esrl.noaa.gov/gmd/grad/.

List of Acronyms

BMS	Baseline Measurement System
DHI	diffuse horizontal irradiance
DNI	direct normal irradiance
DQMS3	Data Quality Management System v.3
GHI	global horizontal irradiance
ISIS	Integrated Surface Irradiance Study
NIP	normal incidence pyrheliometer
NREL	National Renewable Energy Laboratory
PSP	precision spectral pyranometer
SRRL	Solar Radiation Research Laboratory
SURFRAD	Surface Radiation Budget Network

Executive Summary

This report provides analyses of broadband solar radiometric data quality for the National Oceanic and Atmospheric Administration's Integrated Surface Irradiance Study (ISIS) and Surface Radiation Budget Network (SURFRAD) solar measurement networks. The data quality of these networks is compared to that of the National Renewable Energy Laboratory's Solar Radiation Research Laboratory Baseline Measurement System (SRRL-BMS) native data resolutions and hourly averages of the data from the years 2002 through 2013. This report describes the solar radiometric data quality testing and flagging procedures and the method used to determine and tabulate data quality statistics. Monthly data quality statistics for each network were plotted by year against the statistics for the SRRL-BMS. Some of the plots are presented in the body of the report, but most are in the appendix. These plots indicate that the overall solar radiometric data quality of the SURFRAD network is superior to that of the ISIS network and can be comparable to SRRL-BMS.

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1 The Ground Stations

The quality of global horizontal irradiance (GHI) and direct normal irradiance (DNI) from seven Integrated Surface Irradiance Study (ISIS) and seven Surface Radiation Budget Network (SURFRAD) stations were compared to data from the National Renewable Energy Laboratory's (NREL's) Solar Radiation Research Laboratory Baseline Measurement System (SRRL-BMS) for the years from 2002 through 2013. The single criterion for the selection of the data for this comparison was that the station should still be in operation though 2013. The SURFRAD station in Sioux Falls, South Dakota, came online in mid-June of 2003; the other 13 stations were in operation prior to 2002.

1.1 The ISIS Network

The National Oceanic and Atmospheric Administration's Earth System Research Laboratory's Global Monitoring Division operates the ISIS network. There have been 10 stations in the network, three of which dropped out prior to 2013 and were not included in this analysis.

From 1995 through 2001, the ISIS network was operated by the National Oceanic and Atmospheric Administration's Air Resources Laboratory's Atmospheric Turbulence and Diffusion Division. In early 2002, the National Oceanic and Atmospheric Administration's former Surface Radiation Research Branch (now Earth System Research Laboratory) took over operation of the network and changed the data format and resolution (15-minute data) to approach the SURFRAD format of 3-minute averages over 1-second data.

1.1.1 Station Locations

From 1995 to the present, there have been 10 ISIS stations. Each is located in a different state in the contiguous United States, and not all of them have been in existence at the same time. Seven were still in operation in 2013 and were included in this analysis. These 7 ISIS stations and their coordinates and elevations are listed in Table 1.

Table 1. ISIS Stations

Name	Code	Latitude	Longitude	Elevation
Albuquerque, New Mexico	ABQ	35.04° N	106.62° W	1,617 m
Bismarck, North Dakota	BIS	46.77° N	100.77° W	503 m
Hanford, California	HNX	36.31° N	119.63° W	73 m
Madison, Wisconsin	MDN	43.13° N	89.33° W	271 m
Salt Lake City, Utah	SLC	40.77° N	111.97° W	1,288 m
Seattle, Washington	SEA	47.68° N	122.25° W	20 m
Sterling, Virginia	STE	38.98° N	77.47° W	85 m

Three historical ISIS station locations were not used in this study: Desert Rock, Nevada; Tallahassee, Florida; and Oak Ridge, Tennessee. The site in Desert Rock was operated as an ISIS station from July 1995 through September 1998. It was recommissioned as a SURFRAD station in March 1998. It continued to provide data in the ISIS format and in the SURFRAD format

through September 1998. The Tallahassee ISIS station was in operation only from February 1 through October 30, 2002, less than a full year. The ISIS site in Oak Ridge ran from February 1, 2002 through June 8, 2007.

1.1.2 Data Resolution and Availability

ISIS data are available in two native resolutions: 15-minute data from station start-up through November 2001 and 3-minute data from February 2002 to the present (Table 2.)

For this analysis, only the 3-minute ISIS data and hourly averages calculated by NREL were employed. ISIS data may be downloaded from the ISIS network website.[2]

Table 2. ISIS Data Resolution and Availability

Station Code	Resolution (minute)	Dates Used in This Study	Measurements and Instruments Used
ABQ	3	2/2002–Present	GHI-PSP[a] DNI-NIP[b] DHI-8-48[c]
BIS	3	2/2002–Present	GHI-PSP DNI-NIP DHI-8-48
HNX	3	2/2002–Present	GHI-PSP DNI-NIP DHI-8-48
MDN	3	2/2002–Present	GHI-PSP DNI-NIP DHI-8-48
SEA	3	2/2002–Present	GHI-PSP DNI-NIP DHI-8-48
SLC	3	2/2002–Present	GHI-PSP DNI-NIP DHI-8-48
STE	3	2/2002–Present	GHI-PSP DNI-NIP DHI-8-48

[a] precision spectral pyranometer
[b] normal incidence pyrheliometer
[c] diffuse horizontal irradiance

1.2 The SURFRAD Network

SURFRAD was established in 1993 with the primary purpose "to support climate research with accurate, continuous, long-term measurements of the surface radiation budget over the United

[2] See http://www.esrl.noaa.gov/gmd/grad/isis/index.html.

States" ("Surface Radiation Budget Monitoring" 2014).[3] The SURFRAD network is operated by the National Oceanic and Atmospheric Administration's Earth System Research Laboratory's Global Monitoring Division.

1.2.1 Station Locations

Stations in seven locations comprise the SURFRAD operating network: Montana, Colorado, Illinois, Mississippi, Pennsylvania, Nevada, and South Dakota. These stations and their coordinates and elevations are listed in Table 3.

Table 3. SURFRAD Stations

Name	Code	Latitude	Longitude	Elevation
Bondville, Illinois	BND	40.05° N	88.37° W	230 m
Table Mountain, Boulder, Colorado	TBL	40.13° N	105.24° W	1,689 m
Desert Rock, Nevada	DRA	36.63° N	116.02° W	1,007 m
Fort Peck, Montana	FPK	48.31° N	105.10° W	634 m
Goodwin Creek, Mississippi	GWN	34.25° N	89.87° W	98 m
Pennsylvania State University, Pennsylvania	PSU	40.72° N	77.93° W	376 m
Sioux Falls, South Dakota	SXF	43.73° N	96.62° W	473 m

The site in Desert Rock, Nevada, was an ISIS station from July 1995 through September 1998; it was recommissioned as a SURFRAD station in March 1998. It continued to provide data in the ISIS format and the SURFRAD format through September 1998.

1.2.2 Data Resolution and Availability

SURFRAD data are available in two native resolutions: 3-minute data from station start-up through 2008 and 1-minute data from January 1, 2009, onward (see Table 4).

[3] See http://www.esrl.noaa.gov/gmd/grad/surfrad/surfpage0.html.

Table 4. SURFRAD Data Resolution and Availability

Station Code	Resolution (minute)	Dates Used in This Study	Measurements and Instruments Used
BND	3 1	1/1/2002–12/31/2008 1/1/2009–to Present	GHI-Spectrolab SR-75 pyranometer DNI-NIP DHI-8-48
TBL	3 1	1/1/2002–12/31/2008 1/1/2009–Present	GHI-Spectrolab SR-75 pyranometer DNI-NIP DHI-8-48
DRA	3 1	1/1/2002–12/31/2008 1/1/2009–to Present	GHI-Spectrolab SR-75 pyranometer DNI-NIP DHI-8-48
FPK	3 1	1-1/2002–12/31/2008 1/11/2009–6/17/2009	GHI-Spectrolab SR-75 pyranometer DNI-NIP DHI-8-48
GWN	3 1	1/1/2002–12/31/2008 1/2009–Present	GHI-Spectrolab SR-75 pyranometer DNI-NIP DHI-8-48
PSU	3 1	1/1/2002–12/31/2008 1/1/2009–Present	GHI-Spectrolab SR-75 pyranometer DNI-NIP DHI-8-48
SXF	3 1	6/15/2003–12/31/2008 1/1/2009–Present	GHI-Spectrolab SR-75 pyranometer DNI-NIP DHI-8-48

Both 3- and 1-minute SURFRAD data and their hourly averages were used in this analysis. SURFRAD data can be downloaded from the SURFRAD network website.[4]

[4] See http://www.esrl.noaa.gov/gmd/grad/surfrad/index.html.

1.3 NREL's SRRL-BMS

NREL's SRRL is located on South Table Mountain in Golden, Colorado. The SRRL-BMS presently collects 1-minute solar and meteorological data from approximately 70 instruments. The 24-hour automated collection of basic solar measurements began on July 15, 1981, and continued through June of 1983. After a 16-month hiatus, data collection began again in late October 1984 and has been continuous since.

Table 5. NREL's SRRL-BMS

Name	Code	Latitude	Longitude	Elevation
SRRL-BMS, Golden, Colorado	BMS	39.74° N	105.18° W	1,829 m

Table 6. SRRL-BMS Data Resolution and Availability

Station Code	Dates Used in This Study	Measurements and Instruments Used
1, 60	1/1/2002–12/31/2003	GHI-ventilated PSP, zenith-angle-based responsivity function DNI-NIP on Sun-Follower III tracker DHI-ventilated CM22 with shading disk
1,60	1/1/2004–12/31/2005	GHI-ventilated PSP, zenith-angle-based responsivity function DNI-CH1 on Sci-Tec tracker DHI-ventilated PSP with shading ball, thermal correction applied
1,60	1/1/2006–8/31/2008	GHI-ventilated CM22 DNI-NIP on Sun-Follower III tracker DHI-ventilated CM22 with shading disk
1,60	9/1/2008–5/31/2012	GHI-ventilated CM22 DNI-NIP on Sci-Tec tracker[a] DHI-ventilated CM22 with shading disk
1,60	6/1/2002–12/31/2013	GHI-ventilated CM22 DNI-NIP on Sci-Tec tracker DHI-ventilated 8-48 with shading ball

[a] Prior to October 1, 2008, this NIP was on a Sun-Follower III tracker.

SRRL-BMS data can be downloaded from NREL's Measurement and Instrumentation Data Center website.[5]

The map in Figure 1 illustrates the distribution of the solar measurement stations used in this study. ISIS station locations are depicted by bright green dots, SURFRAD stations are represented by blue dots, and the SRRL-BMS is indicated by the red dot.

[5] See http://www.nrel.gov/midc/.

Figure 1. Map showing the locations of the solar measurement stations used in this study

2 Solar Radiometric Data Quality Assessment

To compare solar data from different networks or those from different sites within the same network, it is first necessary to determine the quality of the data from each site independently. To assess the quality of solar broadband radiation data, NREL developed software called SERI QC to test and flag the broadband solar radiometric data point by point.

2.1 SERI QC Concepts

SERI QC is a suite of tests developed to assess solar broadband radiometric data quality point by point. It was developed for use with 1-minute to 60-minute data. SERI QC has been used successfully to assess the quality of data from sites worldwide. For example, the U.S. Department of Energy's Atmospheric Radiation Measurement program has adopted SERI QC to test and flag broadband solar radiation data from its various installations around the world. SERI QC has also been implemented in solar measurement networks in Korea and Saudi Arabia and for data from the World Meteorological Organization's Global Atmosphere Watch archived at the World Radiation Data Centre.

2.1.1 K-space

To assess the quality of solar radiation data, SERI QC compares measured GHI, DNI, and diffuse horizontal irradiance (DHI) data to expected values. Defining the expected *absolute* values of solar parameters in regard to quality assessment is made difficult by the natural variations of solar radiation with time of day, season, and latitude. For these reasons, the SERI QC algorithm and software use unitless values that have been normalized with respect to extraterrestrial radiation. These unitless parameters are defined in the following expressions:

$$Kn = I_n/I_o \tag{1}$$

$$Kt = I_t / (I_o \cos Z) \tag{2}$$

and

$$Kd = Id / (Io \cos Z) \tag{3}$$

where

- I_o = extraterrestrial direct normal radiation
- I_n = direct normal radiation at the earth's surface
- I_t = total global horizontal radiation at the earth's surface
- I_d = diffuse horizontal radiation at the earth's surface
- $I_o \cos Z$ = extraterrestrial radiation on a surface parallel to the earth's surface
- Z = solar zenith angle
- Kn = direct beam transmittance
- Kt = clearness index or effective global horizontal transmittance
- Kd = effective diffuse horizontal transmittance.

Note that in K-space extraterrestrial radiation equals 1.0.

If all three components of solar radiation—GHI, DNI, and DHI—have been measured, the relationship between their K-values is expressed as:

$$Kt = Kn + Kd \tag{4}$$

From this relation, a theoretical value for any one of the K-space components can be calculated and compared to the K-value of its measured counterpart. Equation 4 is the K-space equivalent of the more familiar relation among the three solar radiation components in Equation 5:

$$GHI = DHI + DNI * \cos Z \tag{5}$$

Working in K-space, days, weeks, months, or even years of data can be plotted on a single graph, allowing patterns to become clear to the human eye. In Figure 1, hourly data for the years from 1977 through 1980 from the National Oceanic and Atmospheric Administration's station in Tallahassee, Florida, are plotted on a single K-space diagram: all hours of the day, all days of the month, and all months of the year for each of those 4 years are represented in the plot. The dashed lines in the figure represent the maxima of the expected values for Kt and Kn for Tallahassee, Florida; the solid lines around the bulk of the data points further reduce the range of expected values. Both were determined from the distribution of the data in the plot. The diagonal blue line divides the K-space into theoretically possible and impossible regions. It is theoretically impossible for data points to lie to the left of the diagonal line, because this would mean that Kn is greater than Kt, which would mean, in turn, from Equation 4 that Kd is negative.

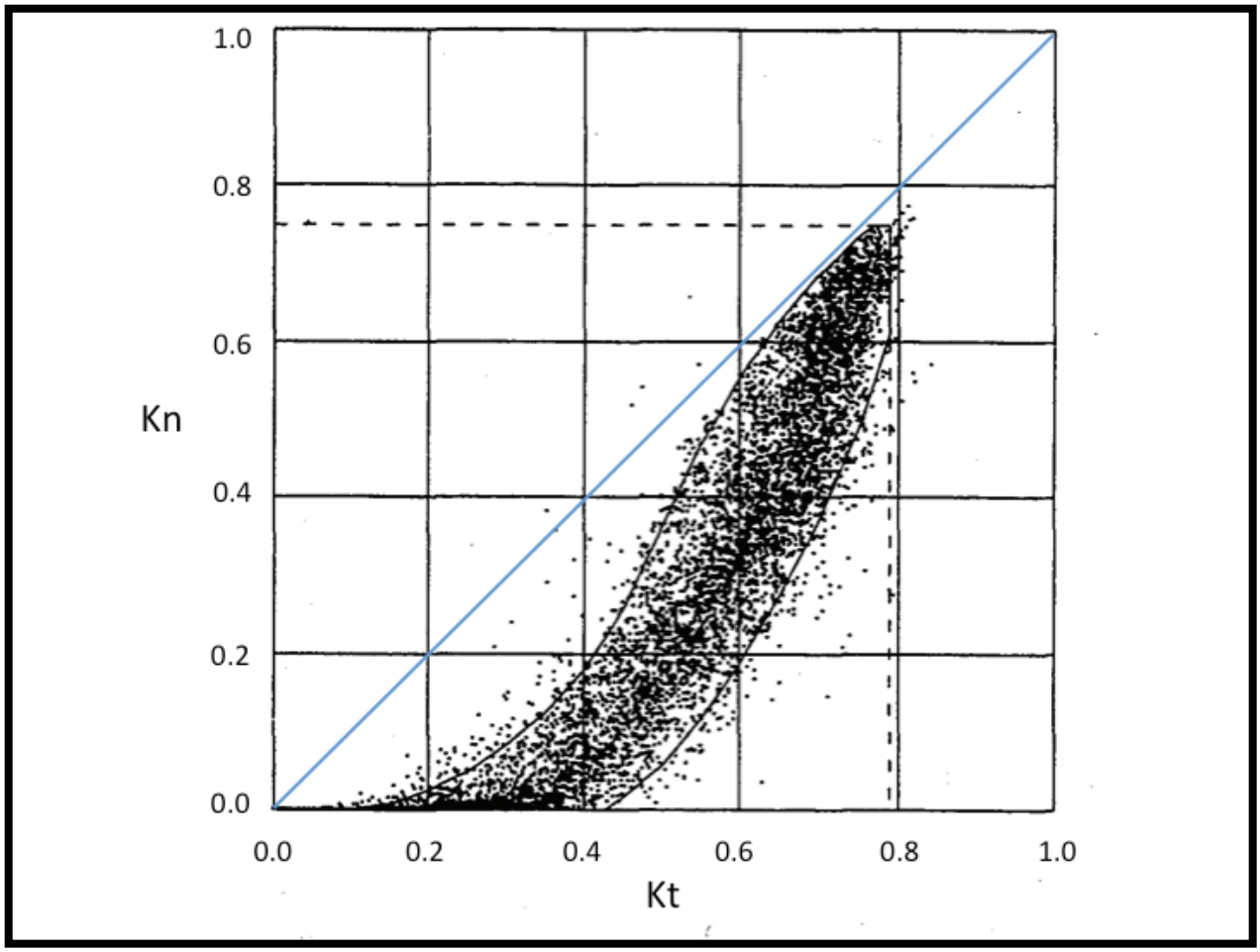

Figure 2. Solar radiation data from 1977 through 1980 for the National Oceanic and Atmospheric Administration's station in Tallahassee, Florida, plotted in K-space. ***Image re-created from Figure 4-1 in Maxwell, Wilcox, and Rymes 1993***

The effects of all atmospheric conditions experienced at Tallahassee from the years 1977 through 1980 are represented in Figure 2. As might be expected, the effects of seasonal variation in the weather and the changes in solar insolation with the seasons should be discernable in K-space, but such effects cannot be distinguished from one another in a plot including data from all seasons and atmospheric conditions together.

2.1.2 Gompertz Function

To better capture the effects of seasonal and climate differences, K-space maxima and boundaries are determined for a site for each of 12 calendar months. Further, to capture the effects of solar zenith angle on solar radiation, the data are classed within each month by air mass regime. The three air mass regimes used in SERI QC are shown in Table 7.

Table 7. Air Mass Regimes Used in SERI QC

Air Mass Regime	Air Mass Range	Solar Zenith Angle (°)
Low	1.00–1.25	0.00–36.96
Medium	1.25–2.50	36.96–66.57
High	2.50–5.76	66.57–80.00

Up to three sets of maxima and boundaries may be set for each month, one for each air mass regime available in the month. For middle- and high-latitude sites, there may be only two sets of maxima and boundaries for the winter months: medium and high air mass. For very-high-latitude sites, there may be only one set of maxima and boundaries for the winter months: the high air mass set. For sites within the Arctic and Antarctic circles, of course no solar data is available during the winter months.

These monthly sets of maxima and boundaries are called Gompertz curves and are described by the double exponential called the Gompertz equation:

$$Kn = A * B^{C*B^{D*Kt}} \tag{6}$$

The boundaries of solar data plotted in K-space take on an "S" shape, as shown in Figure 1. The Gompertz function takes on shapes similar to these K-space boundaries, and the effect of each of the four coefficients—A, B, C, and D—makes the Gompertz function ideal for setting boundaries for solar radiation data plotted in K-space. Coefficient A sets the asymptotic value for Kn; B places the inflection point of the curves along the Kn axis; coefficient C does the same for the inflection point along the Kt axis; and D determines the slope of the curve at the inflection point. Figure 3 illustrates the effects of each of the coefficients on the shape and position of the Gompertz function.

A set of six curves for the left boundary and a set of five for the right boundary were determined to be sufficient for hourly data and for the range of climate and atmospheric conditions found in the United States. Differences in air mass, elevation, and atmospheric conditions can bring about a change in the position of boundaries along the Kt axis. To account for this, a family of curves spaced at increments of 0.025 along the Kt axis has been defined for each boundary shape. Figure 4 depicts the family of curves for the left boundary shape 1.

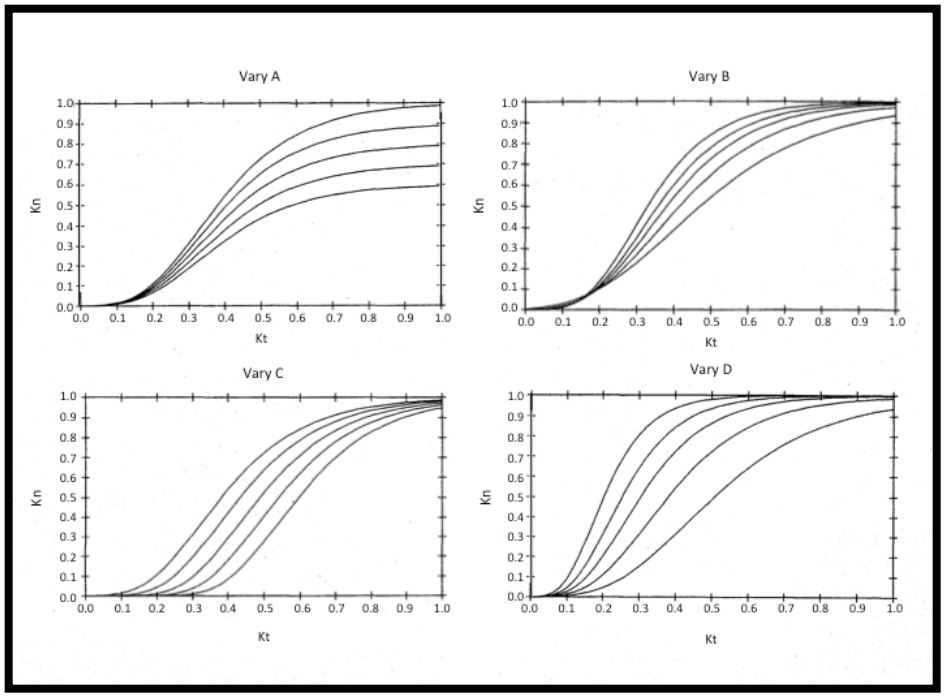

Figure 3. Gompertz curves illustrating the effects of each of the four coefficients. ***Image re-created from Figure 5-1 in Maxwell, Wilcox, and Rymes 1993***

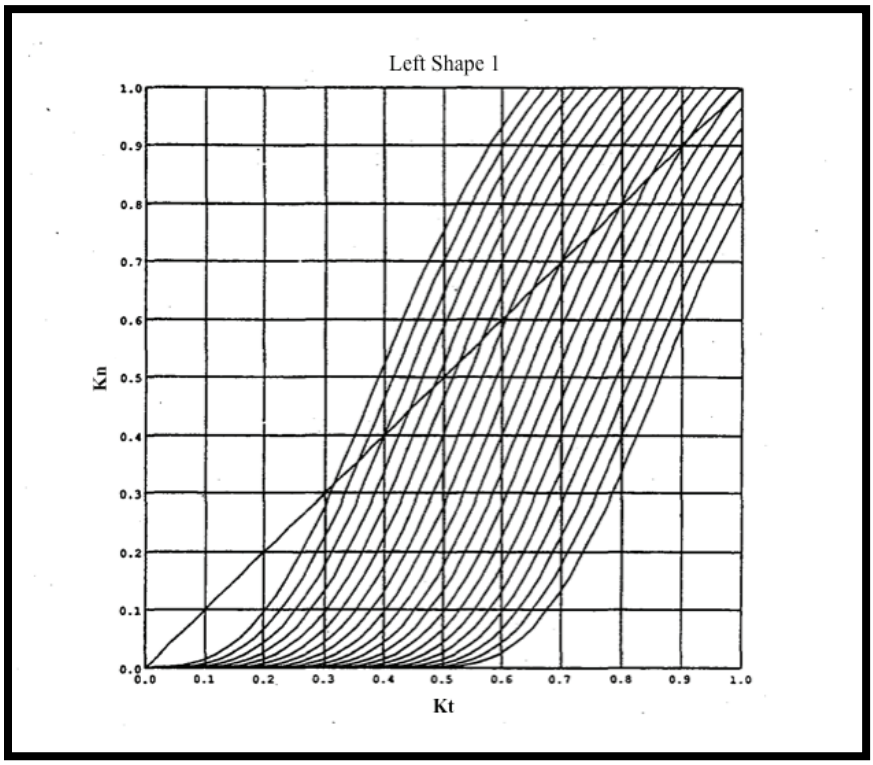

Figure 4. The family of curves for left boundary shape 1. ***Image re-created from Figure 5-4 in Maxwell, Wilcox, and Rymes 1993***

2.1.3 QCFit

NREL has developed a visual tool, QCFit, for establishing Gompertz boundaries. The original version of the software ran on a Vax VMS system; a later version ran in MS-DOS. WinQCFit, the latest version, runs in Windows 7; it was first developed for Windows NT in National Instruments' LabWindows application. WinQCFit's graphical user interface allows the user to easily change curve position and shape. The graphical user interface permits the user to immediately see the effect of boundary changes on the proportion of data included within the Gompertz curves. Boundaries can be widened or narrowed or error increased or decreased with a simple mouse click. Statistics report the effect of boundary changes on the disposition of the data, which aids the user in determining the best set of curves to fit the data.

2.1.4 Data Requirements for Determining Boundaries in K-space

It is important to have at least 3 years of good data from a site in order to sufficiently populate the scatter plots to discern appropriate preliminary boundaries. Five or more years are preferable; at least 10 years of good data should be available to make a final, permanent determination of boundaries and limits. Additional data from subsequent years should be included as it becomes available to better determine final boundary shapes and positions. Using only a single year of data could result in erroneous boundaries: one might select a climatologically anomalous year at that site to set the boundaries on the site data. Failure to update and refine the boundaries could result in subsequent data from nonanomalous years to be flagged as suspect. Additionally, with fewer data points in the scatter plot, data are more scattered and patterns in the data are less obvious; boundaries may be set too wide, allowing too much data to pass quality tests.

It should be noted that "good data" means data from calibrated, well-maintained, well-sited instruments. It is possible for data from regularly maintained, calibrated instruments at a good site to fail data-quality testing, but taking site and instrument variability out of the equation makes determining data quality that much easier.

2.2 SERI QC Testing Procedure

After the K-space data boundary shapes and positions and the Kt and Kn maxima have been determined, testing and flagging the data using SERI QC may now proceed. All flags assigned by SERI QC are two-digit flags, as shown in Table 8.

Because all computations and comparisons are location, date, and time specific, station identification and date and time checks are run first. Next, missing data checks identify the missing solar components and assign them a flag 99. Finally, before testing the data begins, solar zenith and azimuth angles and the K-space equivalents of the nonmissing solar components are calculated.

2.2.1 Testing Nighttime and Twilight Data

Data with a solar zenith angle of 90° or more are identified as nighttime data. Nighttime physical limits tests are performed on these data, and they should be close to zero. Special "twilight" one-component min-max empirical limits tests are run on data for which the corresponding solar zenith angle is greater than 80° but less than 90°.

2.2.2 Daytime One-Component Test

The one-component empirical limits tests against minimum and maximum Kt, Kn, and Kd are performed first on one-, two-, and three-component data that have solar zenith angles less than or equal to 80°. These maxima are the Kt_{max} and Kn_{max} set in WinQCFit; Kd_{max} is found by using the Kt and Kn maxima in Equation 4. Testing is terminated after this test if only one component is present. If two components are available, both are tested against the one-component limits. Testing is then terminated if one fails the one-component test. If one component of the three-component data fails the one-component test, the remaining two components go on to the two-component test. If two or more components of a three-component data point fail, the data go no further than the one-component test.

If both Kt and Kn pass the one-component test, they are compared. If Kn > Kt, which is physically impossible, the data are flagged to indicate the degree to which the data fail (see Table 8), and testing is terminated for this data point. Otherwise, the data move on to the two-component test.

2.2.3 Two-Component Tests

Daytime two-component data passing the one-component tests and comparison move next to two-component testing; whereas three-component data passing the one-component test first go through the three-component test. To assign flags to individual data components, it must be assumed that the other component has been accurately measured.

Two-component test failures are flagged to indicate the manner (high or low) and magnitude of the failure (distance from the boundary to the data point in K-units.) The flags range from 12–92 or 13–93 in increments of 4. An even or odd flag indicates that the component is presumed to be low or high, respectively.

The two-component test is more precise than the one-component test. For this reason, the one-component flag is replaced by a new flag that indicates the result of the two-component test on the data points that pass the one-component and go on to the two-component test. The three-component test, in turn, is more accurate and more reliable than the two-component test, so data passing through the three-component test retain their previously assigned flags if they subsequently pass the two-component test.

Table 8. Flagging Convention for SERI QC

Flag	Description
01	Untested (raw data)
02	Passed one-component test; data fall within max-min limits of Kt, Kn, or Kd
03	Passed two-component test; data fall within ±0.03 of satisfying Kt = Kn + Kd
04	Passed visual inspection; *not used* by SERI QC
05	Failed visual inspection; *not used* by SERI QC
06	Value estimated; passes all pertinent SERI QC tests
07	Failed one-component test; lower than allowed minimum
08	Failed one-component test; higher than allowed maximum
09	Passed three-component test but failed two-component test by >0.05
10–93	Failed two- or three-component tests in one of four ways To determine the test failed and the manner of failure (high or low), examine the remainder of the calculation (flag + 2)/4. **Rem** — **Failure** **0** — Parameter too low by three-component test (Kt = Kn + Kd) **1** — Parameter too high by three-component test (Kt = Kn + Kd) **2** — Parameter too low by two-component test (Gompertz boundary) **3** — Parameter too high by two-component test (Gompertz boundary) The magnitude of the test failure (distance in K-units) is determined from d = (INT (flag + 2)/4)/100. Examples and further discussion of the meaning of flags 10–93 are given in Section 6.4 and Section 9.3 of the *User's Manual for SERI QC Software: Assessing the Quality of Solar Radiation Data.*
94–97	Data fall into a physically impossible region in which Kn > Kt by K-space distances of 0.05 to 0.10 (94), 0.10 to 0.15 (95), 0.15 to 0.20 (96), and ≥0.20 (97)
98	Not used
99	Missing data

2.2.2 Three-Component Tests

If all three solar components are present, a redundancy test is run consisting of the comparison of the measured Kt to an estimated value Kt*. The value Kt* is estimated from Equation 4:

$$Kt^* = Kn + Kd \tag{7}$$

A data point that passes the two-component test and satisfies the criteria Kt and lies within the range Kt* ± 0.03 will be assigned a passing three-component flag.

If a data point satisfies the above criteria (Kt within Kt* ± 0.03) but fails the two-component test by more than 0.05, a flag of 09 is assigned to all three components of the data point. The two-component test is actually carried out on three-component data after the data has passed the three-component test, as shown by the flow chart in Figure 5.

Data points failing the three-component test are assigned flags that indicate the manner (high or low) and magnitude of the failure (distance from the boundary to the data point in K-units). Three-component flags range from 10–90 or 11–91 in increments of 4 (see Figure 12). As shown in Table 8, for both two-component flags greater than 12 and three-component flags greater than 10, the distance d in K-units by which a component may be in error can be calculated by using the following equation:

$$d = [INT(flag +2>/4]/100 \quad (8)$$

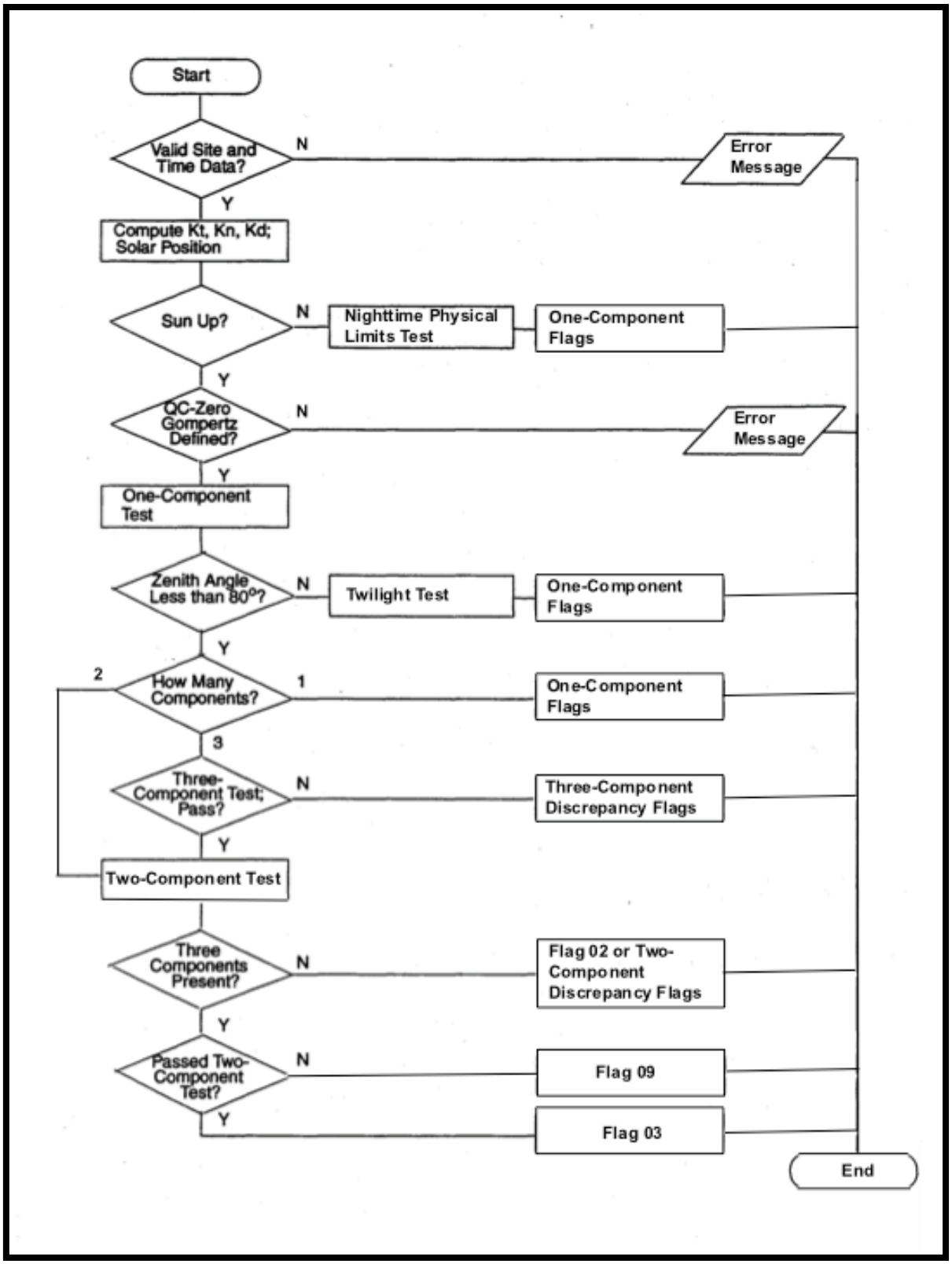

Figure 5. The flow of data through SERI QC. ***Image re-created from Figure 6-1 in Maxwell, Wilcox, and Rymes 1993***

3 Comparison of ISIS and SURFRAD to SRRL-BMS

ISIS and SURFRAD data for the years from 2002 through 2013 were downloaded from the National Oceanic and Atmospheric Administration's Earth System Research Laboratory's Global Monitoring Division website in monthly field-delimited text files. These files include additional measurements not needed for this comparison, so GHI, DNI, and DHI data were extracted from the files and written to monthly files in comma-separated values format. GHI, DNI, and DHI data for the years from 2002 through 2013 were selected and downloaded from the SRRL-BMS as comma-separated values files, so no additional processing was necessary before beginning data quality analysis.

3.1 Testing and Flagging the Data Using SERI QC

Gompertz boundaries were established for each ISIS and SURFRAD station. Because SURFRAD native data resolution changed in January 2009 from 3 minutes to 1 minute, two sets of Gompertz curves were created for each SURFRAD station. The SRRL-BMS at NREL has been in operation since 1981, so Gompertz boundaries are well-established; these boundaries were obtained from Measurement and Instrumentation Data Center administrator Afshin Andreas for use in flagging the SRRL-BMS data.

The SERI QC software is a function subroutine written in C code. As such, it requires software to call it and to feed data into it for flagging. Previously, SERI QC was run inside a Windows database application, Augustyn & Co.'s Data Quality Management System v.3, or DQMS3. As DQMS3 became unstable and was unsupported in Windows 7, it became of paramount importance to develop a method to run SERI QC.

To this end, RADFLAGS, a C program originally written to run in the Linux operating system, was developed to read ASCII text files containing solar radiation data and to call SERI QC to test and flag the data. The output file is in comma-separated values format and contains the input data and SERI QC flags.

The SERI QC flags output by RADFLAGS were compared to SERI QC flags output by DQMS3. There were small differences in low- to moderate-level two- and three-component flags—for example, a flag 25 in which DQMS would issue a flag 23; however, in the hour just after sunrise and the hour just before sunset when the solar zenith angle is changing rapidly, no radical differences were found in the flags assigned by the two programs to the same input data. The differences likely arose from small differences in precision in the calculations of solar position by the two codes running on two different platforms. No differences were found in flags on data from late-morning hours to early afternoon, so we are confident that RADFLAGS is functioning properly.

SURFRAD 3-minute (2002–2008) and 1-minute (2009–2013) data, ISIS 3-minute data (2002–2013), and SRRL-BMS 1-minute data (2002–2013) were tested and flagged using the SERI QC suite of tests called by RADFLAGS. The data and flags were written to new comma-separated values files for use in tabulating data quality statistics and calculating hourly data.

3.2 Calculating Hourly Data

For this comparison, we also wanted to analyze the quality of the hourly averages of the native resolution data. Although calculated hourly averages are available on the Measurement and Instrumentation Data Center for SRRL-BMS data, hourly averages of the ISIS and SURFRAD native resolution data had to be calculated.

An in-house NREL program called RADTIME, which is written in C code and runs in MS-DOS, calculates hourly averages from subhourly native resolution data previously flagged by SERI QC. RADTIME utilizes the SERI QC flags to filter the data going into the averages; it throws out bad data and thereby ensures reasonable output values.

Using RADTIME, hourly averages for the years from 2002 to 2013 were calculated from the 3-minute ISIS and SURFRAD (2002–2008) data and 1-minute SURFRAD (2009–2013) data and written to comma-separated values files. RADTIME filtered the flagged data, using only data flagged good (see Table 8) to calculate hourly averages. Before testing could begin, Gompertz boundaries had to be established for the hourly ISIS and SURFRAD data; Gompertz curves for the downloaded SRRL-BMS hourly average data were acquired from Afshin Andreas at SRRL.

The hourly average data were tested in RADFLAGS using the appropriate Gompertz curves, and SERI QC flags were assigned to all data points. The flagged data were then written to comma-separated values files.

3.3 Deriving Data Quality Statistics

To compare the data quality of the SURFRAD and ISIS networks to that of the SRRL-BMS, an algorithm was needed to categorize the SERI QC data quality flags into data quality statistics. Just such an algorithm had been developed for the U.S. Department of Energy's Atmospheric Radiation Measurement program several years previous to this work. The algorithm classifies SERI QC flags into color-coded groups: black for missing data, green for good quality data, yellow for data of suspect quality, and red for bad data. The correspondence among SERI QC flags and the Atmospheric Radiation Measurement color flag scheme is given in Table 9.

Table 9. Correspondence Among Atmospheric Radiation Measurement Color Flags and SERI QC Flags

Flag Color	Corresponding SERI QC Flags	Color Flag Meaning
Black	99	Missing data
Green	01–03, 09–21	Good data
Yellow	22–41	Suspect data, use with caution
Red	07, 08, 42–97	Bad data, do not use

Figure 6 illustrates the Atmospheric Radiation Measurement color flag scheme for 3 days of data from June 2013 from the Albuquerque, New Mexico, ISIS station. The red and yellow flags alert us to problems in the data, but to understand these problems a look as the actual SERI QC flags is necessary. A comparison of data from June 1 to that of June 3, however, shows that a continuing problem may be at work at this site: the GHI and DNI are flagged red (bad) between

approximately sunrise and 10:30 LST on both days, then all three components are flagged yellow (suspect) between approximately 10:30 and 11:00 or 11:30 LST. All three components are then good until about 13:00 LST, at which point all are suspect before being flagged bad. However, June 1 was clear all day, but clouds moved in after 15:00 LST on June 3, so it is uncertain if the flagging pattern is the same in the late afternoon on the two days. It would be necessary to examine clear days both before and after these example days to ascertain whether a real problem exists and to determine its likely cause.

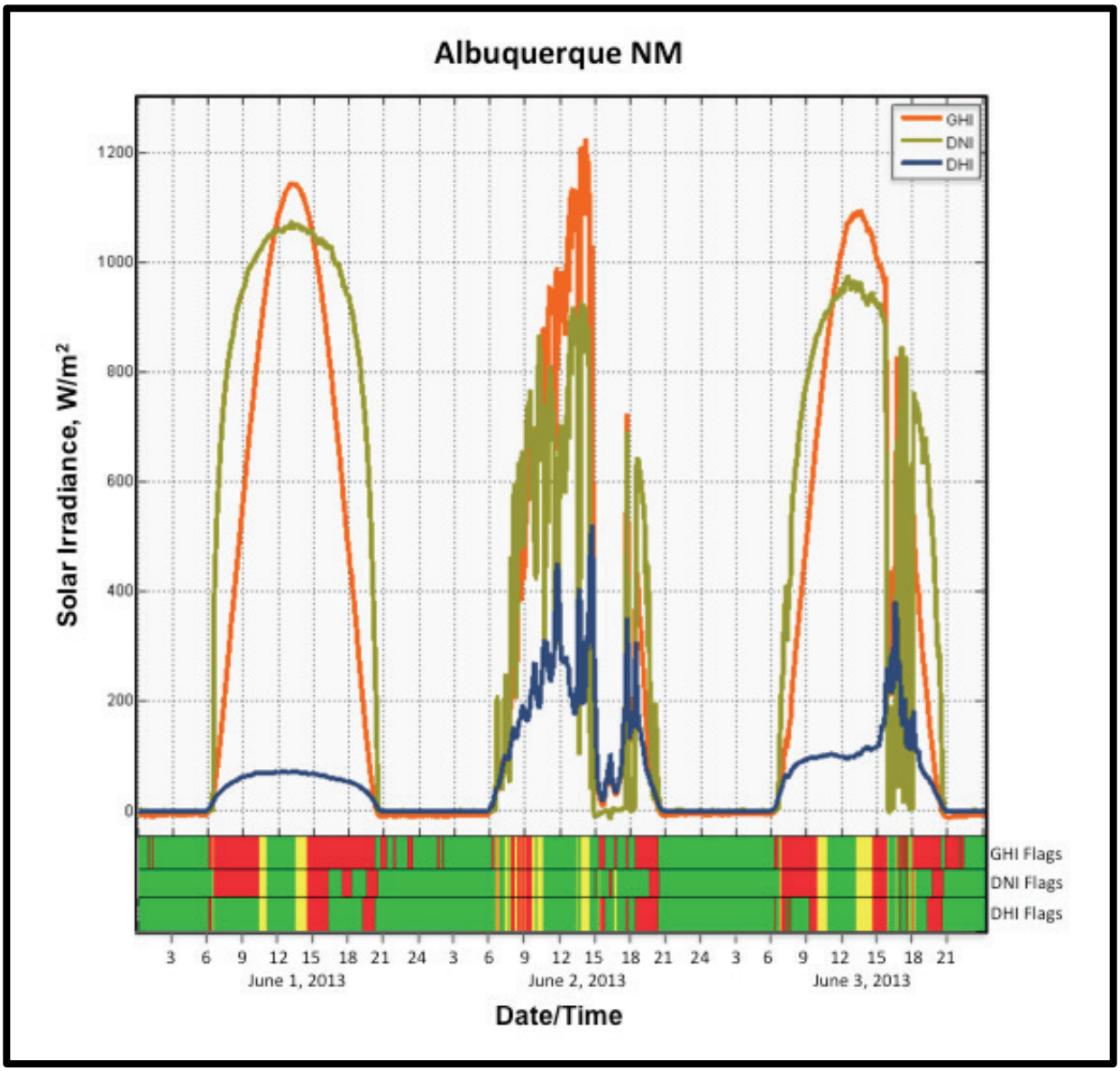

Figure 6. An example of the Atmospheric Radiation Measurement color flag scheme demonstrating green, yellow, and red

A short program called RADSTATS was written to convert SERI QC flags into Atmospheric Radiation Measurement color flags and to tabulate the color flags into monthly statistics.

RADSTATS reads flags in the comma-separated values files output by RADFLAGS and outputs a second comma-separated values file that lists the following for each month:

1. Number of points expected
2. Actual number of points available
3. And for each component:
    A. Percent of data missing
    B. Percent of data with green flags
    C. Percent of data with yellow flags
    D. Percent of data with red flags

These statistics can be plotted to provide a visual comparison of the data quality among the SURFRAD and ISIS networks and SRRL-BMS. A portion of the file output by RADSTATS for the ISIS site in Albuquerque is shown in Figure 7.

```
Monthly and Total DQA Statisitcs for Site: ABQ
Year, Month, Expected No. Points, Available No. Points, GHI Pct Missing, GHI Pct Green, GHI Pct Yellow, GHI Pct Red,DNI Pct Missing, DNI Pct Green, DNI
Pct Yellow, DNI Pct Red,DHI Pct Missing, DHI Pct Green, DHI Pct Yellow, DHI Pct Red
2002,01,14880,54,0.0,100.0,0.0,0.0,0.0,100.0,0.0,0.0,0.0,100.0,0.0,0.0
2002,02,13440,13440,0.0,99.8,0.0,0.2,0.0,99.9,0.1,0.0,0.0,99.3,0.1,0.6
2002,03,14880,14844,0.0,95.2,4.8,0.0,0.3,94.9,4.8,0.0,0.0,94.7,4.8,0.6
2002,04,14400,13891,0.0,99.6,0.0,0.4,0.8,98.9,0.0,0.3,0.0,99.0,0.0,0.9
2002,05,14880,14849,0.0,99.3,0.5,0.2,0.0,99.4,0.5,0.0,0.0,98.7,0.5,0.7
2002,06,14400,14370,0.0,99.3,0.4,0.3,0.0,99.4,0.6,0.1,0.0,98.6,0.6,0.8
2002,07,14880,14849,0.0,91.8,6.2,2.0,20.4,72.5,6.2,0.9,0.0,91.4,6.6,1.9
2002,08,14880,14849,0.0,99.6,0.0,0.4,0.7,99.2,0.0,0.1,0.0,98.9,0.0,1.0
2002,09,14400,14370,0.0,99.1,0.1,0.8,1.1,98.4,0.1,0.5,0.0,98.6,0.1,1.3
2002,10,14880,11892,0.0,95.2,0.1,4.6,10.6,89.3,0.1,0.1,0.0,98.9,0.1,0.9
2002,11,14400,14283,0.1,60.1,5.1,34.7,0.1,92.3,5.2,2.4,0.0,92.4,5.2,2.5
2002,12,14880,14849,0.0,98.1,1.7,0.2,0.0,98.1,1.7,0.2,0.0,97.6,1.7,0.7
2003,01,14880,14849,0.0,98.0,1.5,0.4,0.0,98.4,1.6,0.0,0.0,97.9,1.6,0.5
2003,02,13440,13416,0.0,96.2,0.9,2.9,0.0,98.3,1.3,0.5,0.0,97.4,1.3,1.3
2003,03,14880,14880,0.0,95.6,1.8,2.6,0.0,98.0,1.9,0.1,0.0,97.5,1.9,0.6
2003,04,14400,14400,1.2,89.7,1.7,7.4,1.3,96.8,1.7,0.1,1.3,96.3,1.8,0.6
2003,05,14880,14880,0.0,90.2,1.2,8.6,0.0,98.4,1.3,0.3,0.0,97.6,1.3,1.1
2003,06,14400,13920,0.4,81.1,1.9,16.6,0.0,97.5,2.2,0.3,0.0,96.6,2.2,1.2
2003,07,14880,14880,0.0,82.2,1.7,16.1,0.0,98.1,1.8,0.1,0.0,97.4,1.8,0.8
2003,08,14880,14880,0.0,88.4,0.7,10.8,0.8,98.2,0.8,0.2,0.0,98.3,0.8,0.9
2003,09,14400,14400,0.5,83.6,1.6,14.3,0.8,97.3,1.6,0.3,0.0,97.4,1.6,1.0
2003,10,14880,14880,0.0,89.6,1.9,8.5,0.0,97.8,2.0,0.2,0.0,97.1,2.0,0.9
2003,11,14400,14400,0.0,95.6,1.3,3.1,0.0,98.1,1.7,0.2,0.0,97.5,1.7,0.8
2003,12,14880,14880,0.0,97.0,1.3,1.7,0.0,98.5,1.3,0.1,0.0,97.9,1.3,0.8
```

Figure 7. A portion of the quality statistics file for 3-minute data in Albuquerque, New Mexico

3.4 Results

The data quality comparisons were carried out on two levels: monthly and annual. Monthly statistics were calculated for the native resolution data and for the calculated hourly averages. Annual statistics were calculated for the native resolution data only.

3.4.1 Monthly Statistics

Figure 8 shows the monthly data quality statistics for the 3-minute 2002 ISIS GHI that passed data quality tests (green flags) plotted with the corresponding data quality statistics for the one-minute 2002 SRRL-BMS GHI. Figure 9 shows a similar plot for the 3-minute 2002 SURFRAD GHI and 1-minute 2002 SRRL-BMS GHI statistics. Figure 10 represents the percentage of hourly average ISIS GHI data that passed data quality tests with the corresponding percentage of the SRRL-BMS hourly average GHI. Figure 11 shows the same for SURFRAD GHI and SRRL-BMS GHI.

Figures 12–15 show the DNI equivalents of plots 8–11, respectively.

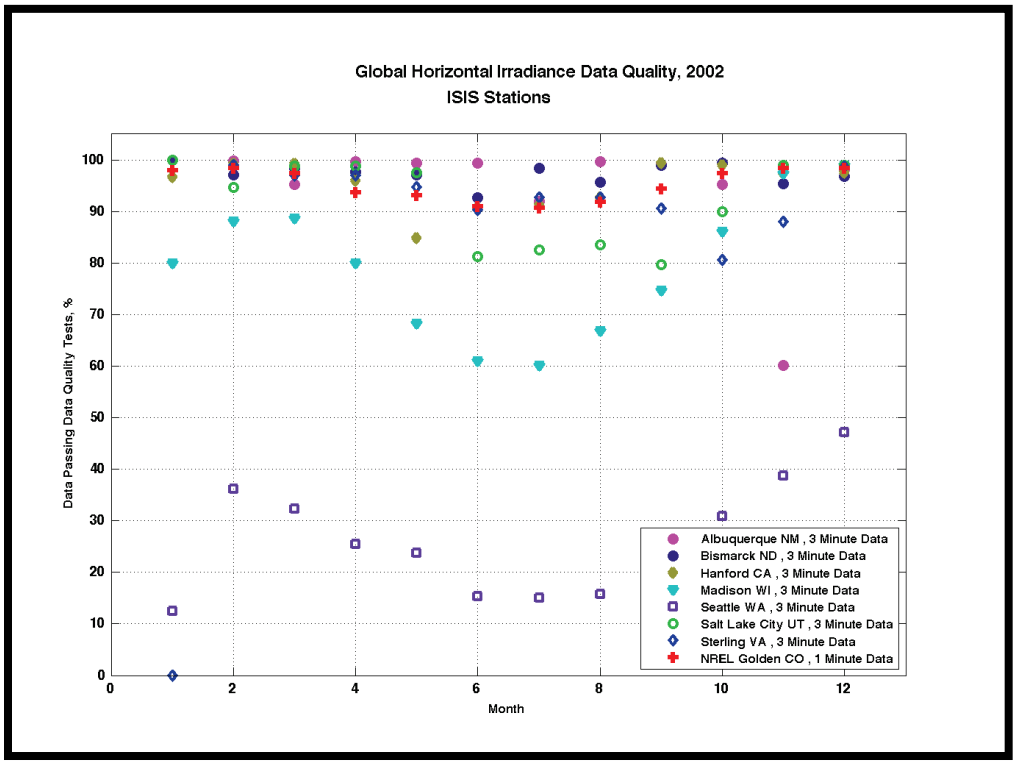

Figure 8. ISIS and SRRL-BMS 2002 GHI data that passed quality tests

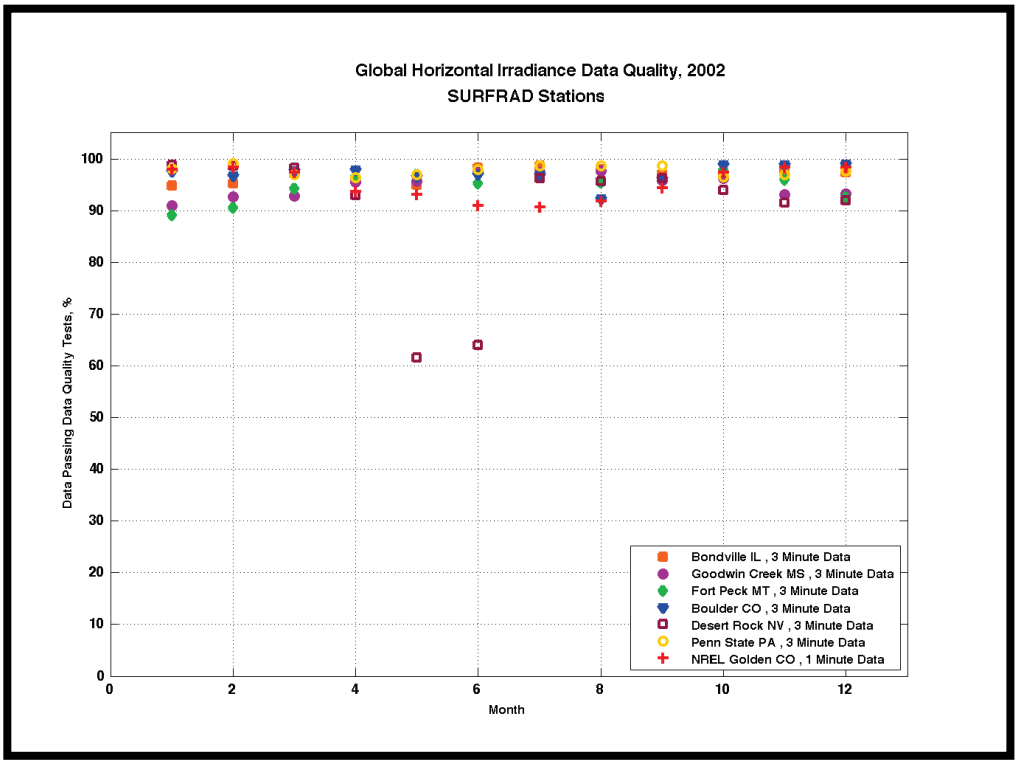

Figure 9. SURFRAD and SRRL-BMS 2002 GHI that passed data quality tests

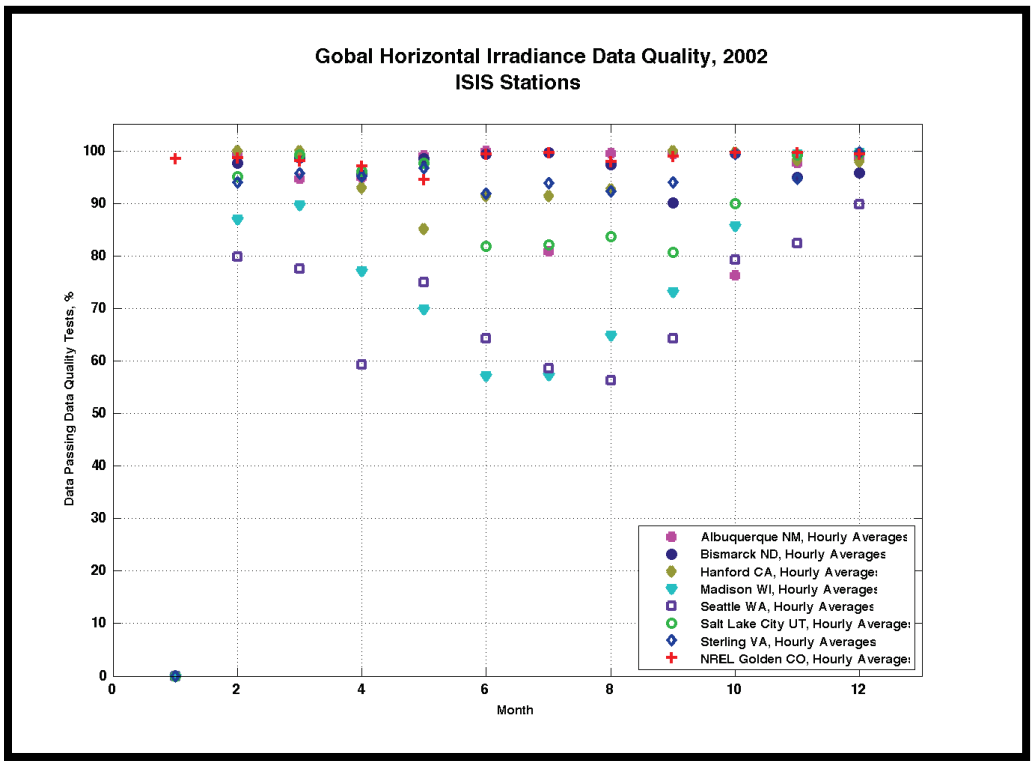

Figure 10. ISIS and SRRL-BMS 2002 hourly average GHI that passed data quality tests

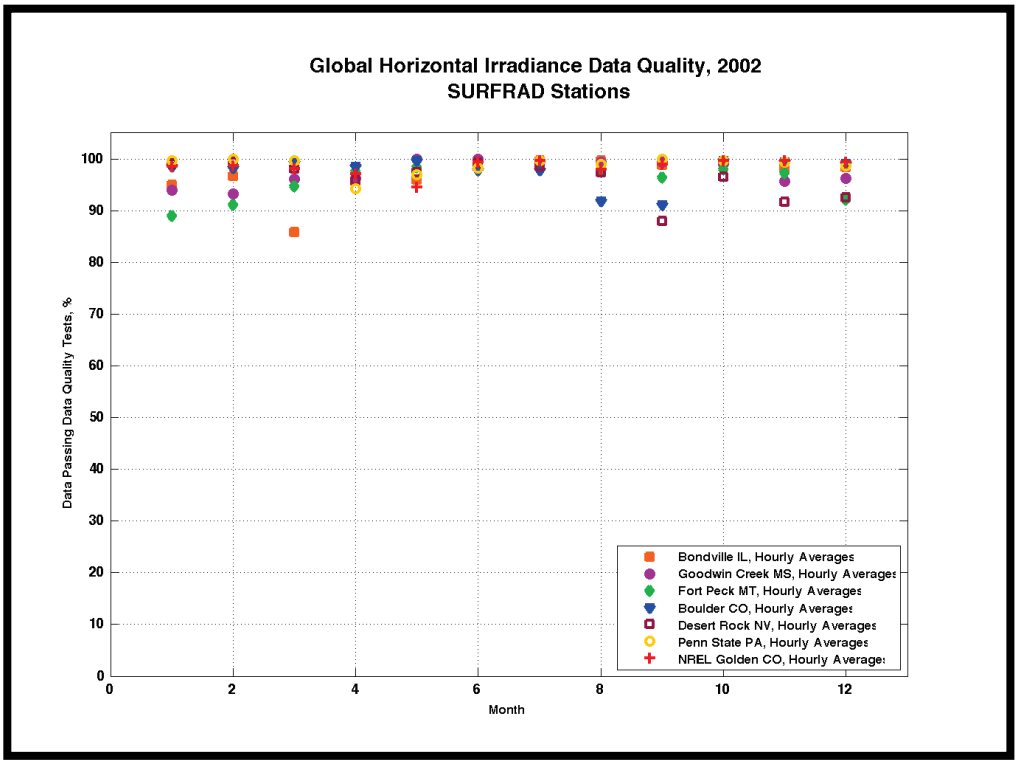

Figure 11. SURFRAD and SRRL-BMS 2002 hourly average GHI that passed data quality tests

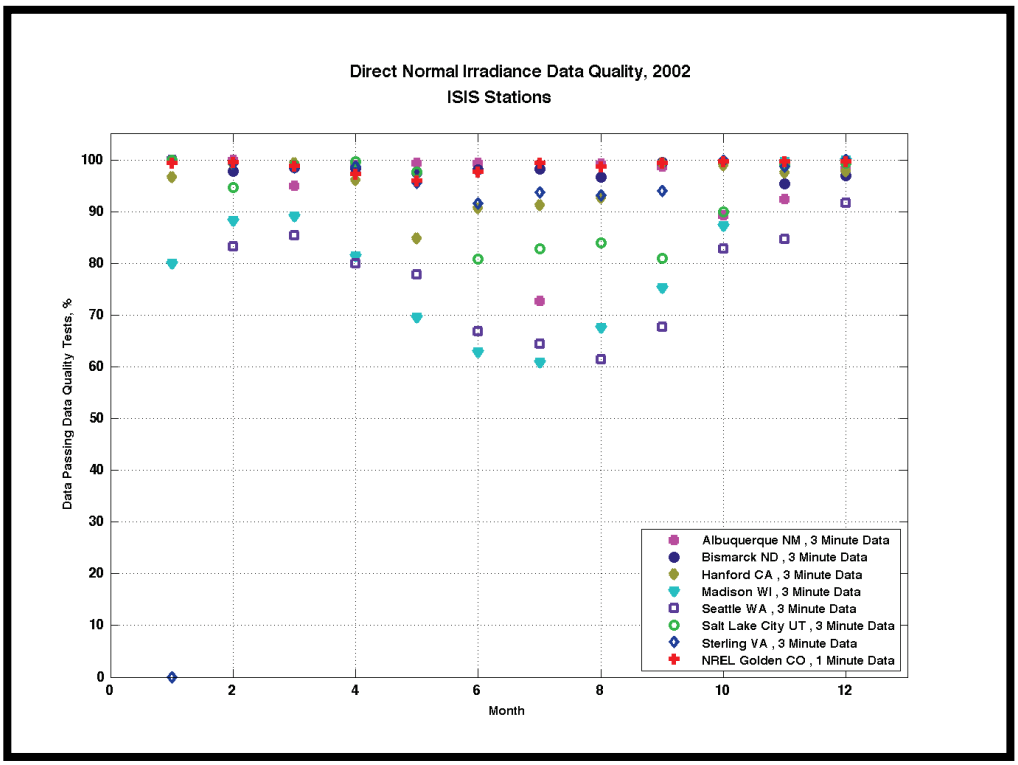

Figure 12. ISIS and SRRL-BMS 2002 DNI that passed data quality tests

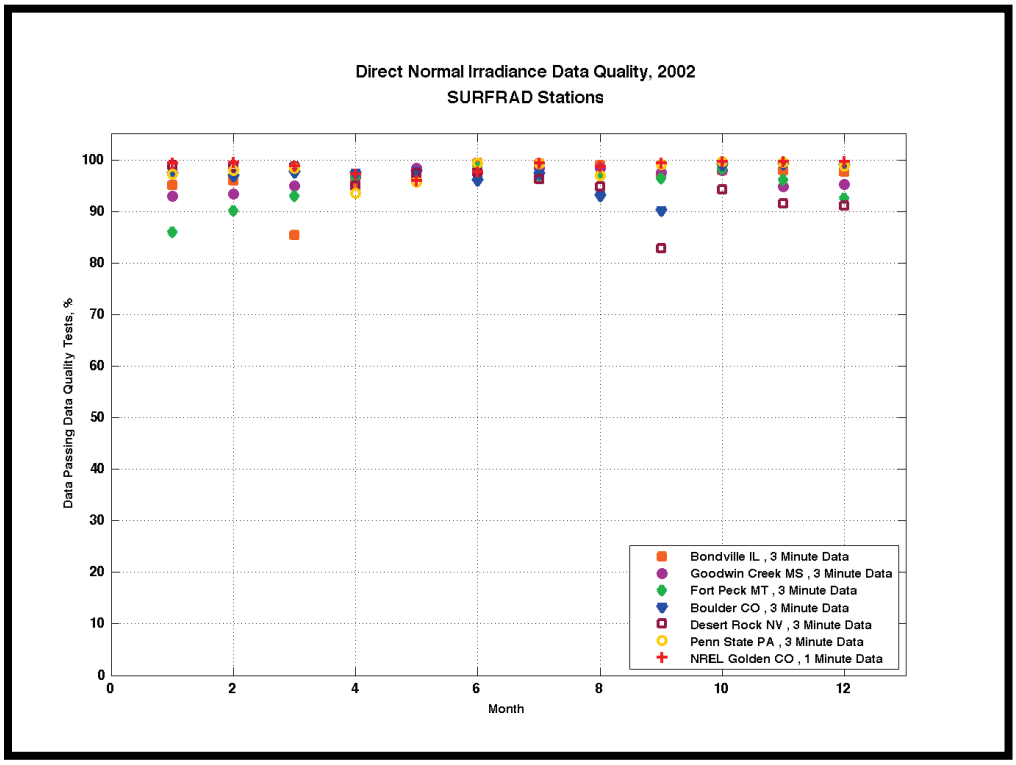

Figure 13. SURFRAD and SRRL-BMS 2002 DNI that passed data quality tests

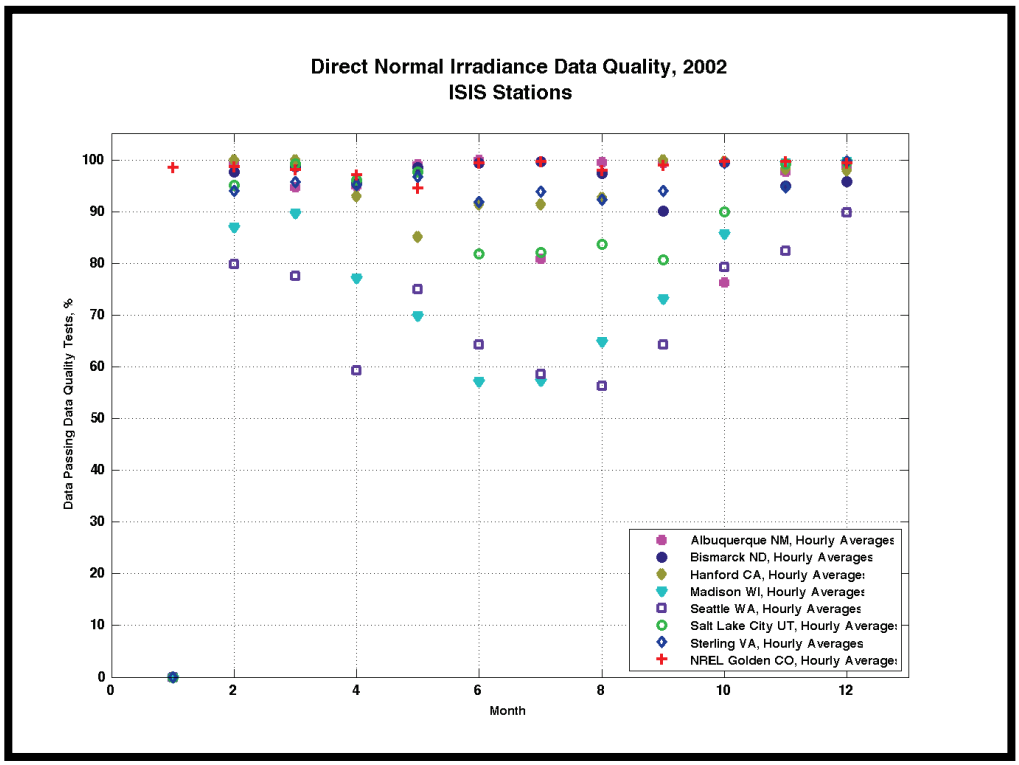

Figure 14. ISIS and SRRL-BMS 2002 hourly average DNI that passed data quality tests

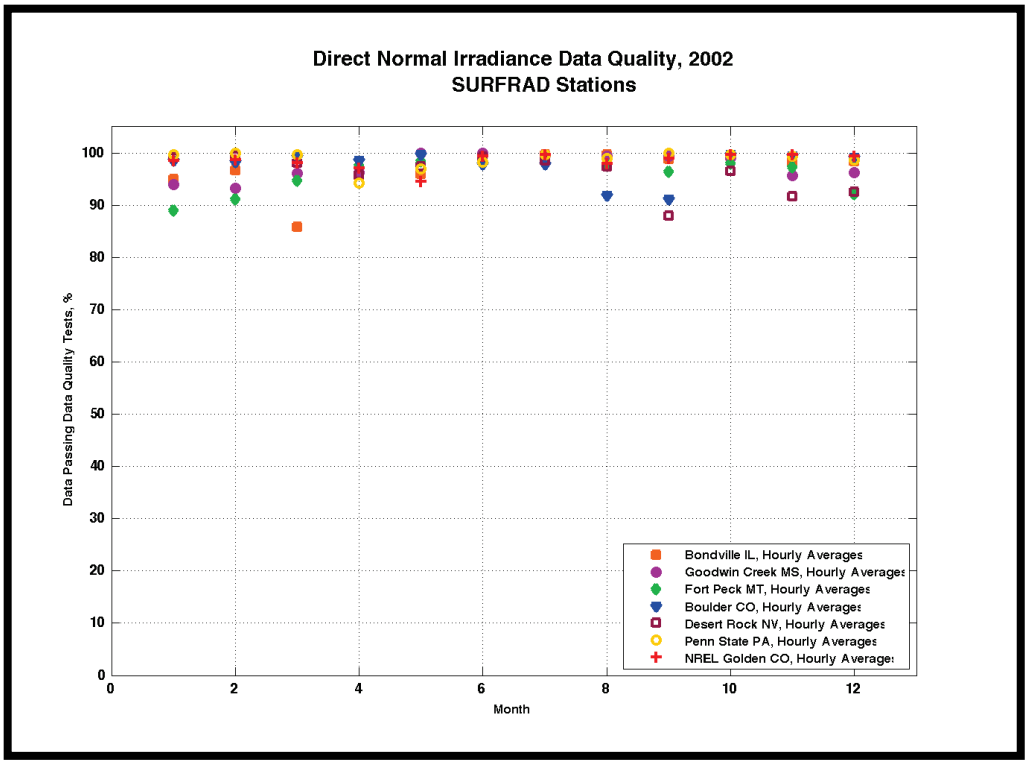

Figure 15. SURFRAD and SRRL-BMS 2002 hourly average DNI that passed data quality tests

In all four pairs of plots, we observe that the SURFRAD station data points are both clustered more closely together and gathered nearer to the 100% line than are the ISIS data points. This trend is exaggerated in the summer months, because data quality at two ISIS stations in particular—Madison, Wisconsin, and Seattle, Washington—decreases as much as 30% from February to July.

A comparison of ISIS and SURFRAD GHI and DNI data quality statistics for subsequent years (see Appendix, Figures 18–105) corroborates this observation. Overall, the spread in data quality among the ISIS stations each year from 2002 through 2013 is observed to be greater than the spread in data quality among SURFRAD stations in each of the same years.

ISIS stations for which 50% or less of monthly GHI data frequently passed data quality tests are those in Seattle, Washington; Bismarck, North Dakota; and Albuquerque, New Mexico. Overall network data quality is lowest during the years from 2005 through 2010. The years 2004 and 2011 represent transition years between the poor data quality from 2005 through 2010 and the better data quality of first two and last two years of the study. Data quality in the network during the last two years of this study is commensurate with those from the years 2002 through 2003.

ISIS DNI data quality is similar, with the added problem that a large amount of data began to go missing in 2004, beginning with Seattle, Washington, and eventually growing to all or almost all data missing for 2007 from four sites: Seattle, Washington; Hanford, California; Bismarck, North Dakota; and Albuquerque, New Mexico. Additionally, some sites are missing all or most data for one or more months from the years 2004 through 2011.

Monthly GHI data quality at SURFRAD stations is generally at or above 85% every month throughout the study period and above 90% for the last three years at all stations. Notable exceptions include Desert Rock, Nevada, in May and June of 2002; Fort Peck, Montana, from March through August 2003; and Penn State, Pennsylvania, from February through June 2007. There are other, shorter lived or less egregious examples, but these instances are of the longest duration or lowest data quality (below 70% good) in the study.

SURFRAD monthly DNI data quality is above 80% at most stations every month of the study period. Exceptions are not as striking as they are in the GHI, but notable ones include Goodwin Creek, Mississippi, in June and July 2003 and April 2011; Penn State, Pennsylvania, in August 2004 and July 2005; and Sioux Falls, South Dakota, in August 2006.

The quality of SRRL-BMS data is good throughout the study period. During the first 4 years of the study, GHI data quality varied from month to month, from a low of approximately 88% up to 100% that passed data quality tests. In 2007, the lowest data quality value was approximately 96% good (July). In 2008 and onward, data quality and consistency improved: 98% to 100% of the monthly GHI passed data quality tests.

In 2002, 95% or more of SRRL-BMS DNI data passed quality tests each month. After 2002, DNI data quality improved so that 97% or more was good, with the single exception of October 2010, when approximately 92% of DNI passed data quality tests.

Filtering and averaging the data to obtain hourly averages generally improved the data quality of even some of the worst sites. For example, the data quality of the GHI hourly averages from the Seattle and Albuquerque ISIS sites in 2013 is improved compared to the data quality of the corresponding 3-minute native resolution data. The Bismarck ISIS site in 2003 shows slight improvement in data quality for DNI hourly averages compared to that of the native resolution data.

Occasionally, the data quality of the hourly averages is lower than that of the native resolution data. For example, in almost every month of 2003, the data quality of the hourly average DNI from the Seattle ISIS site is lower than that of the corresponding 3-minute DNI data that went into the hourly averages. In 2010, the data quality of the GHI hourly averages from the Sterling ISIS site is worse than that of the native resolution 3-minute data from that year.

The data quality of the SRRL-BMS hourly average GHI is higher than that of the corresponding 1-minute native resolution data, particularly for the years from 2002 to 2004. September and October of 2010 are exceptions when the hourly average GHI has less data passing quality tests than does the native resolution data.

A comparison of the data quality of SRRL-BMS DNI hourly averages to that of the data quality of the native resolution 1-minute DNI is mixed: some months show slightly improved data quality, and some show a slight decline in data quality with averaging. In 2004, for example, hourly average DNI data quality is marginally better than the data quality of the 1-minute DNI in January and August, and it is a little worse in April and July.

3.4.2 Annual Statistics

Annual data quality statistics were derived for the native resolution data from each ISIS and SURFRAD site and for SRRL-BMS. The statistics for all sites for each year were plotted for all four categories—good, suspect, bad, and missing—of the GHI and the DNI data as stacked columns. Figure 16 represents the GHI statistics for 2002 for ISIS, SURFRAD, and SRRL-BMS. The corresponding DNI statistics for 2002 are shown in Figure 17. Annual GHI and DNI data quality statistics are presented in Figures 106–127 (see Appendix).

Ninety percent or more of the native resolution GHI data at each of the SURFRAD sites active in 2002 passed data quality tests, as shown in Figure 16. The same figure shows that 90% or more GHI are reported good for 2002 for five of the seven ISIS sites; less than 30% of Seattle GHI passed data quality tests; and approximately 78% of Madison's 2002 GHI is good. Slightly more than 95% of the SRRL-BMS native resolution GHI data from 2002 are good.

Figure 17 shows that annual DNI data quality for the six SURFRAD sites active in 2002 is at or above approximately 95%. For most ISIS sites, 2002 DNI data quality statistics are slightly better than the corresponding GHI statistics. For example, almost 77% of Seattle's DNI is good, compared to 27.5% of GHI that passes data quality tests. DNI data quality from 2002 for SRRL-BMS is also better than GHI data quality; almost 99% of DNI passed data quality tests.

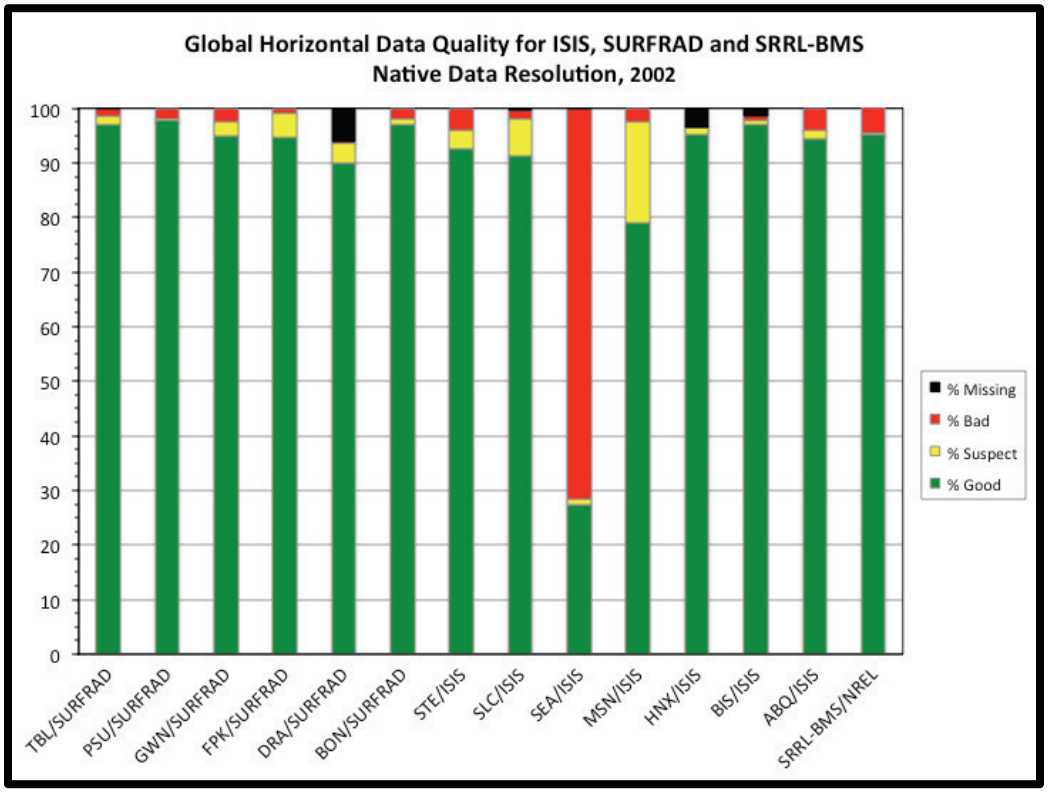

Figure 16. ISIS, SURFRAD, and SRRL-BMS 2002 GHI data quality (See text for data resolution.)

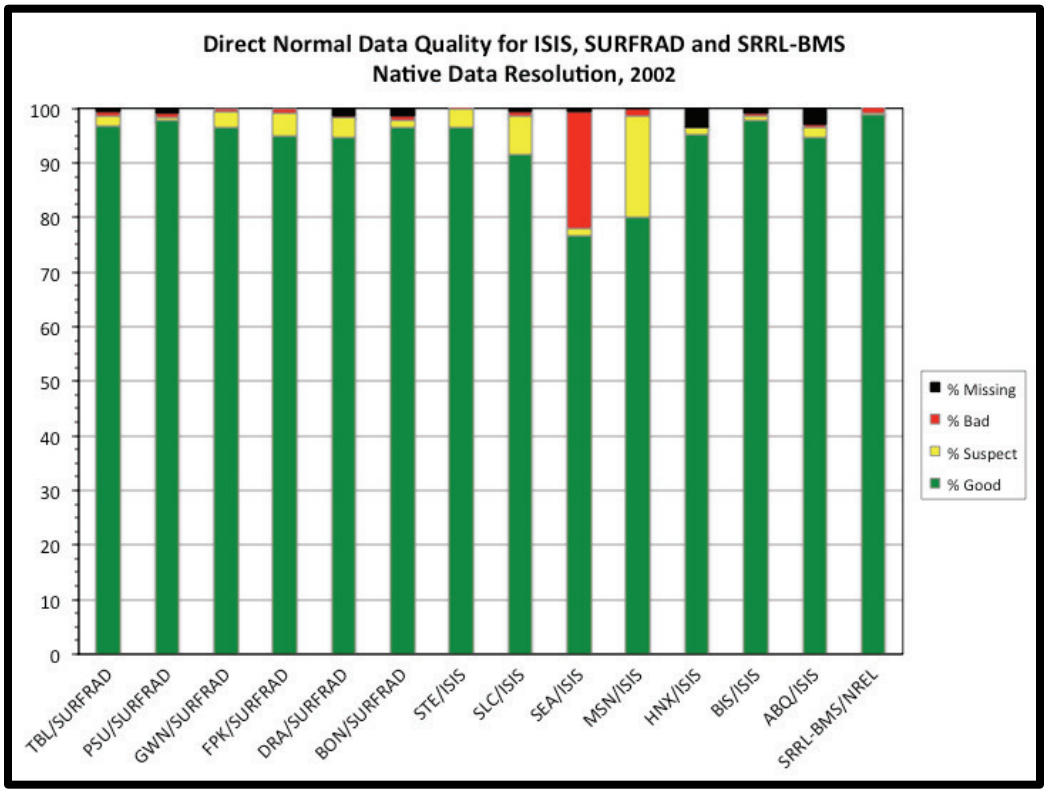

Figure 17. ISIS, SURFRAD, and SRRL-BMS 2002 DNI data quality (See text for data resolution.)

Figures 106–127 (see Appendix) illustrate the GHI and DNI annual statistics for the native resolution data from all ISIS and SURFRAD sites and SRRL-BMS for the years from 2003 through 2013. These figures display aggregated statistics for a year from each site and feature ISIS and SURFRAD data quality statistics plotted together with SRRL-BMS statistics to make comparisons more straightforward.

Results for individual stations may vary (e.g., 2003 at Goodwin Creek, Mississippi), but the overall impression left by the plots of the annual statistics is that a higher percentage of native resolution DNI data from each network passes data quality tests each year than does GHI. This could be because of the larger amount of GHI flagged "bad" (red). On the other hand, the DNI is more often missing (black) than the corresponding GHI (e.g., 2006).

As shown in these figures portraying monthly data quality statistics, certain ISIS stations repeatedly demonstrate low data quality: in 2008, its best year, a little less than 35% of GHI data passed data quality tests at the Seattle, Washington, site. DNI data quality at this site runs from near 77% good for the first three years of the study to less than 45% in 2005, to all DNI missing from 2006 through 2008 and in 2010, and finally to DNI data quality recovering to almost 80% good.

SURFRAD network data quality, both GHI and DNI, is more consistent than that of the ISIS network. Its worst year in this study was 2003 (largely due to Fort Peck's performance), after which data quality improved such that more than 90% of each component passed data quality tests each year from 2004 through 2013.

For the first 4 years of this study, the data quality of the native resolution GHI data varied from a high of 95.2% in 2002 to a low of 87.2% in 2005. DNI data quality during these years was very good: 98.8% in 2002 and 99% in 2005. After this, GHI data quality improved to compare well to DNI data quality: never less than 98.5% of GHI passed data quality tests in each year from 2006 to 2013. DNI data quality remained excellent, never falling below 98.6% good (2010).

4 Conclusions

NREL has been collecting solar radiation data at the present location of the SRRL-BMS since late 1984. Along with development by NREL of solar radiation data quality assessment algorithms, this 30-year record of experience has made NREL a recognized expert in the field of broadband solar radiation measurements and data analysis.

In this study, NREL's own SERI QC algorithms were used to test the quality of solar irradiance data from ground measurement sites in two networks and NREL's SRRL-BMS. The resulting flags on GHI and DNI data were categorized into four classes: good, suspect, bad, and missing. Monthly and annual statistics for the occurrence of each class were then calculated. The data quality statistics for the two National Oceanic and Atmospheric Administration networks were plotted with the statistics for SRRL-BMS data to aid in the comparison.

Although ISIS data quality improved during the last 2 to 3 years of this study, and SURFRAD data quality is very good across that network, SRRL-BMS data quality has been consistently high in the GHI since 2006 and throughout the study in the DNI. SRRL-BMS data quality is, in fact, higher than that of all ISIS and SURFRAD stations every year of the study, excepting Penn State, Pennsylvania, in 2003 (90% good compared to 90.1% good). After 2005, SRRL-BMS GHI data quality is superior to that of all ISIS and SURFRAD stations without exception. Therefore, the statistical results of this study establish the high quality of NREL's SRRL-BMS solar irradiance data and its suitability for use as "ground truth" for validating satellite solar irradiance models.

Glossary

Diffuse horizontal irradiance (DHI)	The component of solar radiation that strikes a point from the sky, excluding the solar disk. In the absence of atmosphere, there should be almost no diffuse sky radiation. An unclear atmosphere or reflections from clouds produce high values of diffuse.
Direct normal irradiance (DNI)	Solar radiation coming from the direction of the sun, striking a surface normal to the direction of the beam. Also called beam radiation
Global horizontal irradiance (GHI)	Total solar radiation: the sum of DNI, DHI, and ground-reflected radiation; however, because ground-reflected radiation is usually insignificant compared to direct and diffuse radiation, for all practical purposes global radiation is said to be the sum of direct and diffuse radiation. Solar radiation striking a horizontal surface.
Insolation	Solar radiation at the surface of the earth
Irradiance	Solar radiation; irradiant energy from the sun
Pyrheliometer	An instrument with a narrow field of view for measuring DNI. Pyrheliometers are mounted on sun-following trackers so that the instrument is always aimed at the sun
Pyranometer	An instrument with a hemispherical field of view, used for measuring total or global solar radiation, specifically GHI; a pyranometer with a shadow band, shading disk, or ball blocking the DNI measures the DHI

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Appendix

Figures 8–5 in Section 3.4.1 present the percentage of 3-minute and hourly average 2002 GHI and DNI data from ISIS and SURFRAD stations that passed data quality tests compared to like data from NREL's SRRL-BMS. This appendix includes eight similar plots for each of the years from 2003 through 2013; a total of 88 plots comprise Figures 18–105.

Figure 16 and Figure 17 in Section 3.4.2 illustrate the percentage of GHI and DNI data, respectively, from each site in the ISIS and SURFRAD networks and from the SRRL-BMS in each of the color flag classifications for 2002. This appendix includes similar plots for the years from 2003 through 2013; a total of 22 plots comprise Figures 106–127.

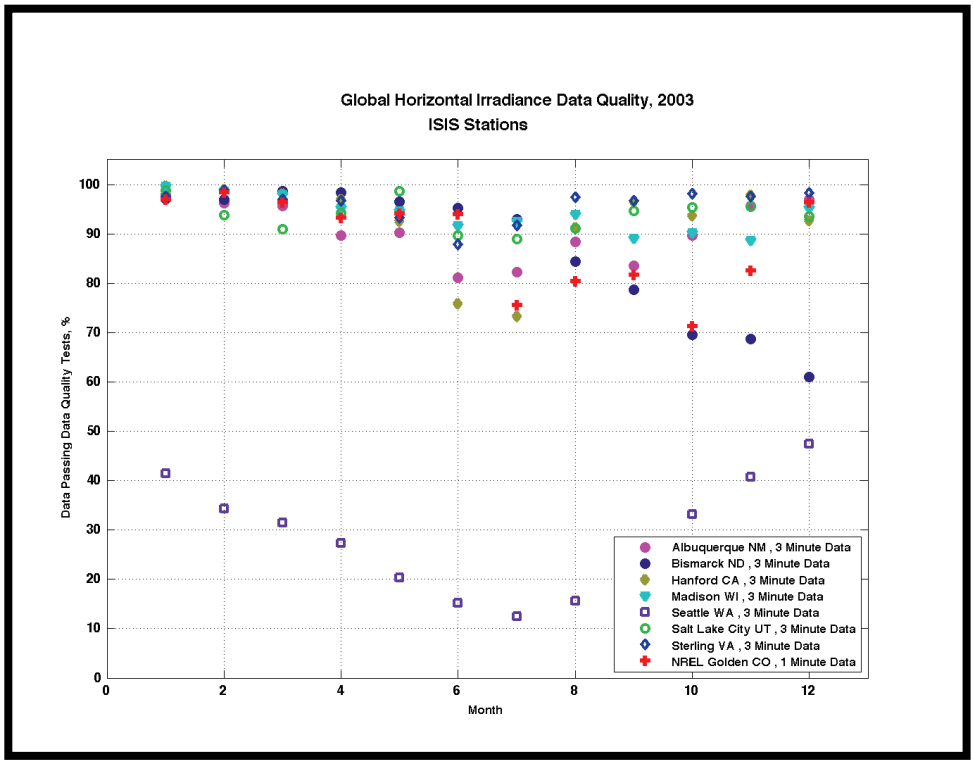


Figure 18. ISIS and SRRL-BMS 2003 GHI that passed data quality tests

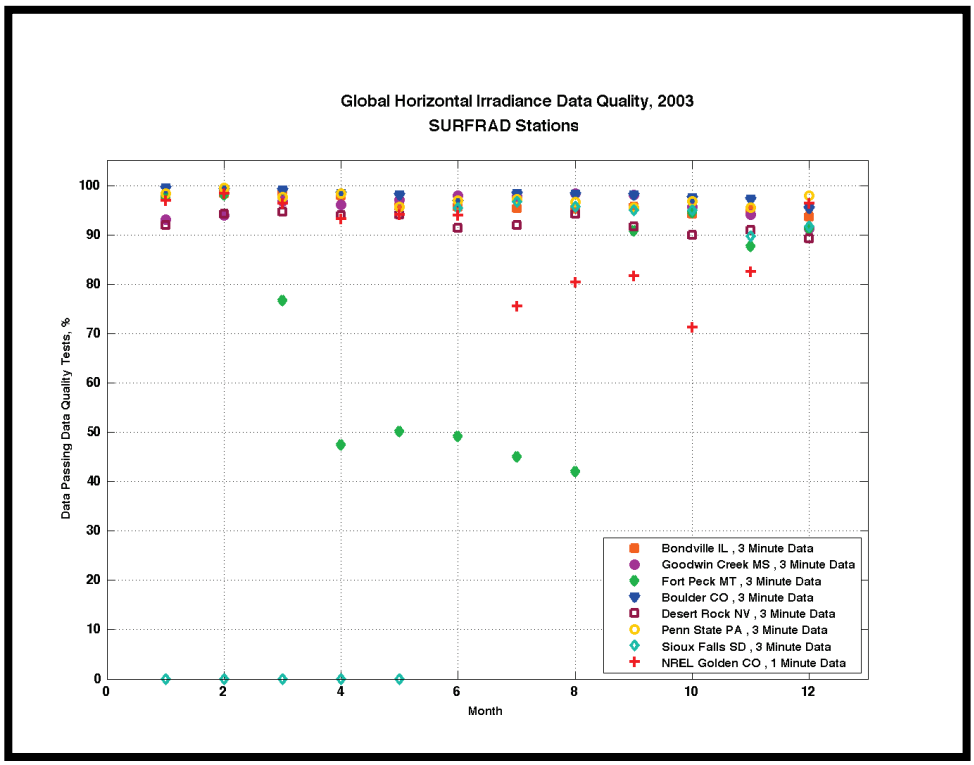


Figure 19. SURFRAD and SRRL-BMS 2003 GHI that passed data quality tests

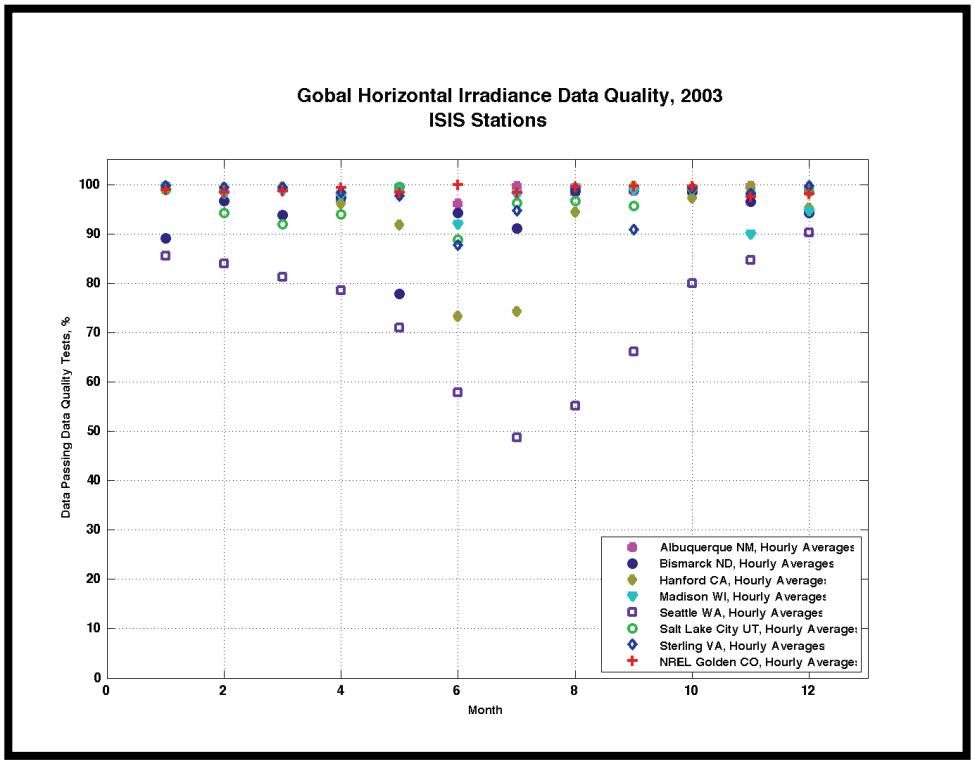


Figure 20. ISIS and SRRL-BMS 2003 hourly average GHI that passed data quality tests

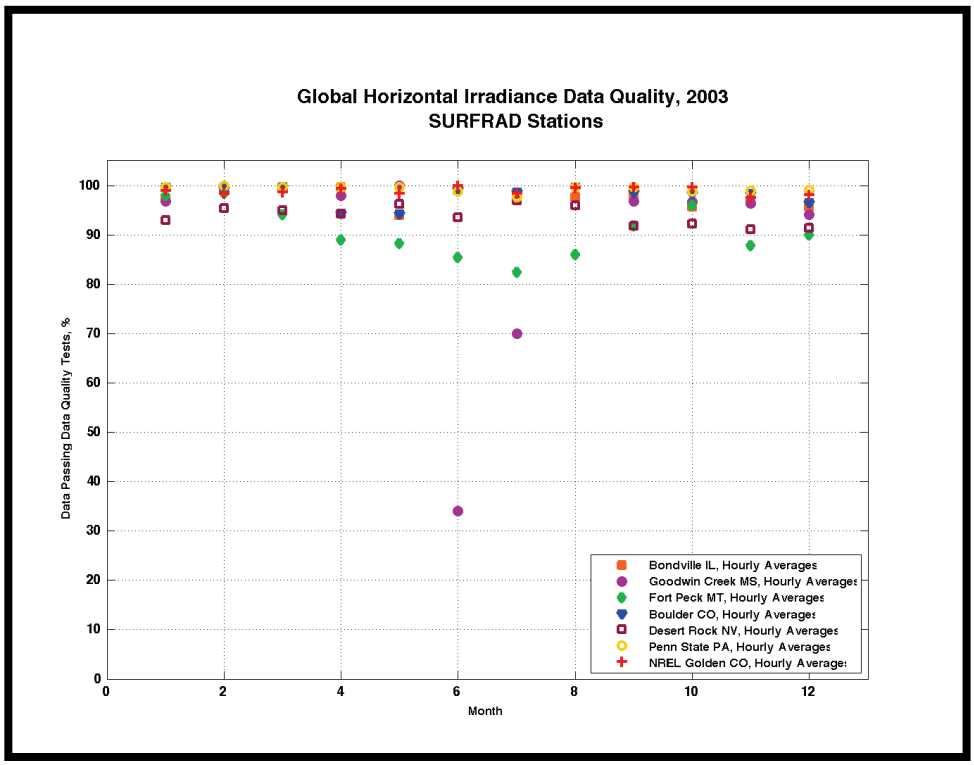


Figure 21. SURFRAD and SRRL-BMS 2002 hourly average GHI that passed data quality tests

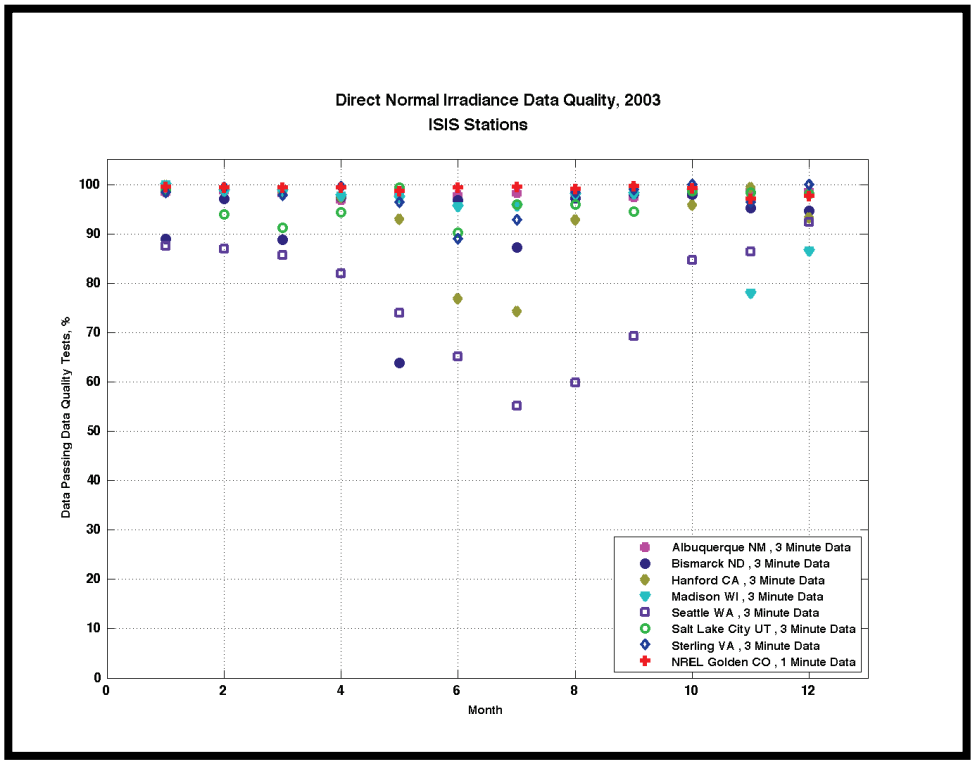


Figure 22. ISIS and SRRL-BMS 2003 DNI that passed data quality tests

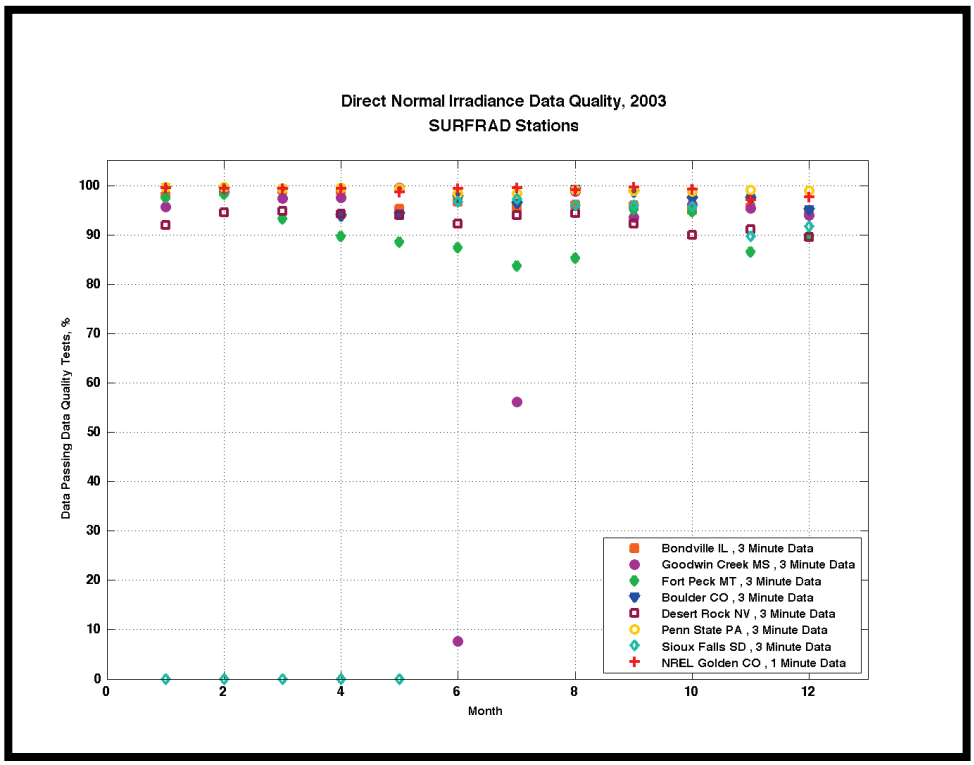


Figure 23. SURFRAD and SRRL-BMS 2003 DNI that passed data quality tests

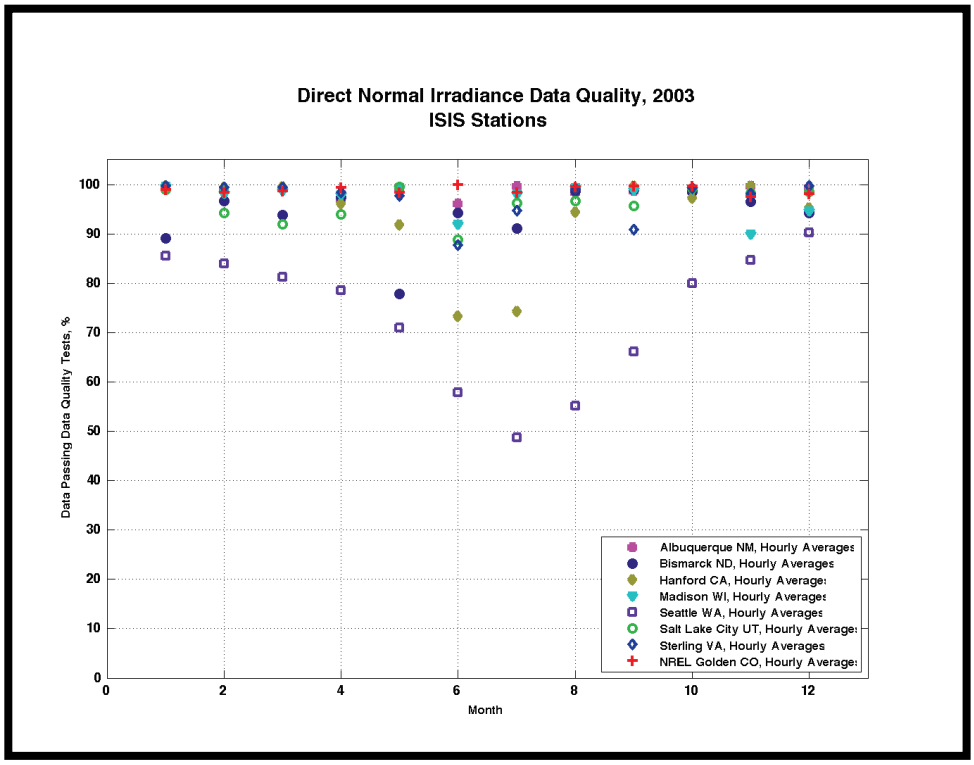


Figure 24. ISIS and SRRL-BMS 2003 hourly average DNI that passed data quality tests

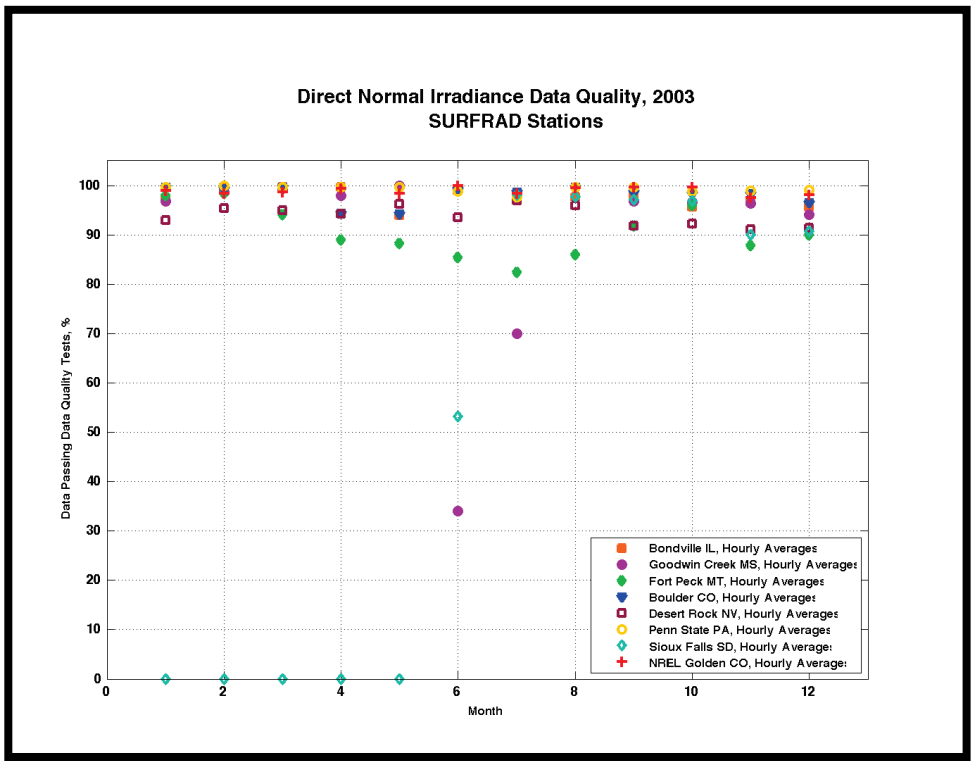


Figure 25. SURFRAD and SRRL-BMS 2003 hourly average DNI that passed data quality tests

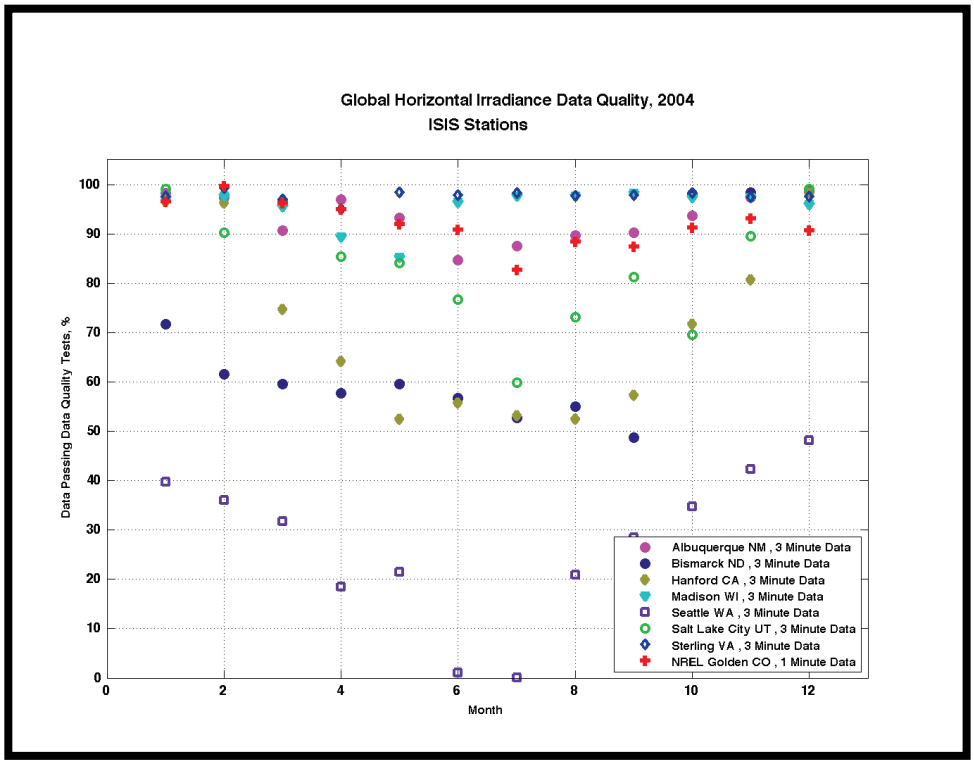


Figure 26. ISIS and SRRL-BMS 2004 GHI that passed data quality tests

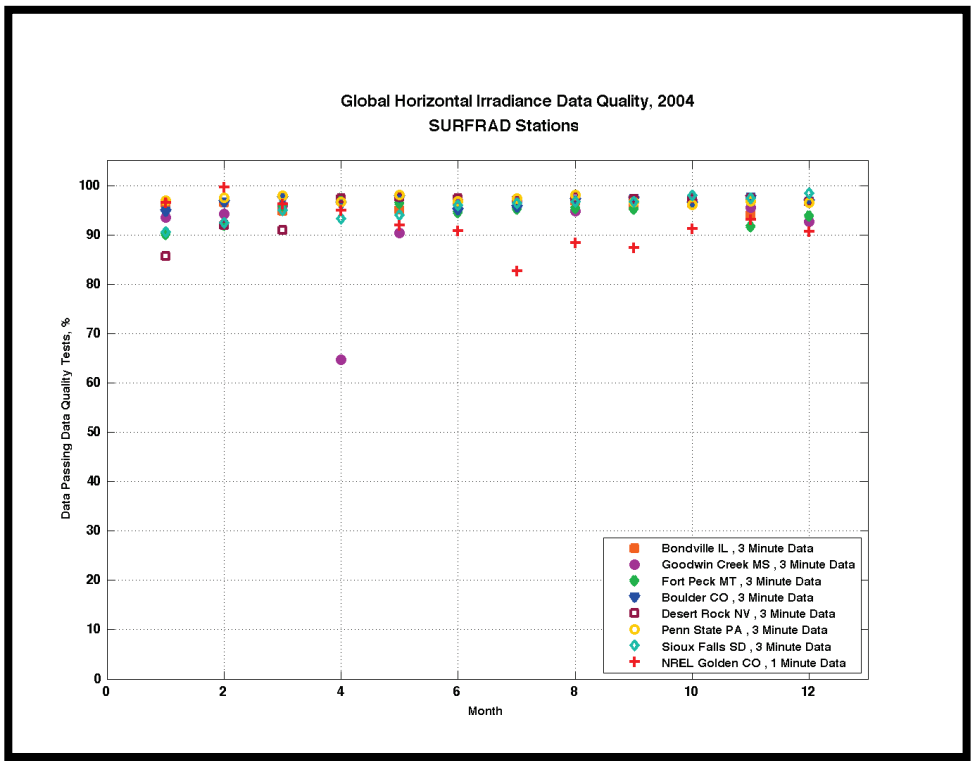


Figure 27. SURFRAD and SRRL-BMS 2004 GHI that passed data quality tests

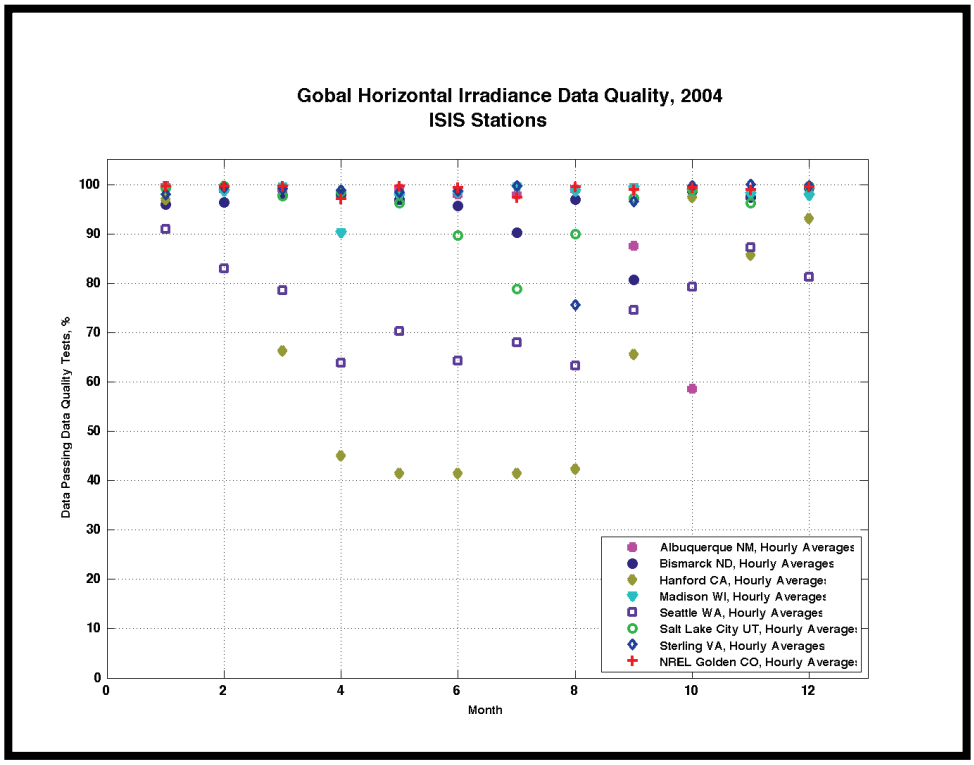
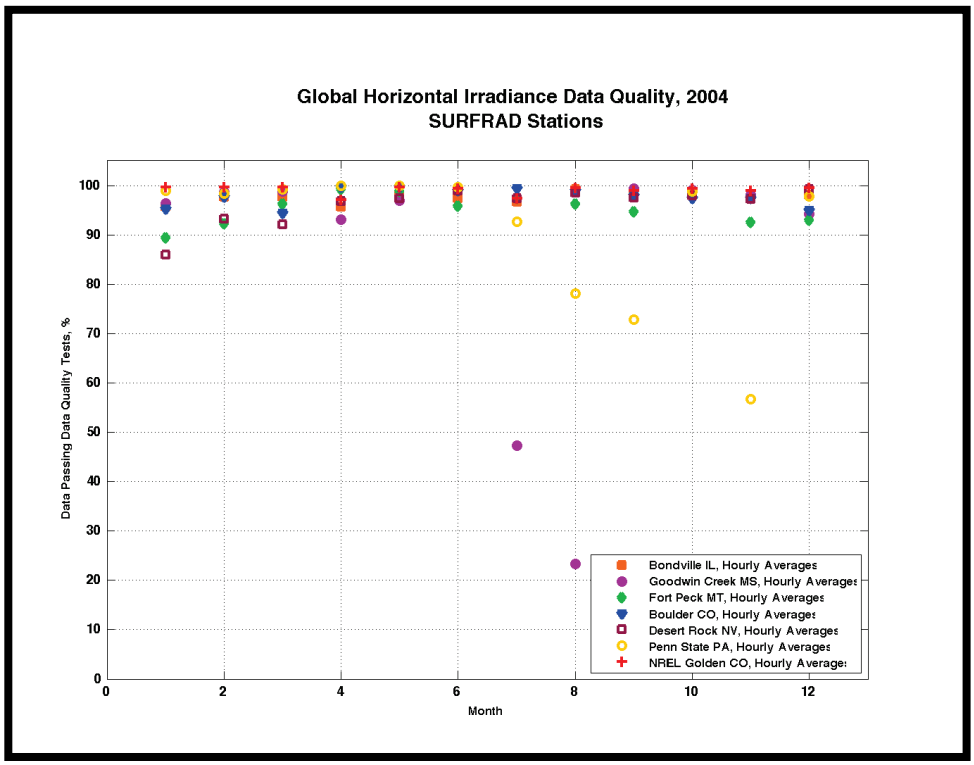


Figure 28. ISIS and SRRL-BMS 2004 hourly average GHI that passed data quality tests



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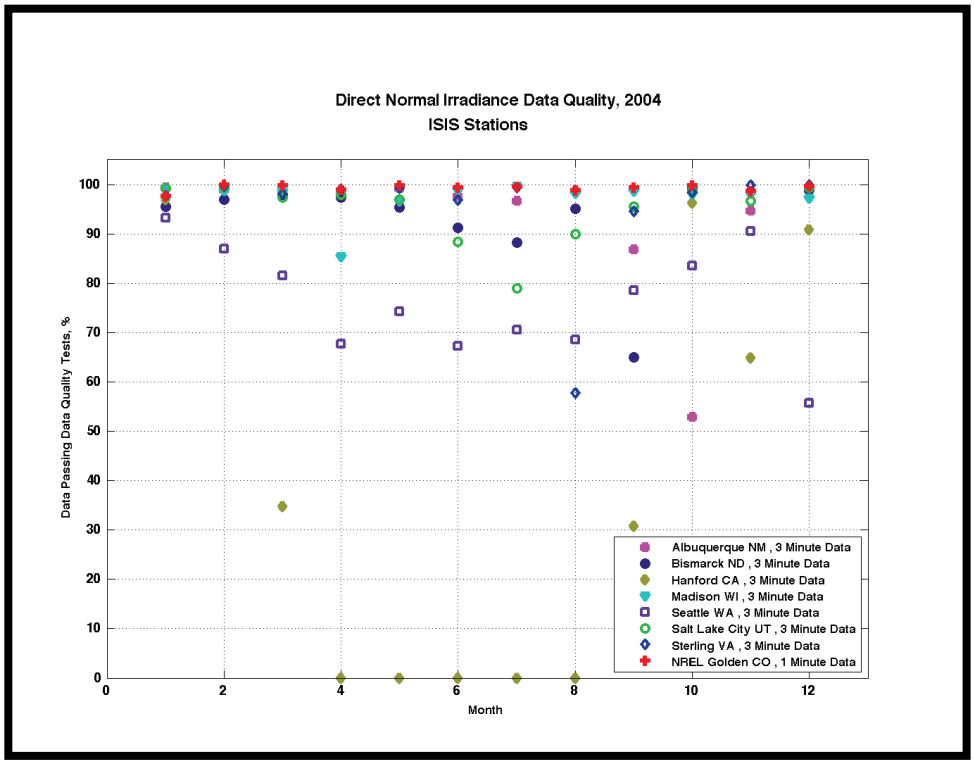
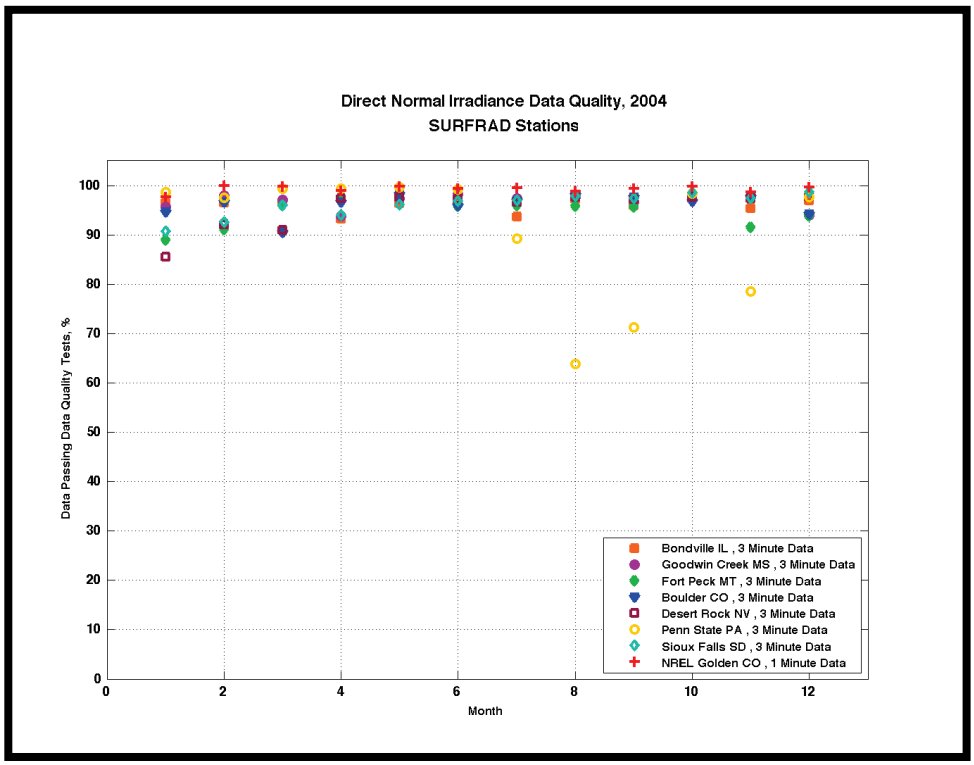


Figure 30. ISIS and SRRL-BMS 2004 DNI that passed data quality tests



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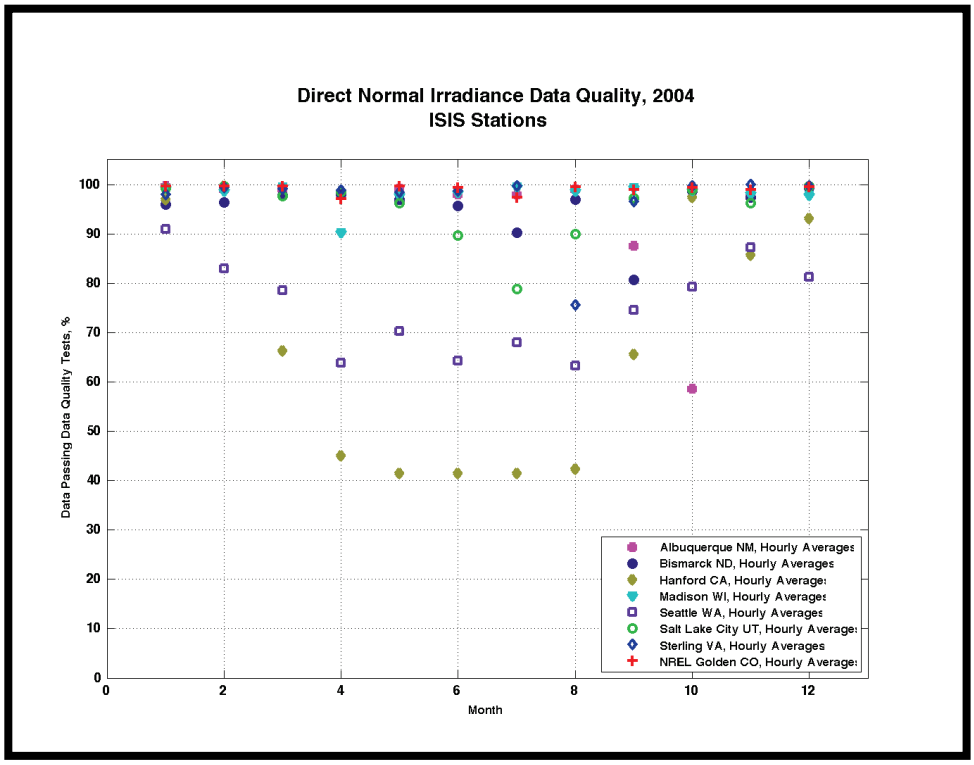
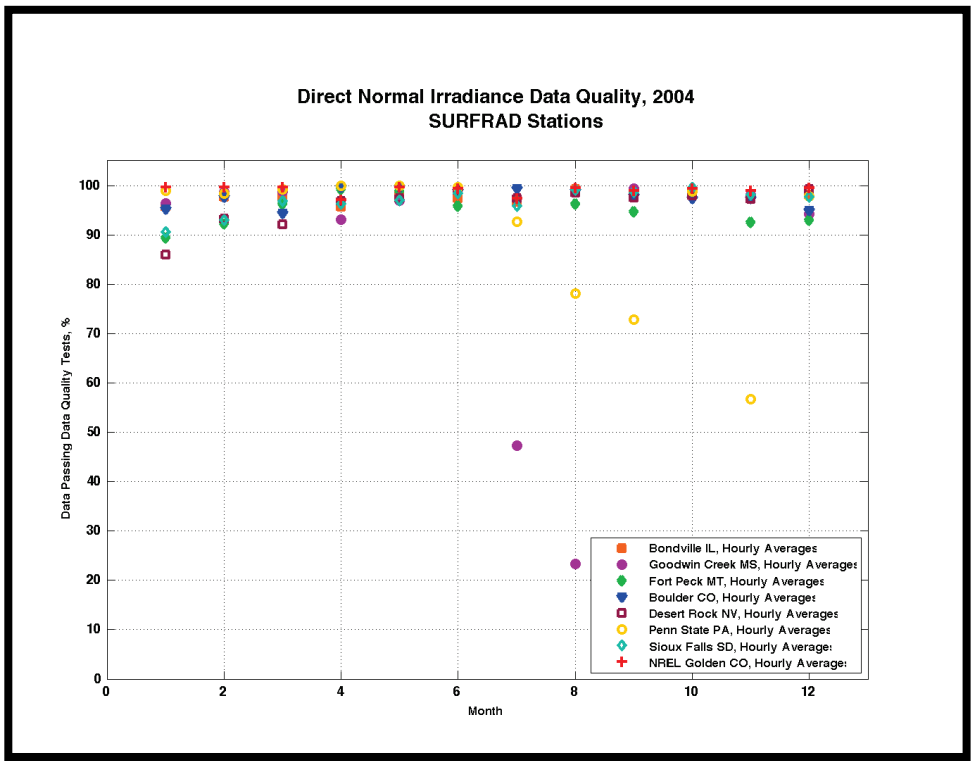


Figure 32. ISIS and SRRL-BMS 2004 hourly average DNI that passed data quality tests



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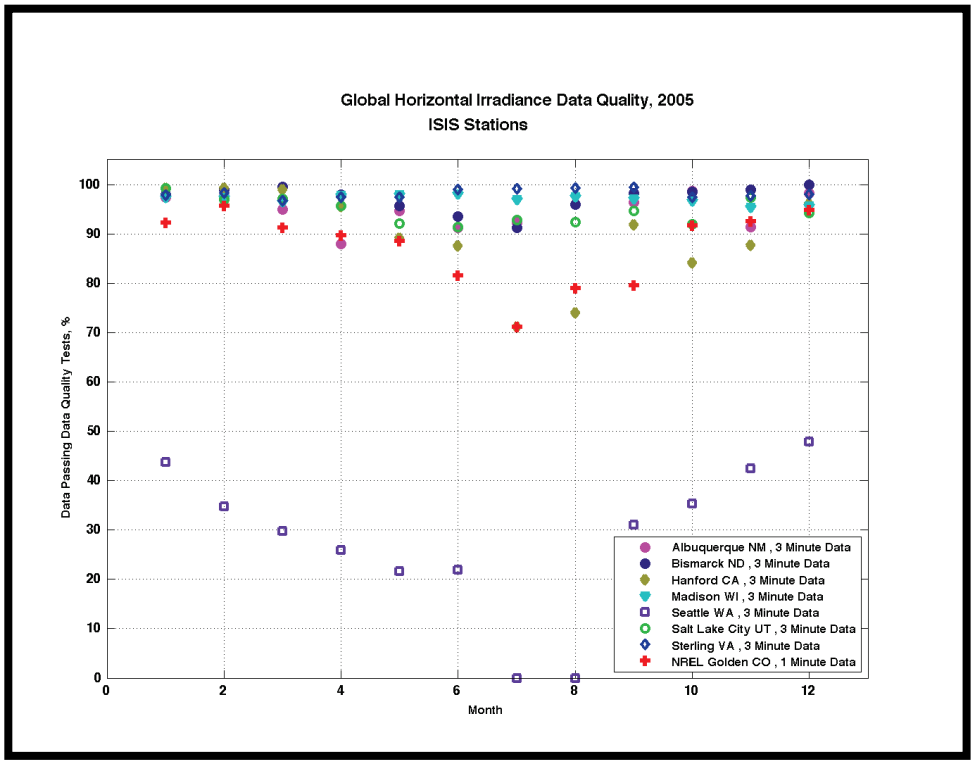

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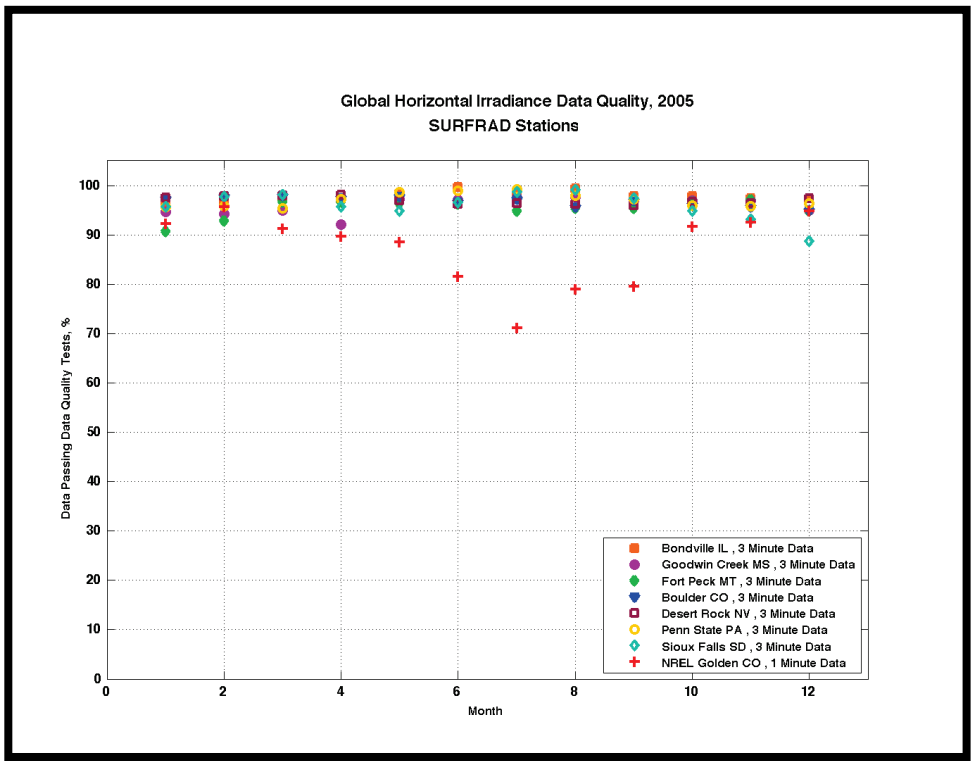

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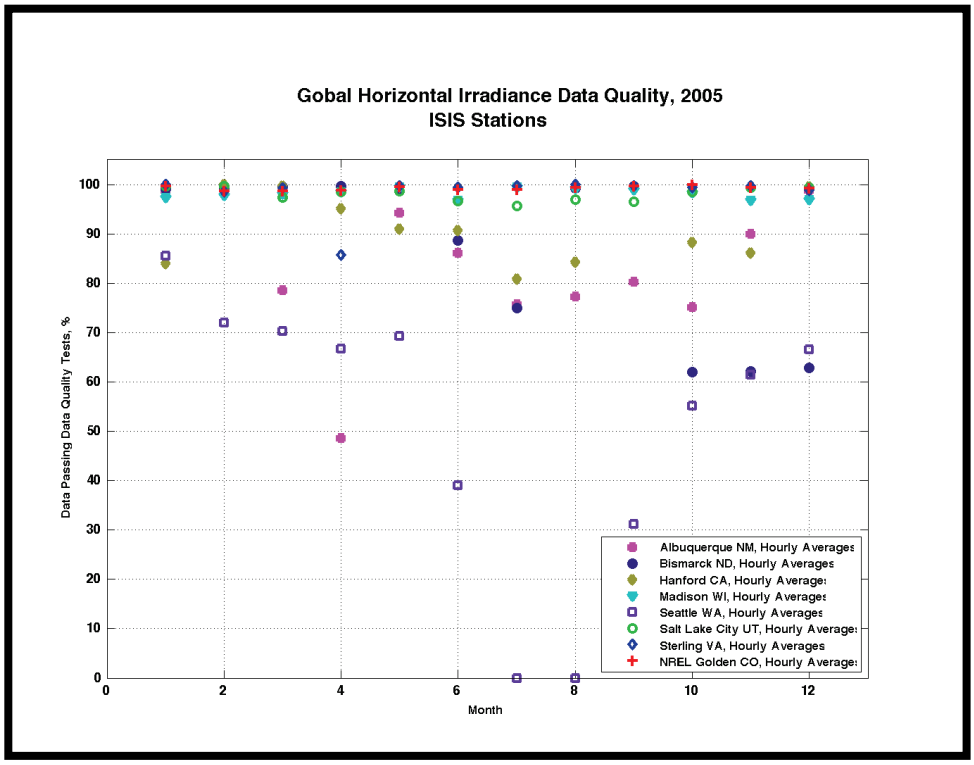

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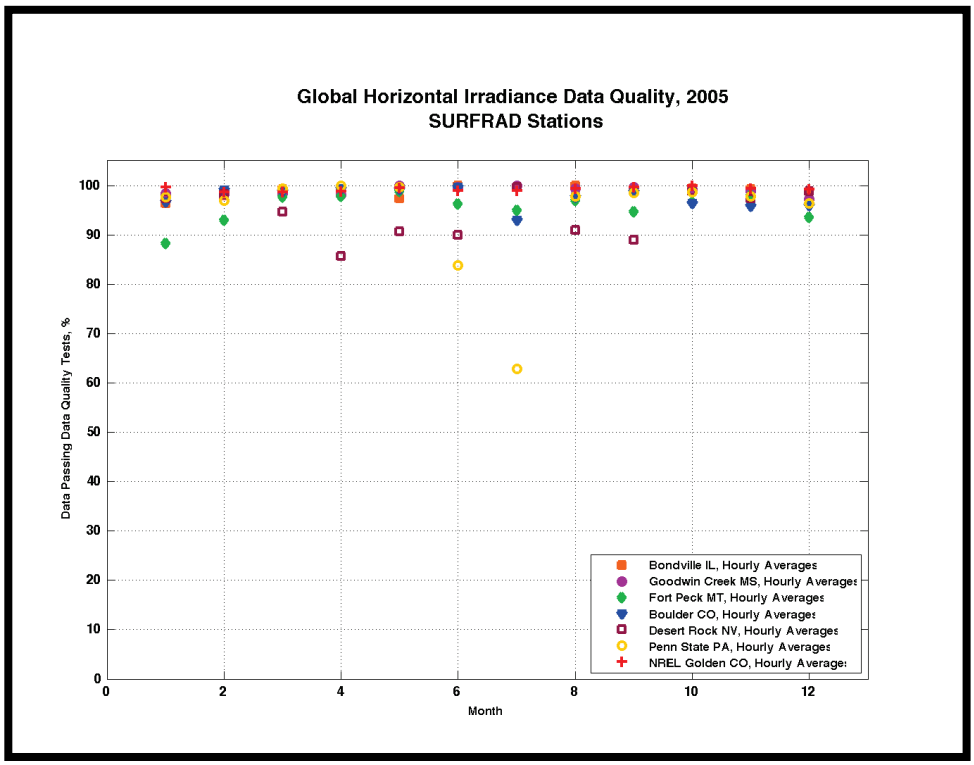

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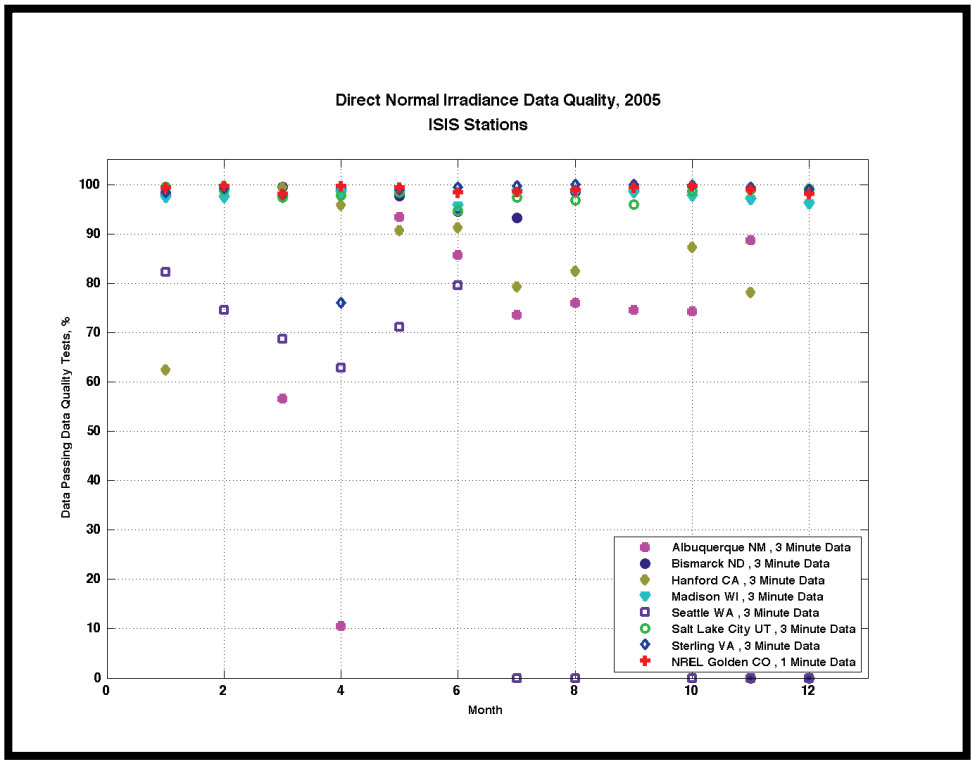

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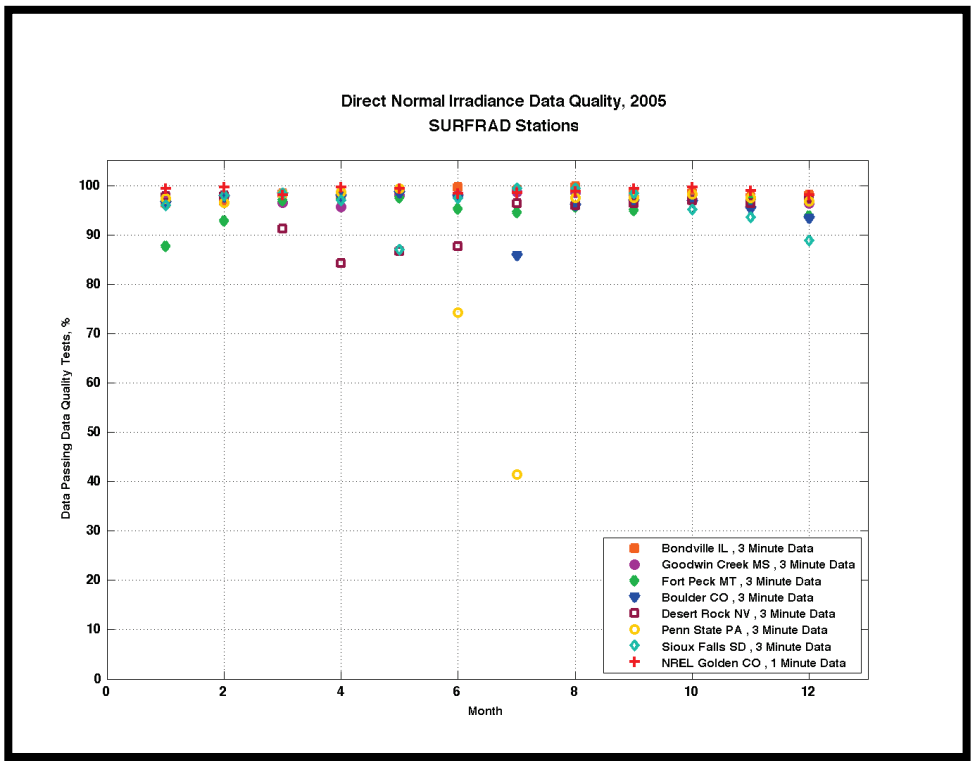

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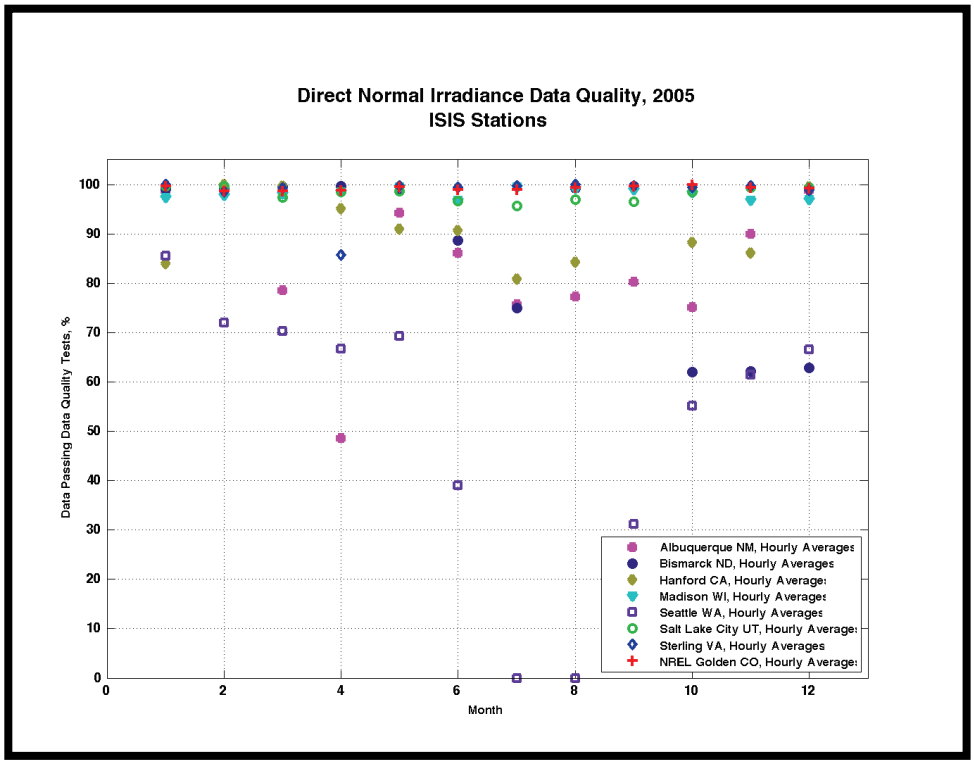

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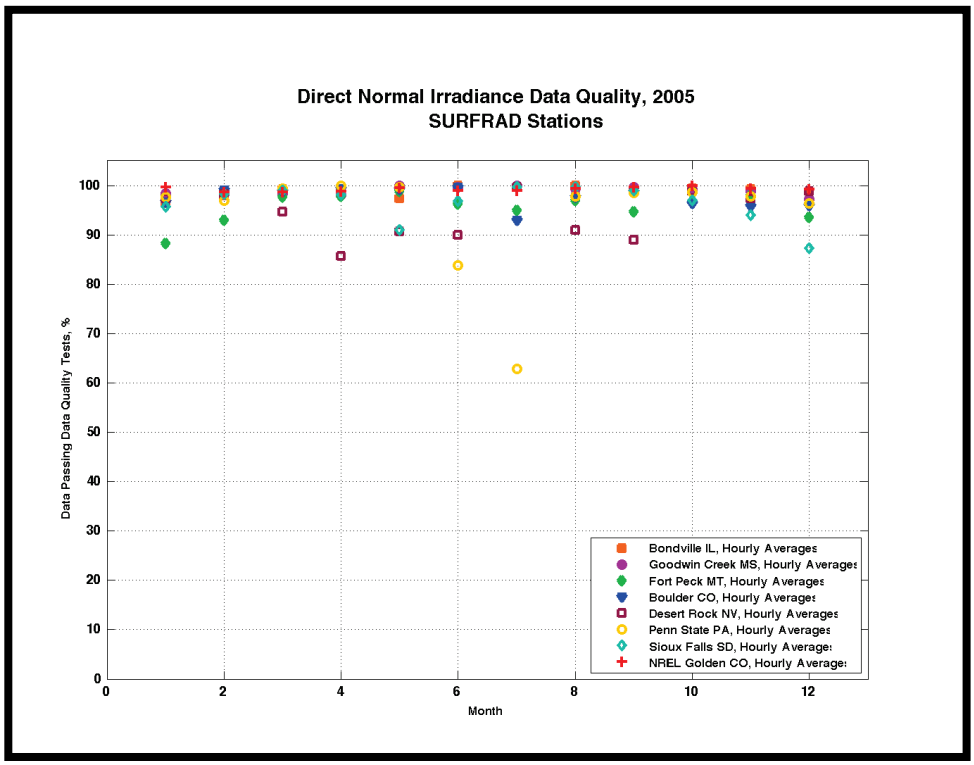

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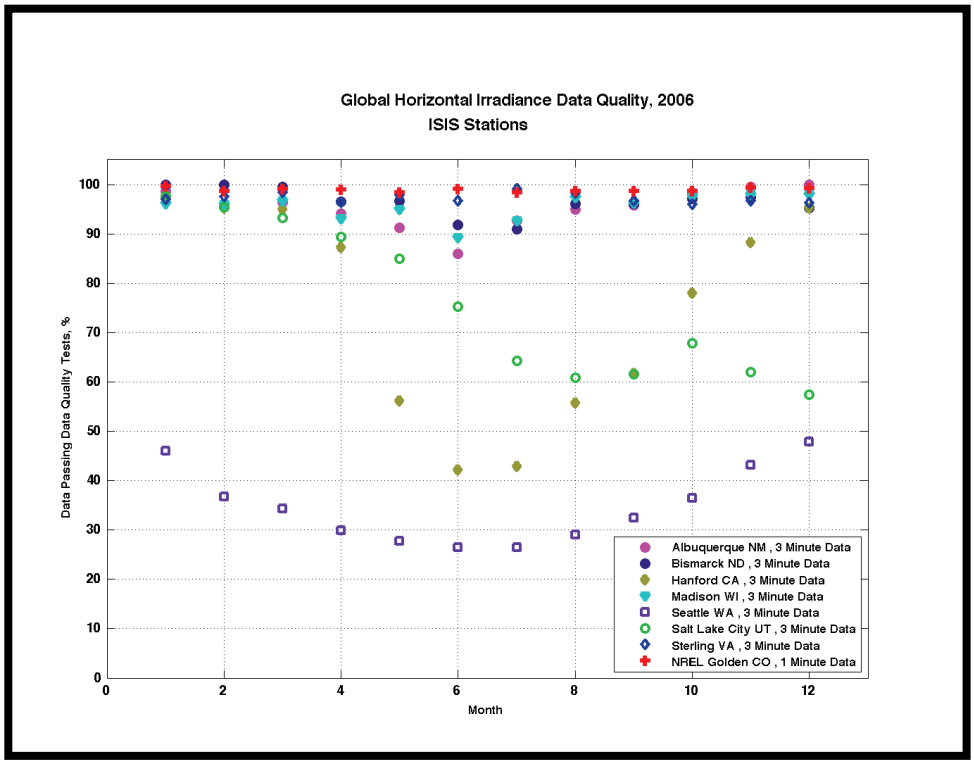

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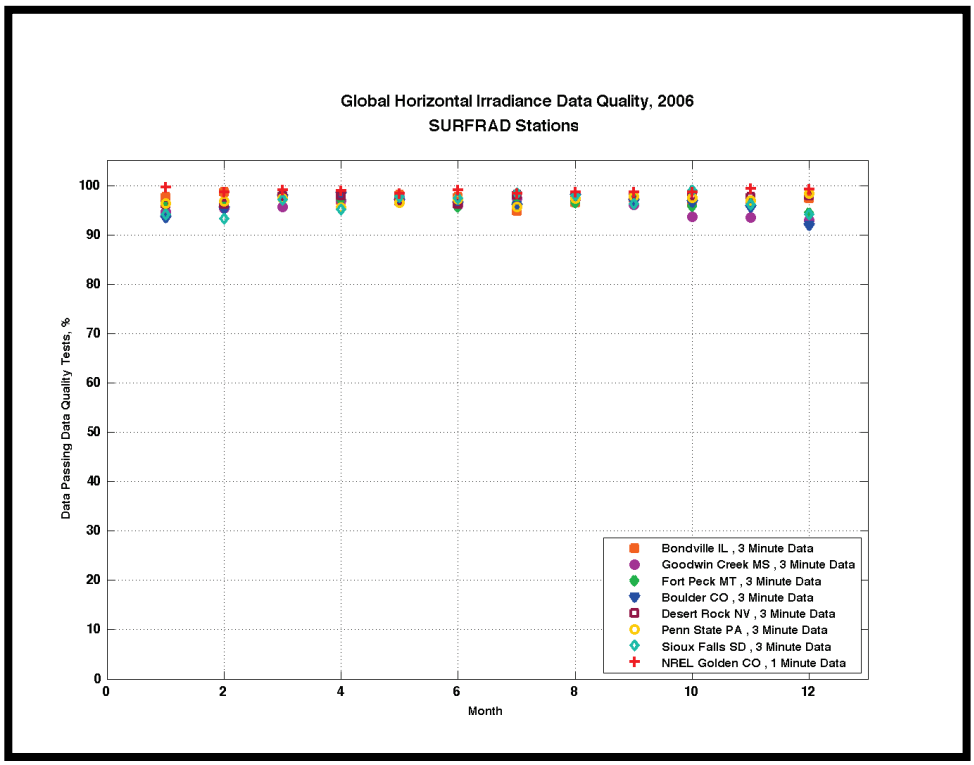

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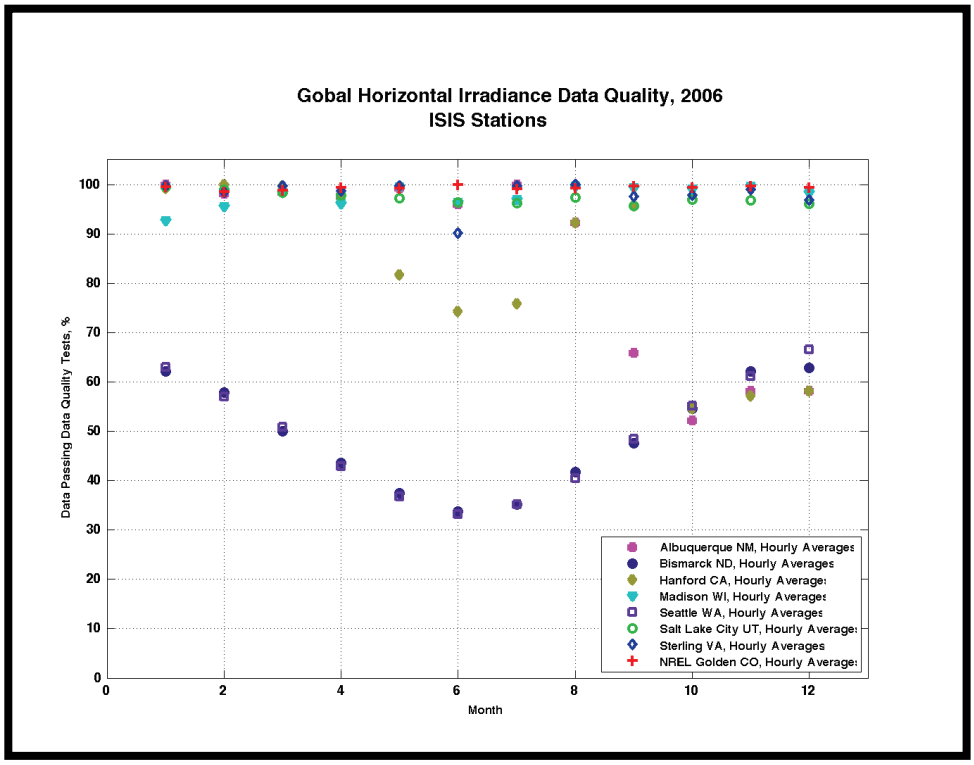

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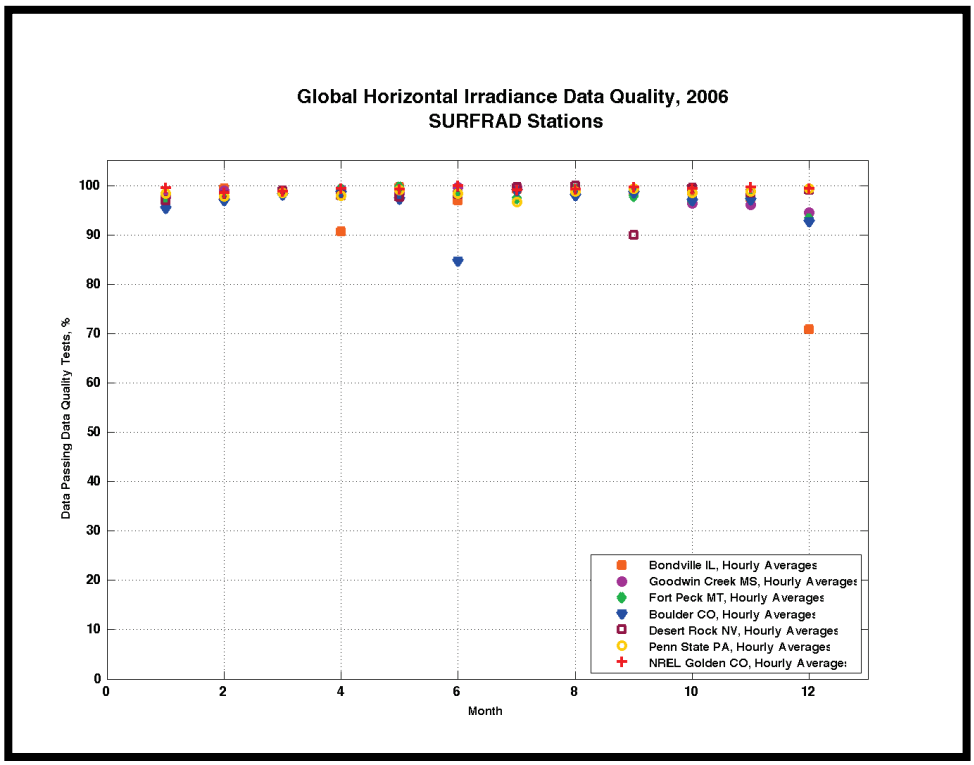

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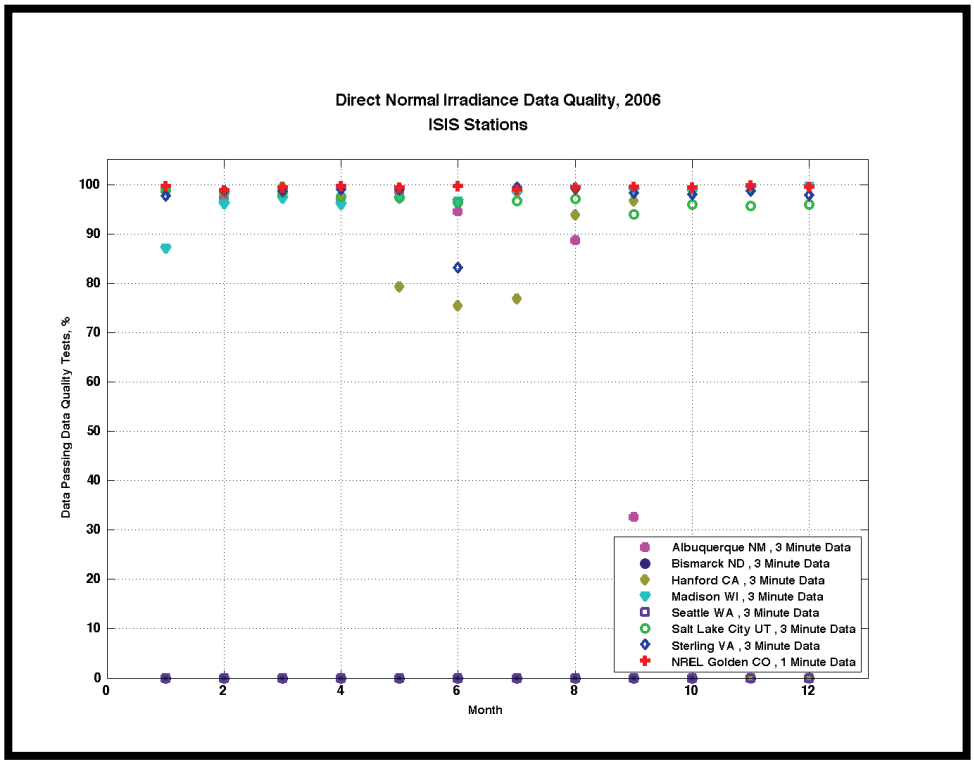

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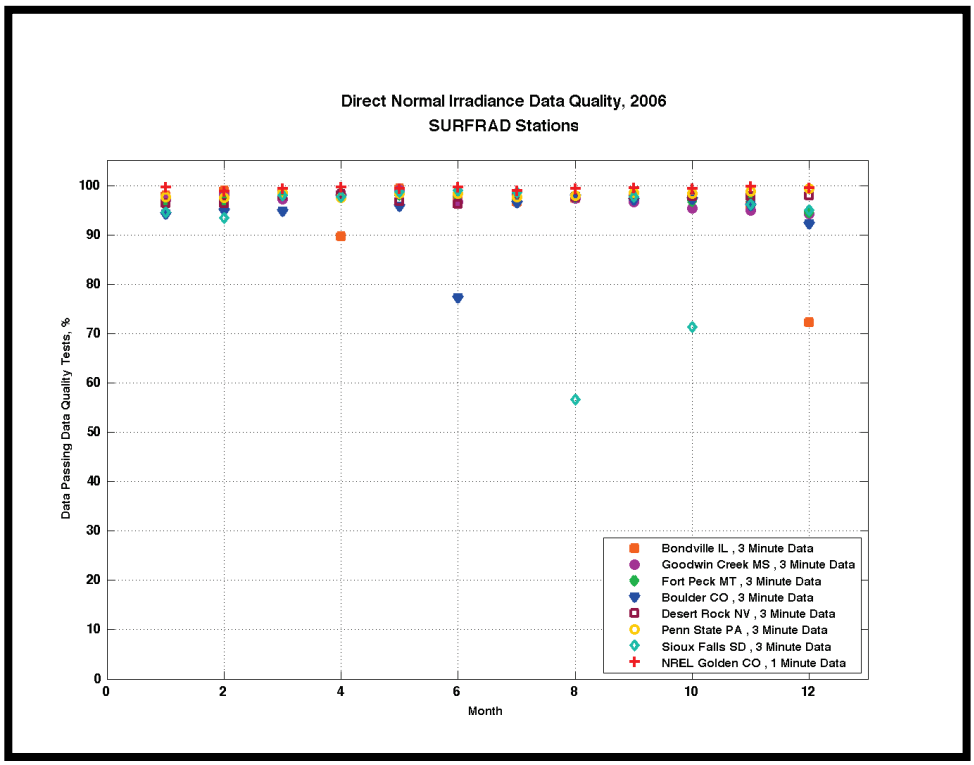

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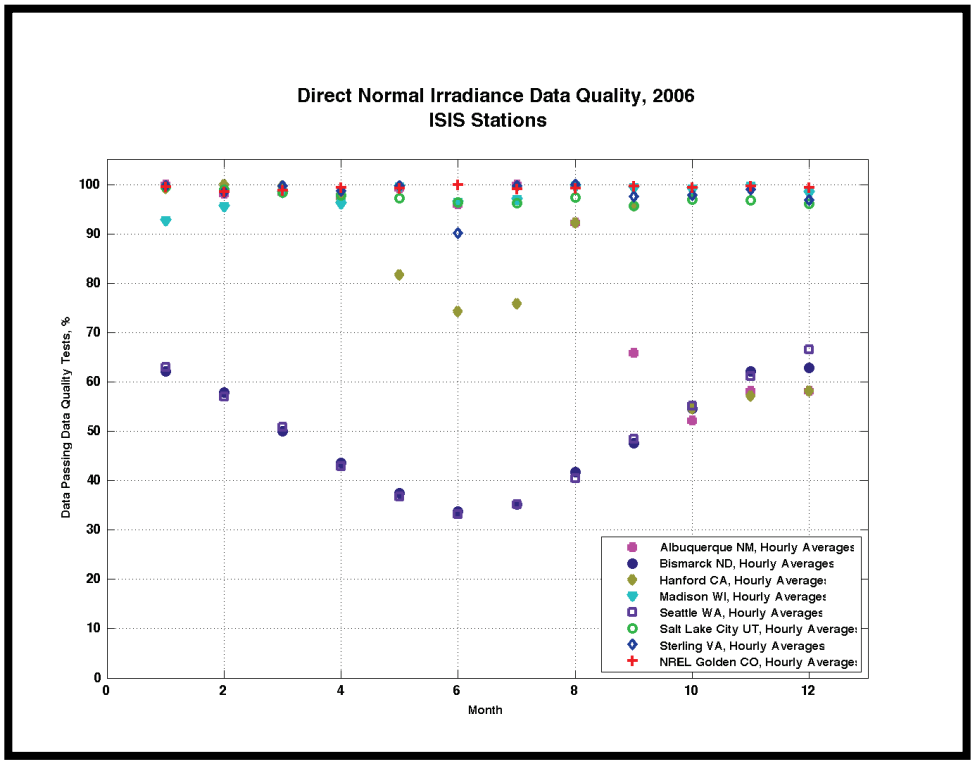

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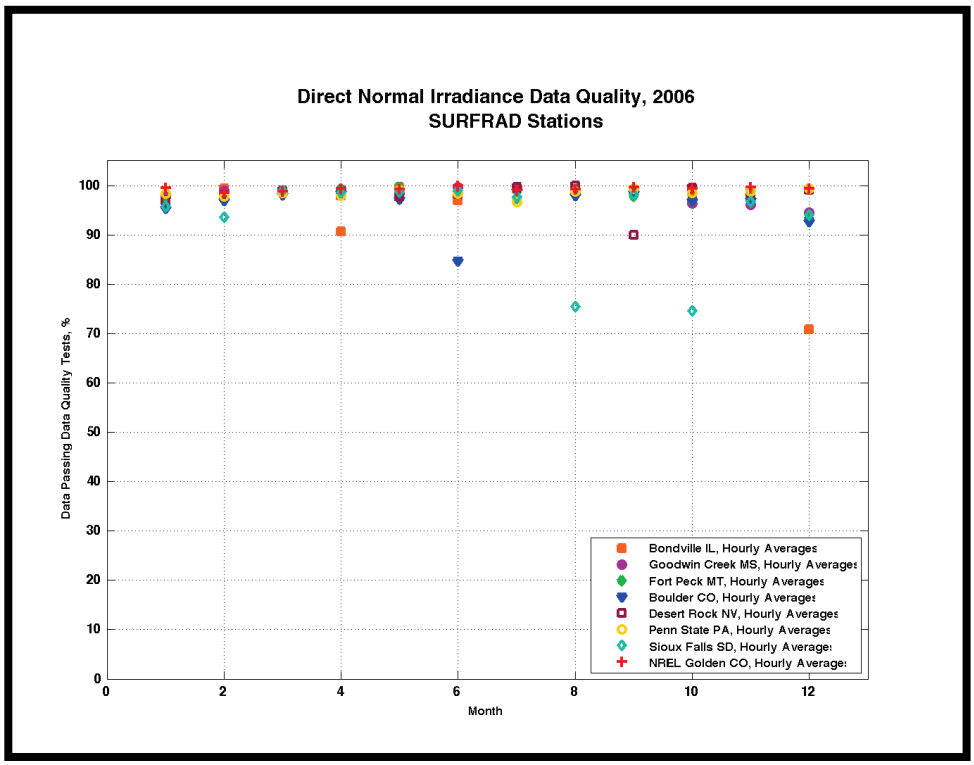

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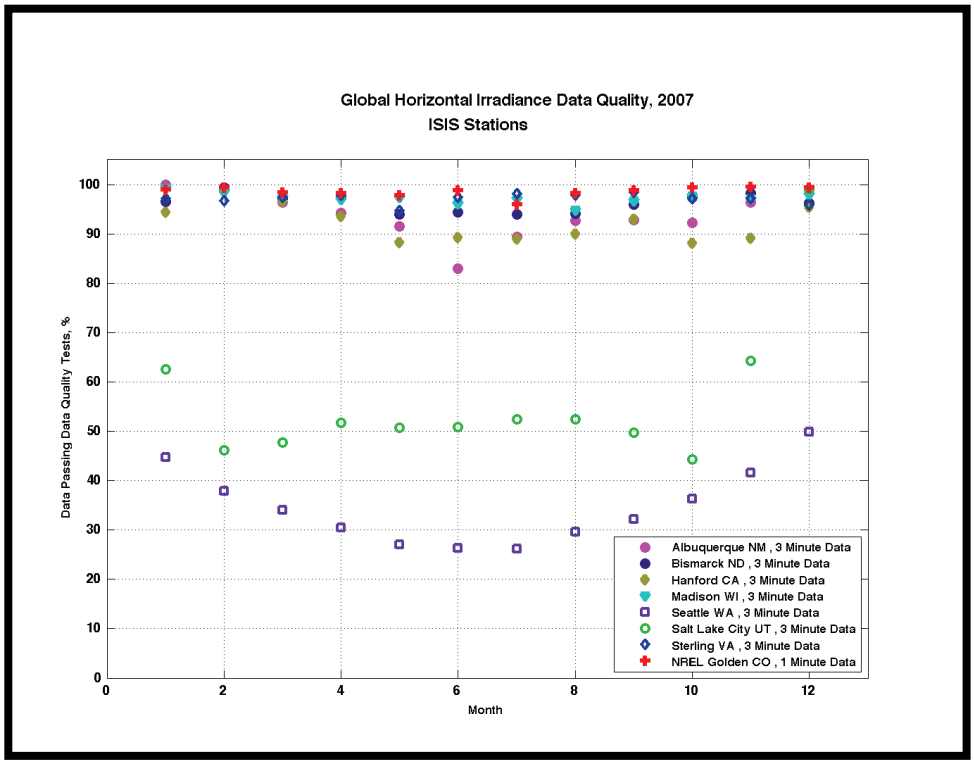

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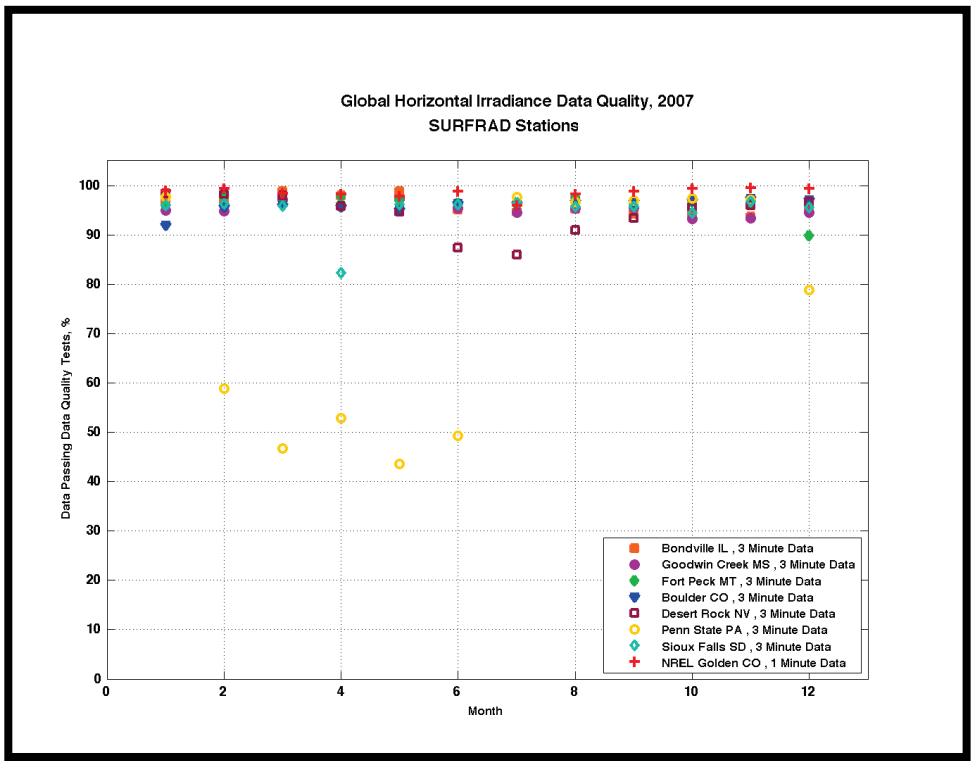

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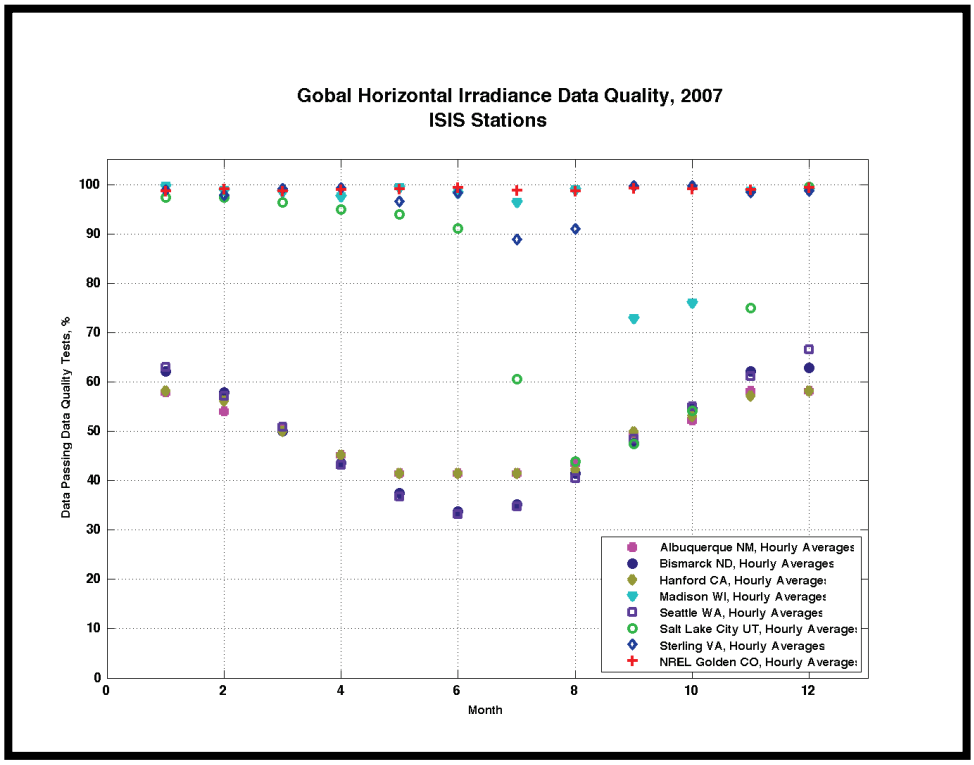

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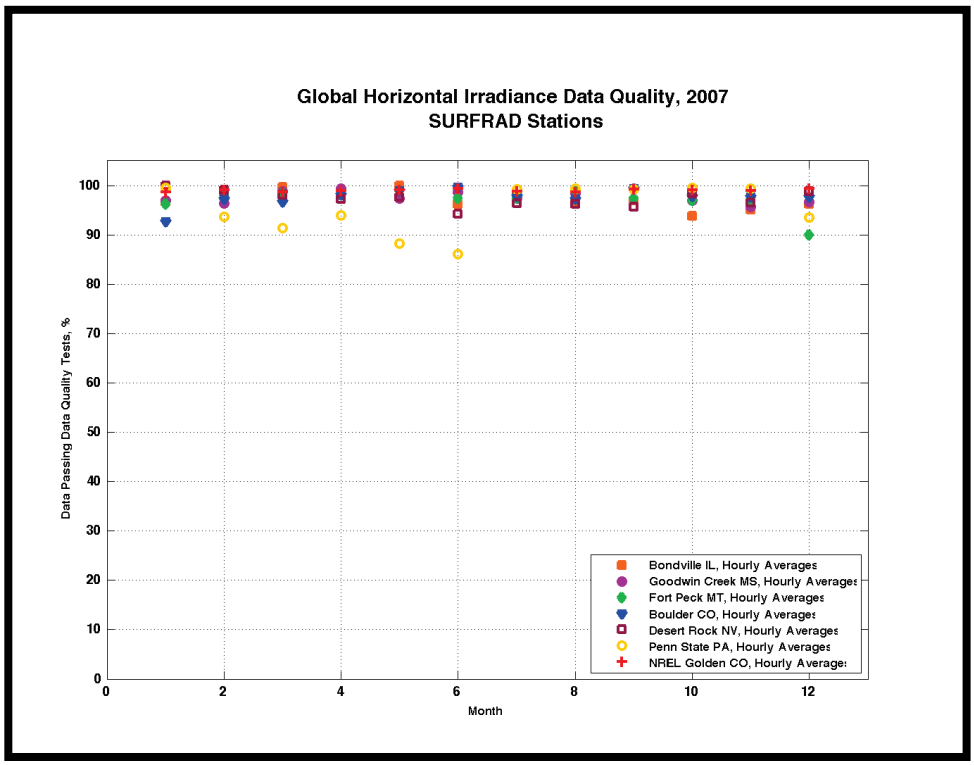

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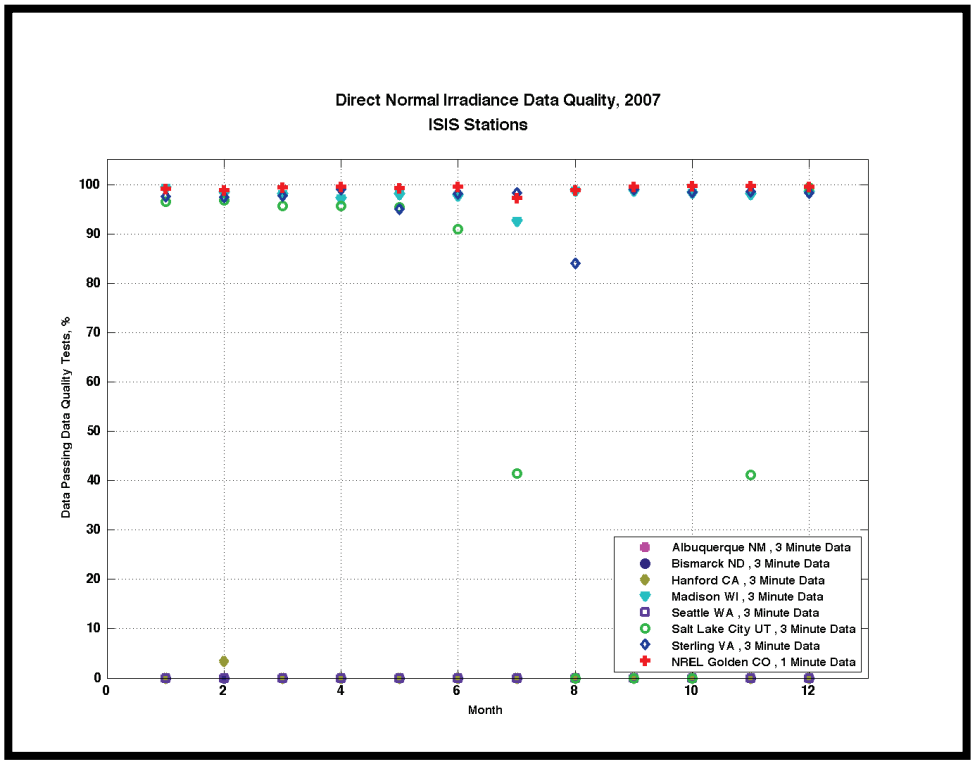


Figure 54. ISIS and SRRL-BMS 2007 DNI that passed data quality tests

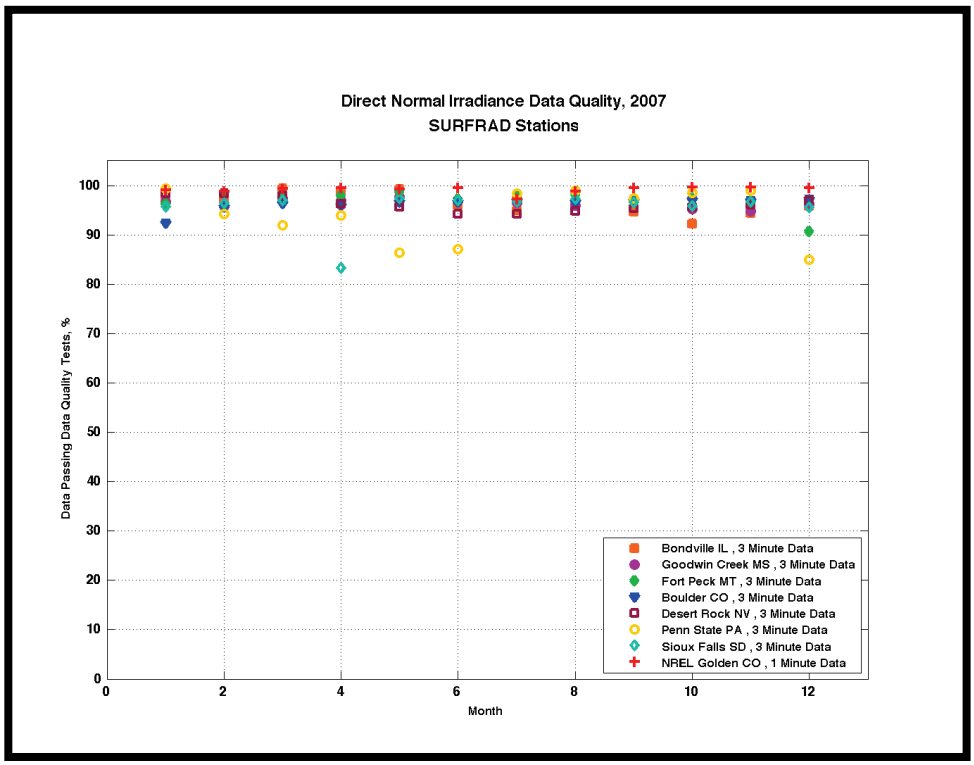


Figure 55. SURFRAD and SRRL-BMS 2007 DNI that passed data quality tests

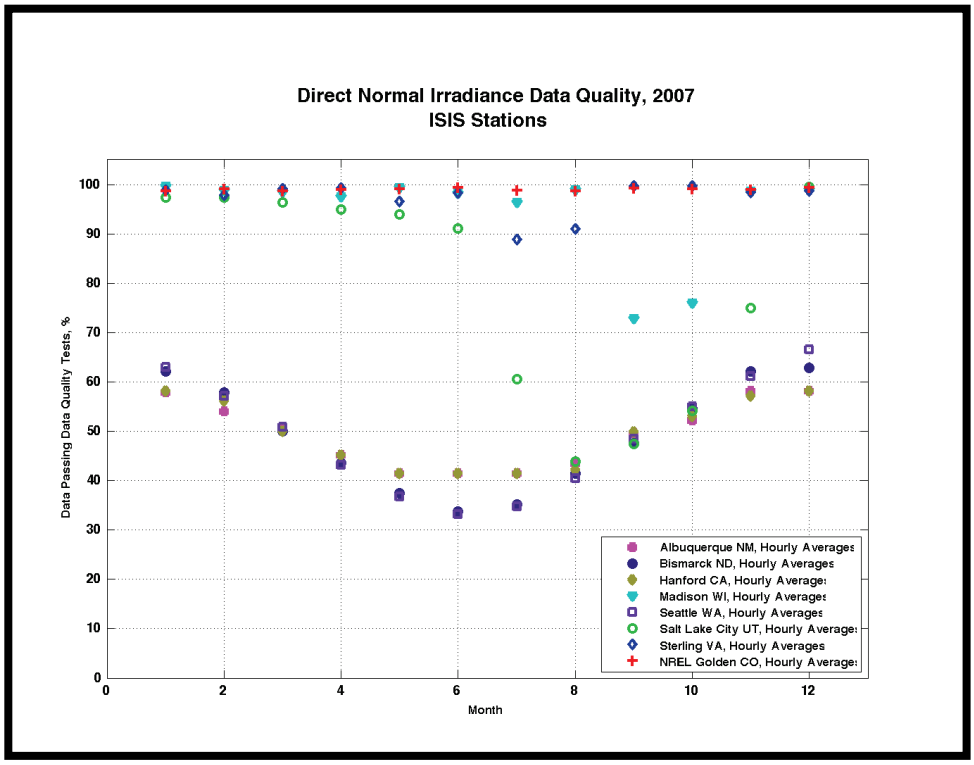


Figure 56. ISIS and SRRL-BMS 2007 hourly average DNI that passed data quality tests

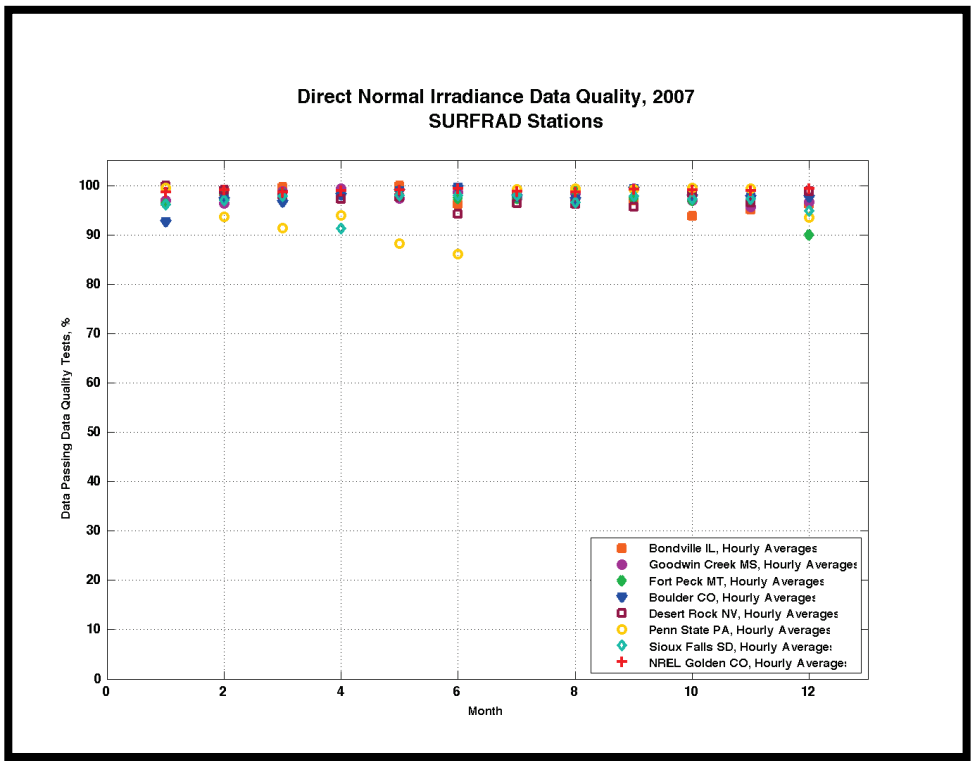


Figure 57. SURFRAD and SRRL-BMS 2007 hourly average DNI that passed data quality tests

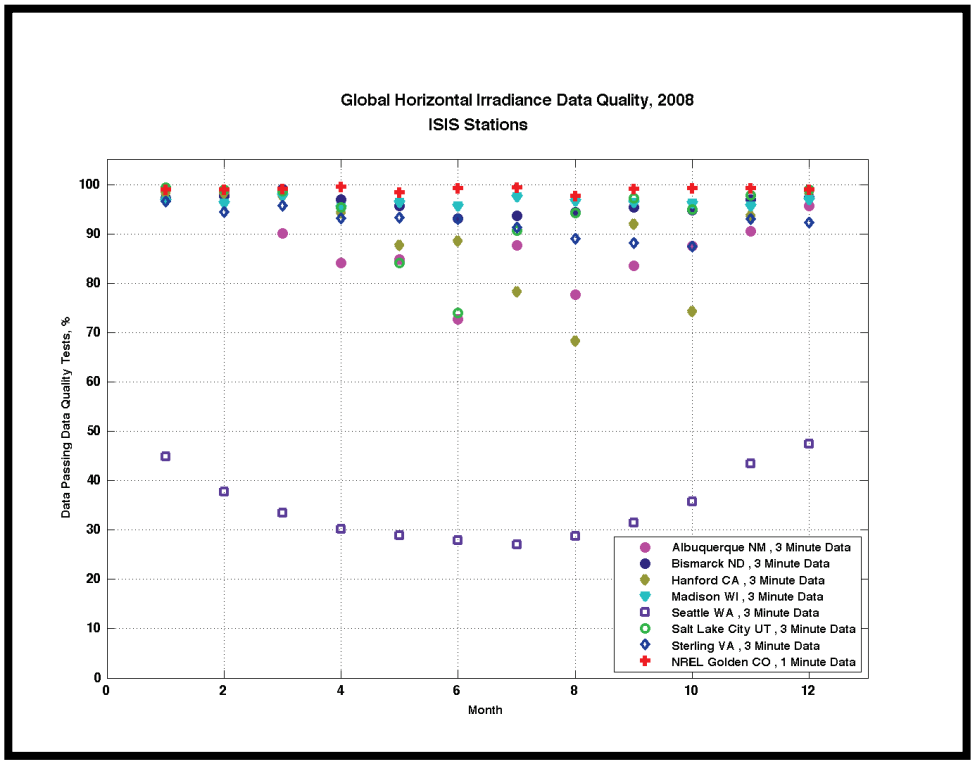
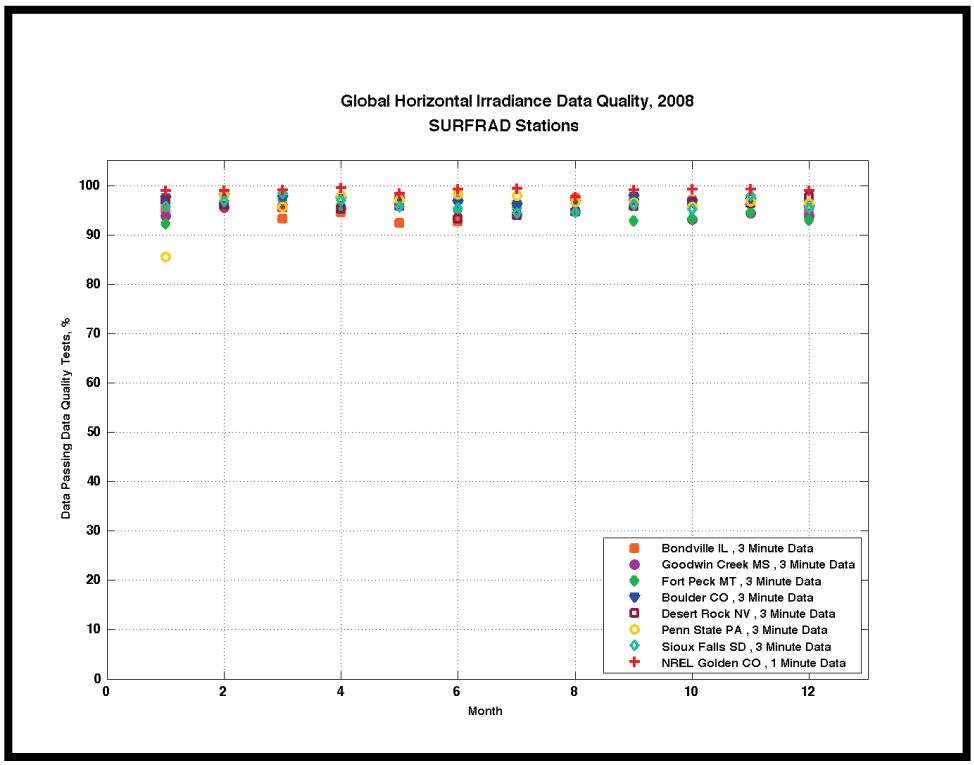


Figure 58. ISIS and SRRL-BMS 2008 GHI that passed data quality tests



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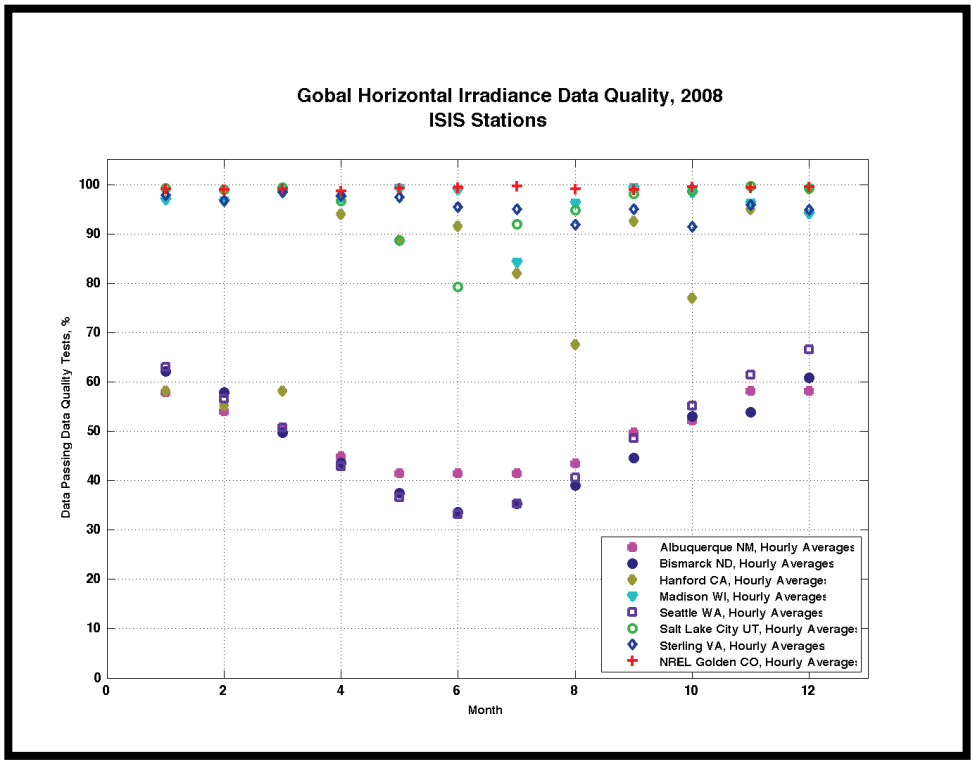


Figure 60. ISIS and SRRL-BMS 2008 hourly average GHI that passed data quality tests

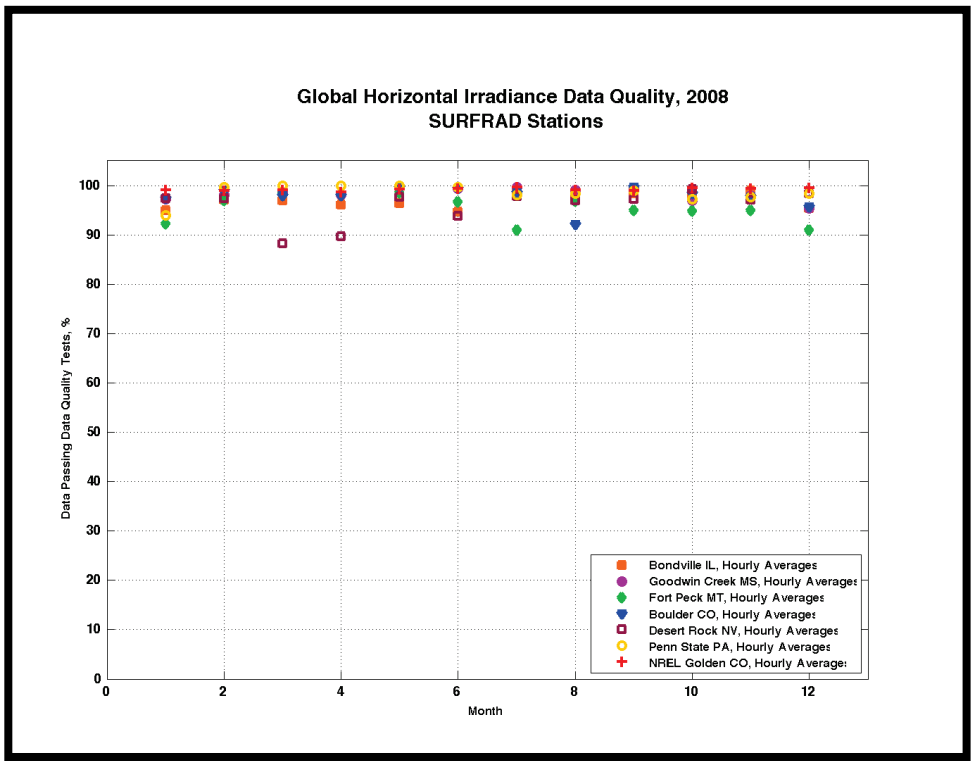


Figure 61. SURFRAD and SRRL-BMS 2008 hourly average GHI that passed data quality tests

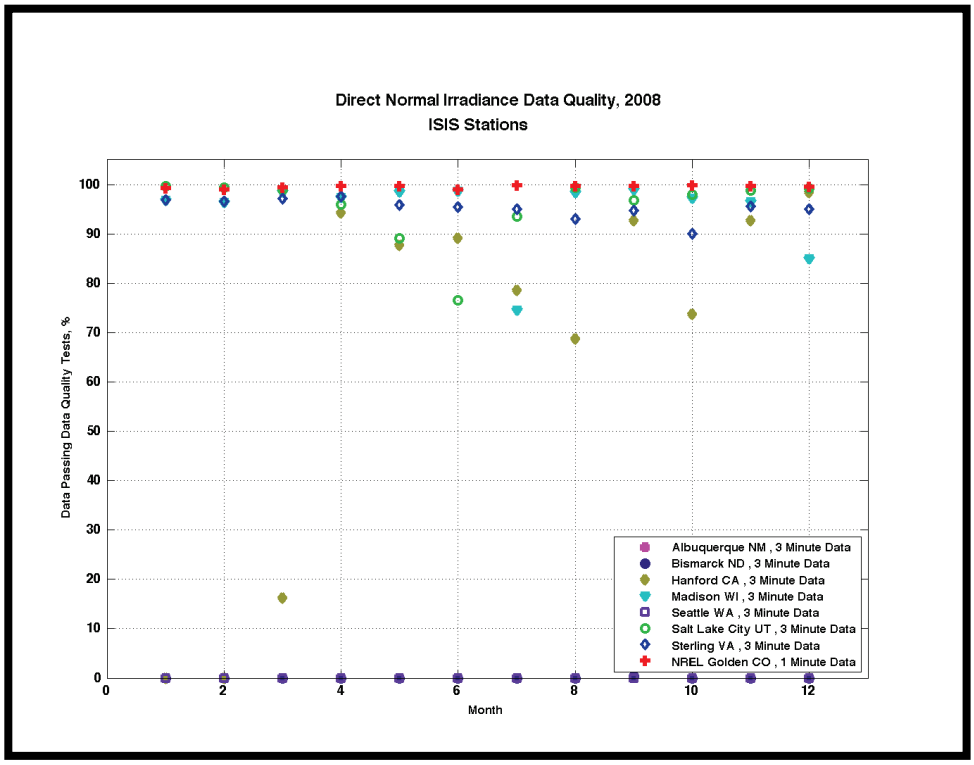


Figure 62. ISIS and SRRL-BMS 2008 DNI that passed data quality tests

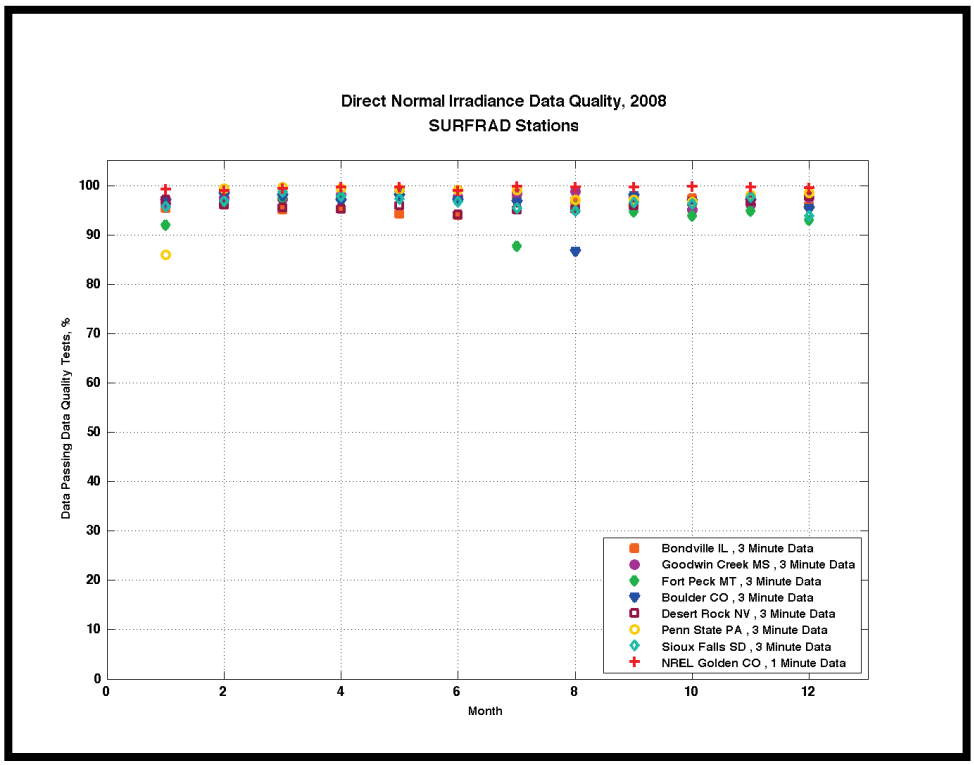


Figure 63. SURFRAD and SRRL-BMS 2008 DNI that passed data quality tests

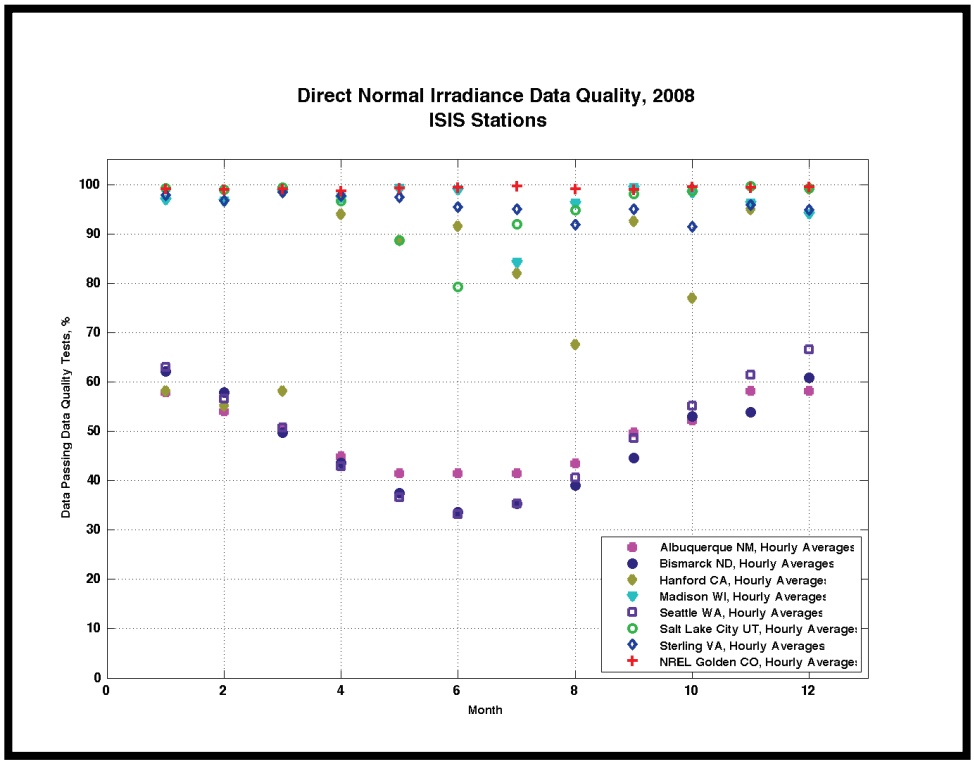


Figure 64. ISIS and SRRL-BMS 2008 hourly average DNI that passed data quality tests

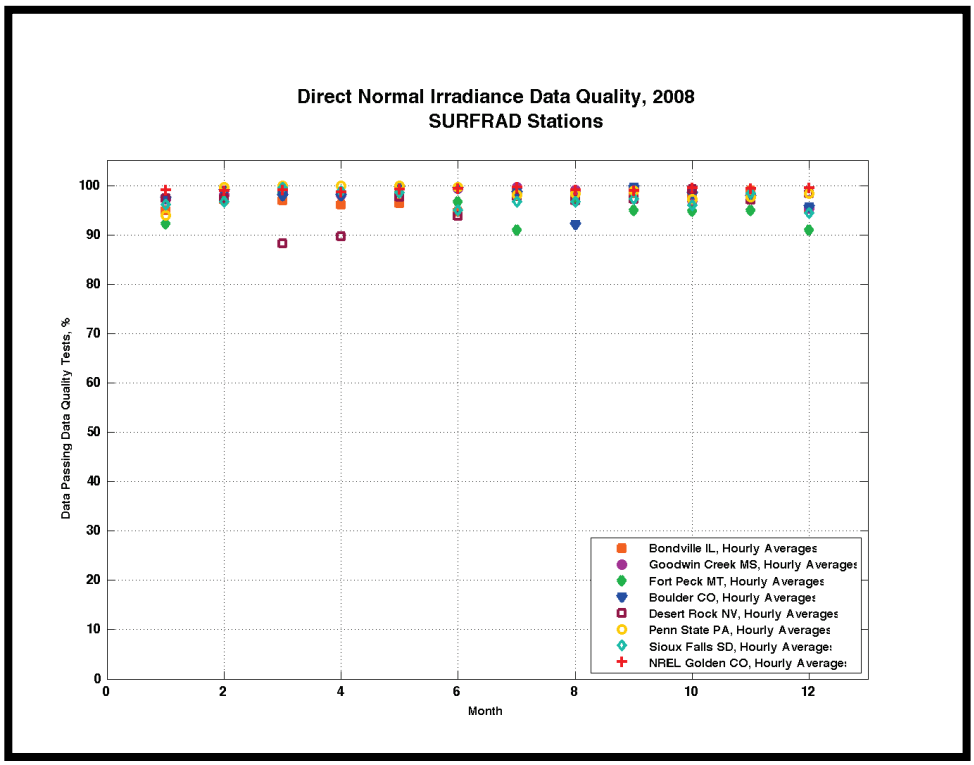


Figure 65. SURFRAD and SRRL-BMS 2008 hourly average DNI that passed data quality tests

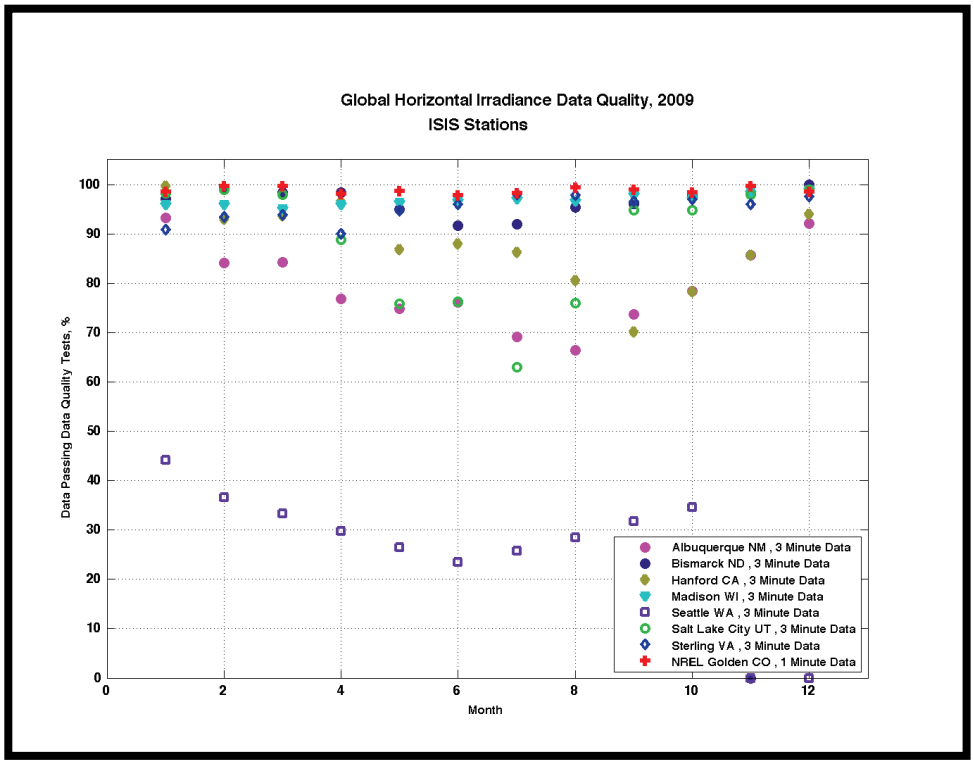


Figure 66. ISIS and SRRL-BMS 2009 GHI that passed data quality tests

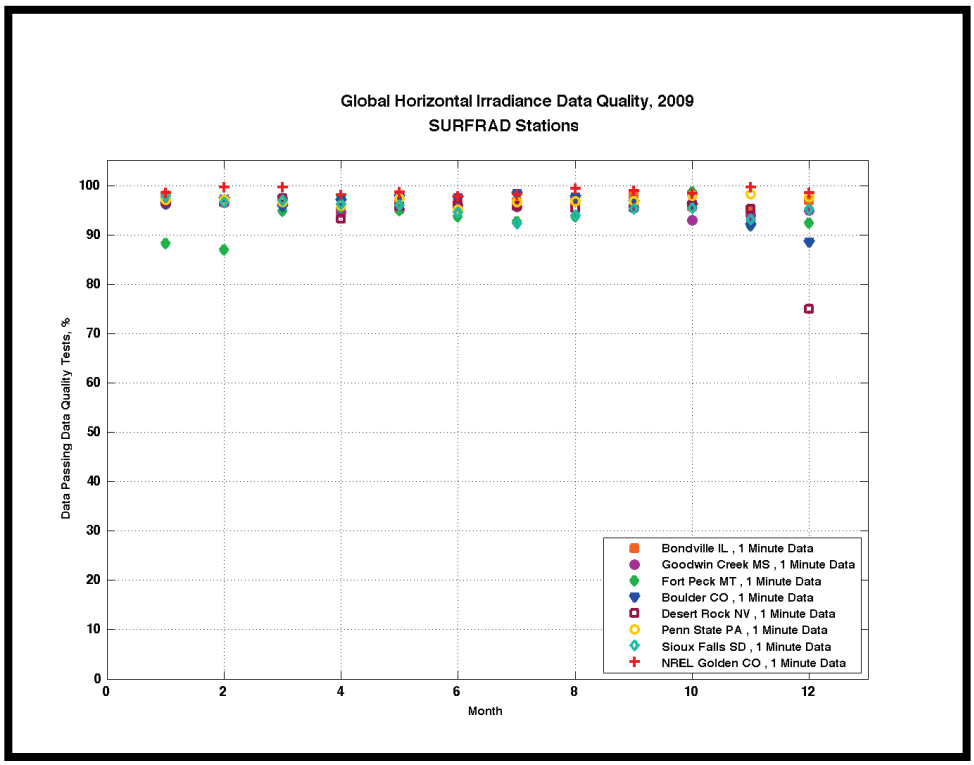


Figure 67. SURFRAD and SRRL-BMS 2009 GHI that passed data quality tests

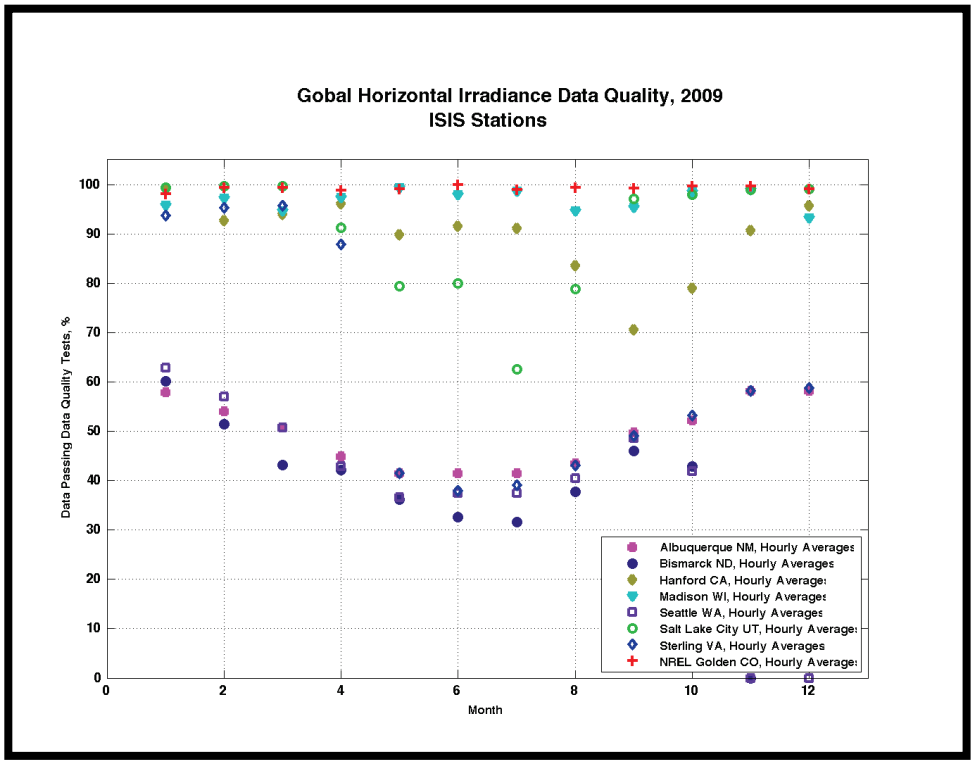


Figure 68. ISIS and SRRL-BMS 2009 hourly average GHI that passed data quality tests

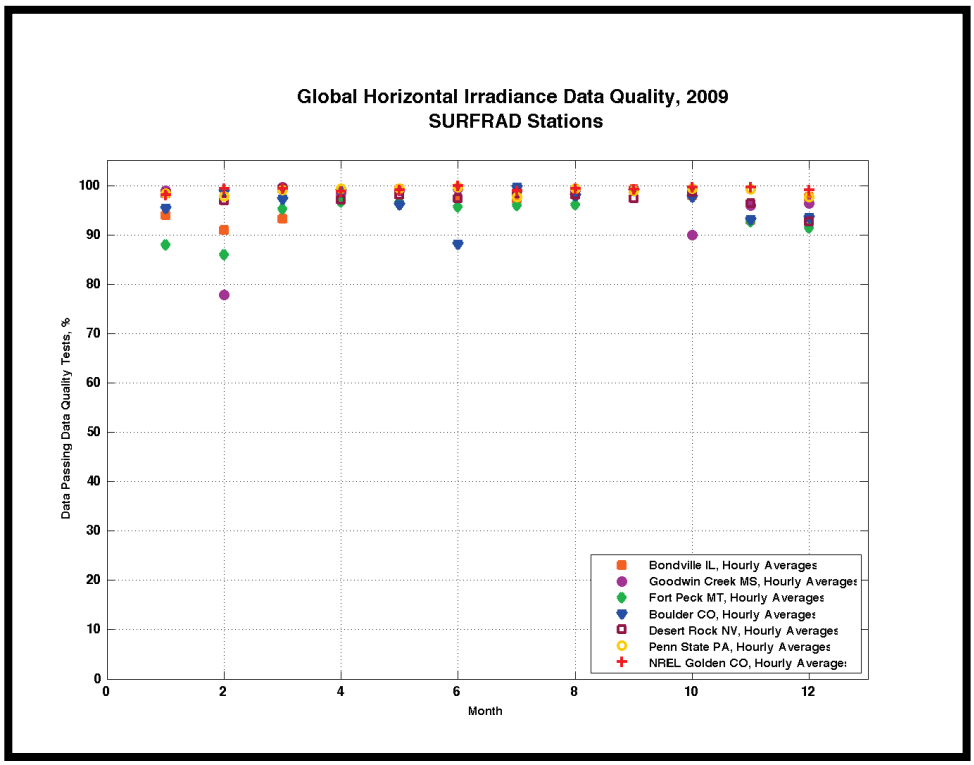


Figure 69. SURFRAD and SRRL-BMS 2009 hourly average GHI that passed data quality tests

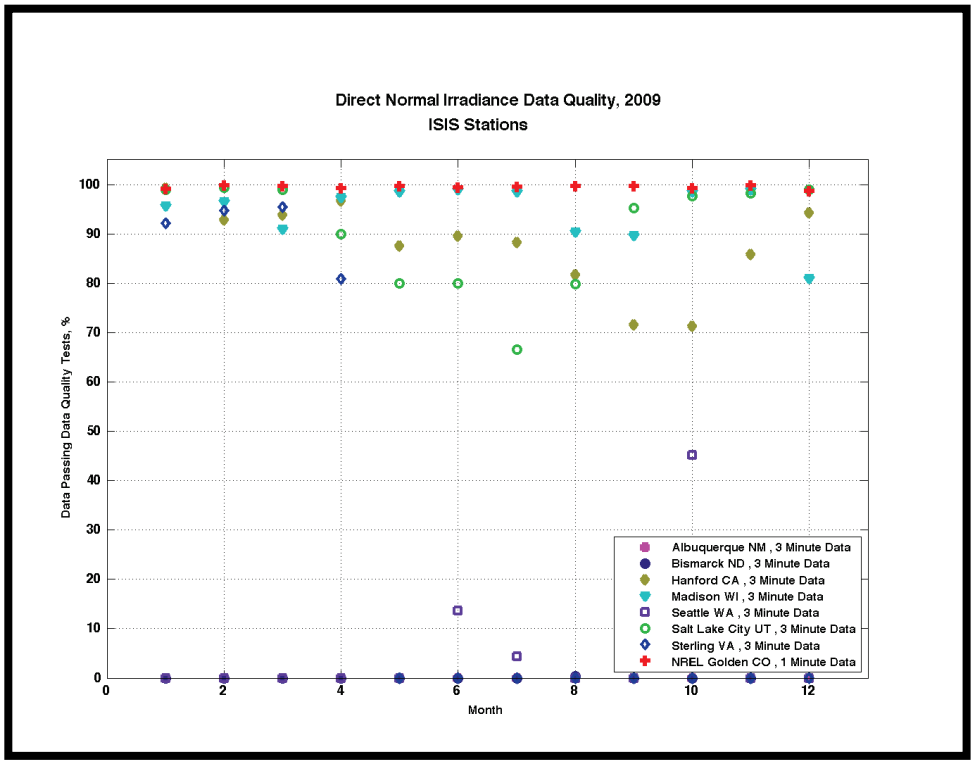


Figure 70. ISIS and SRRL-BMS 2009 DNI that passed data quality tests

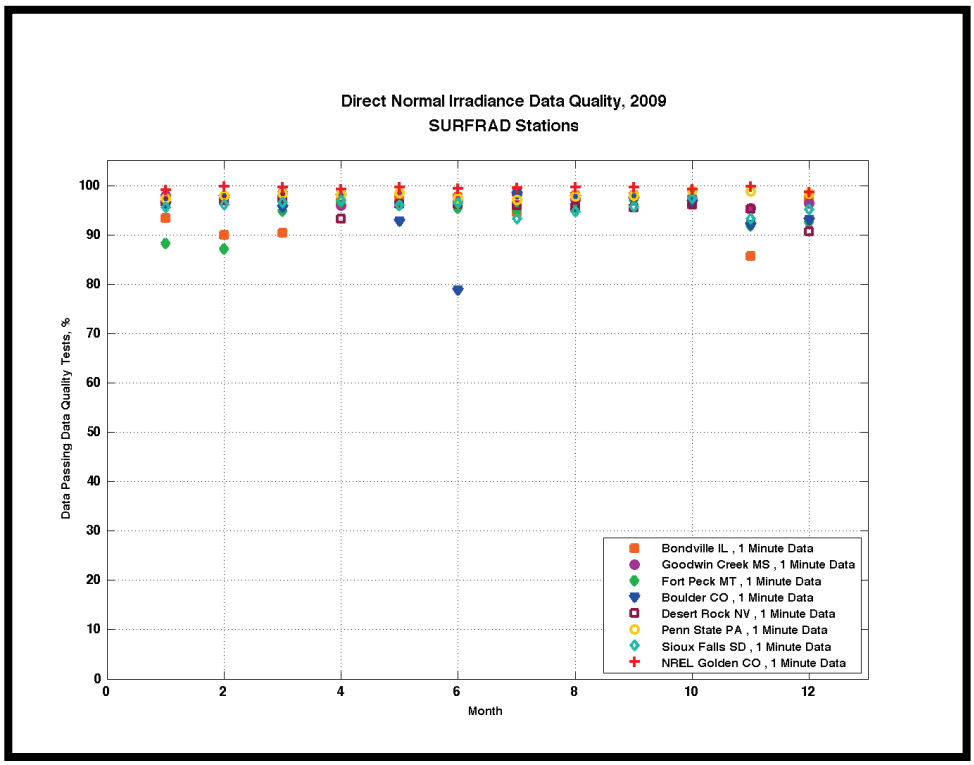


Figure 71. SURFRAD and SRRL-BMS 2009 DNI that passed data quality tests

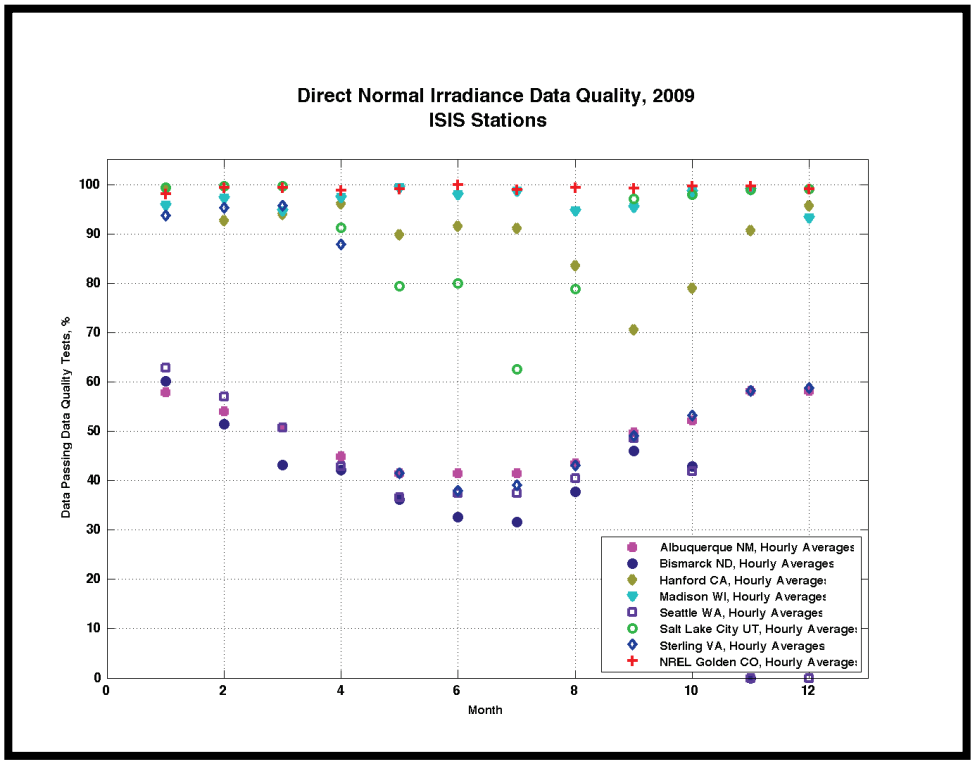


Figure 72. ISIS and SRRL-BMS 2009 hourly average DNI that passed data quality tests

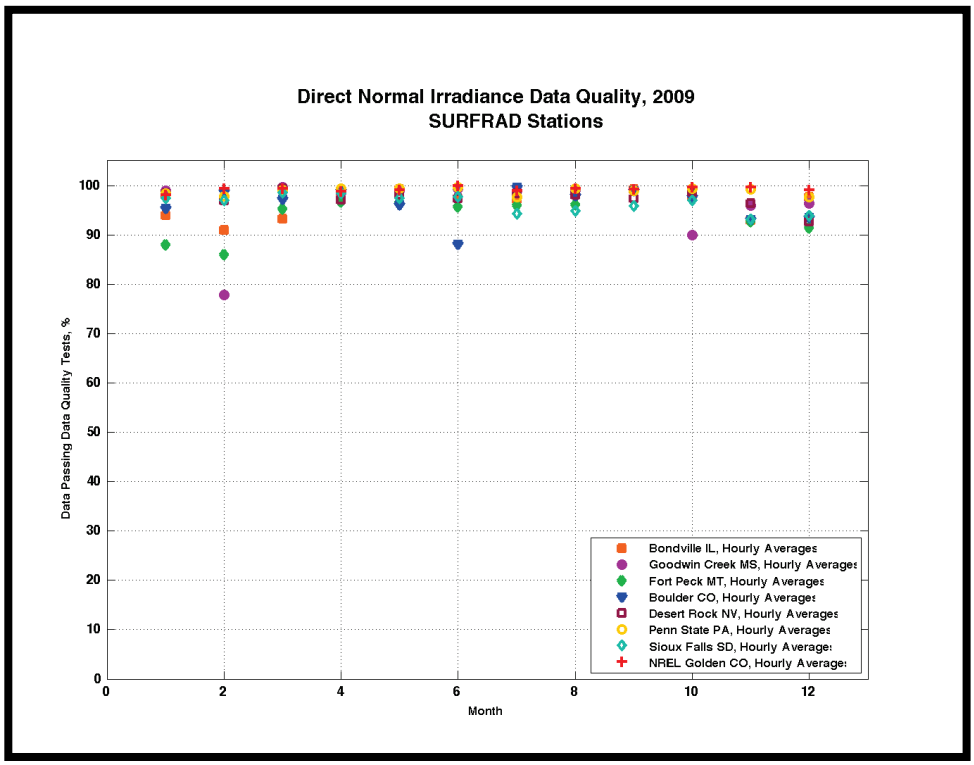


Figure 73. SURFRAD and SRRL-BMS 2009 hourly average DNI that passed data quality tests

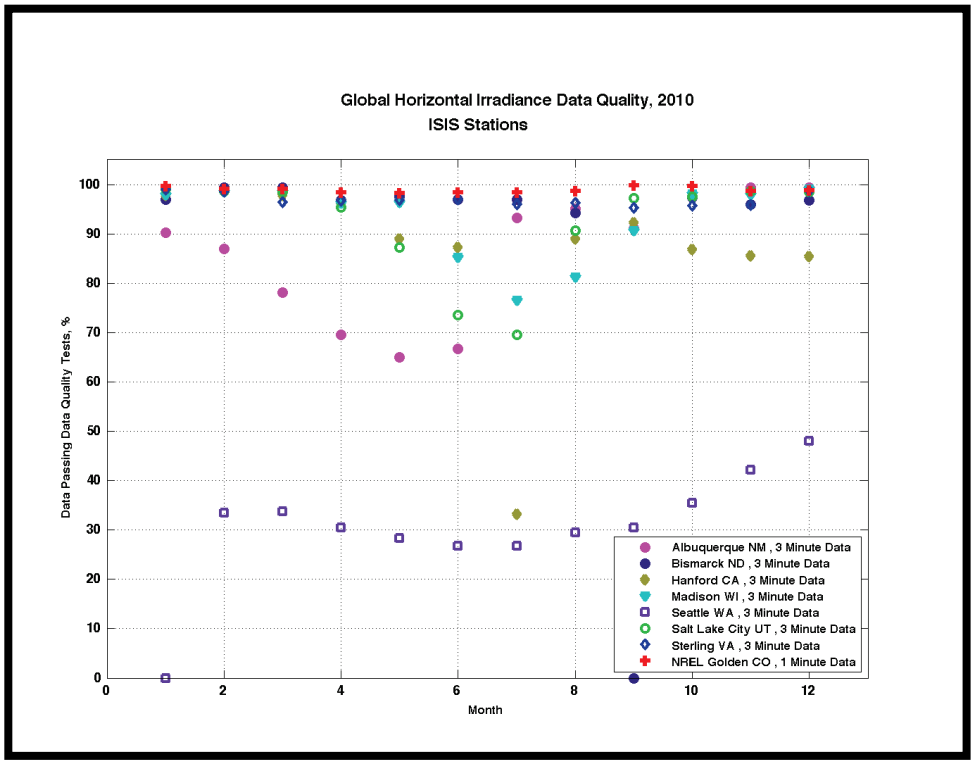


Figure 74. ISIS and SRRL-BMS 2010 GHI that passed data quality tests

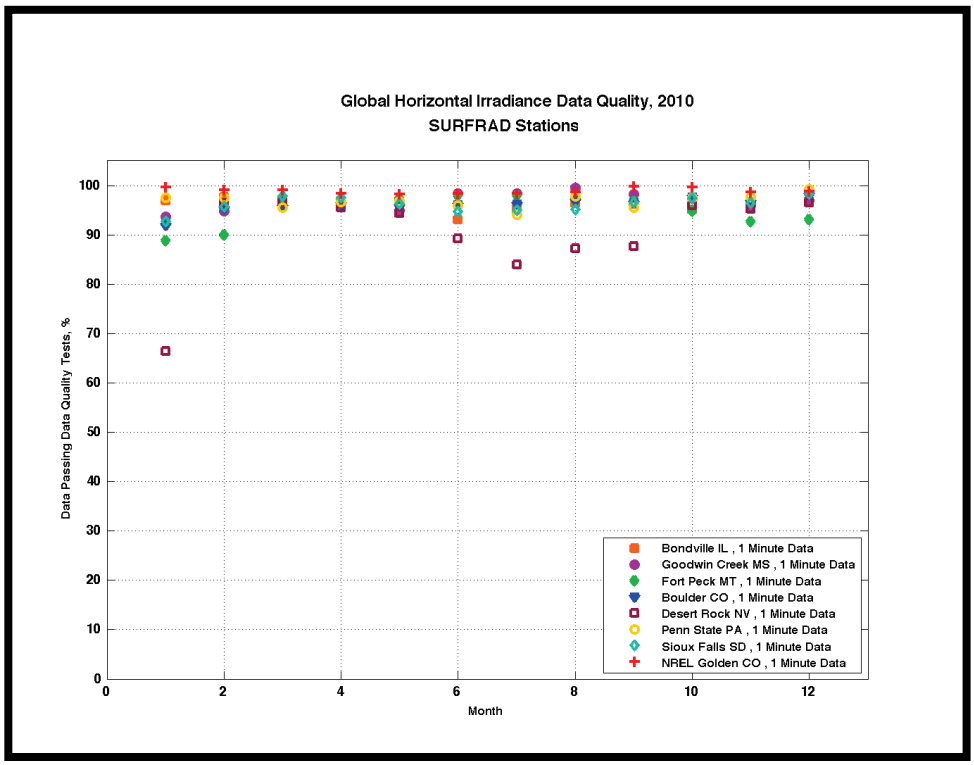


Figure 75. SURFRAD and SRRL-BMS 2010 GHI that passed data quality tests

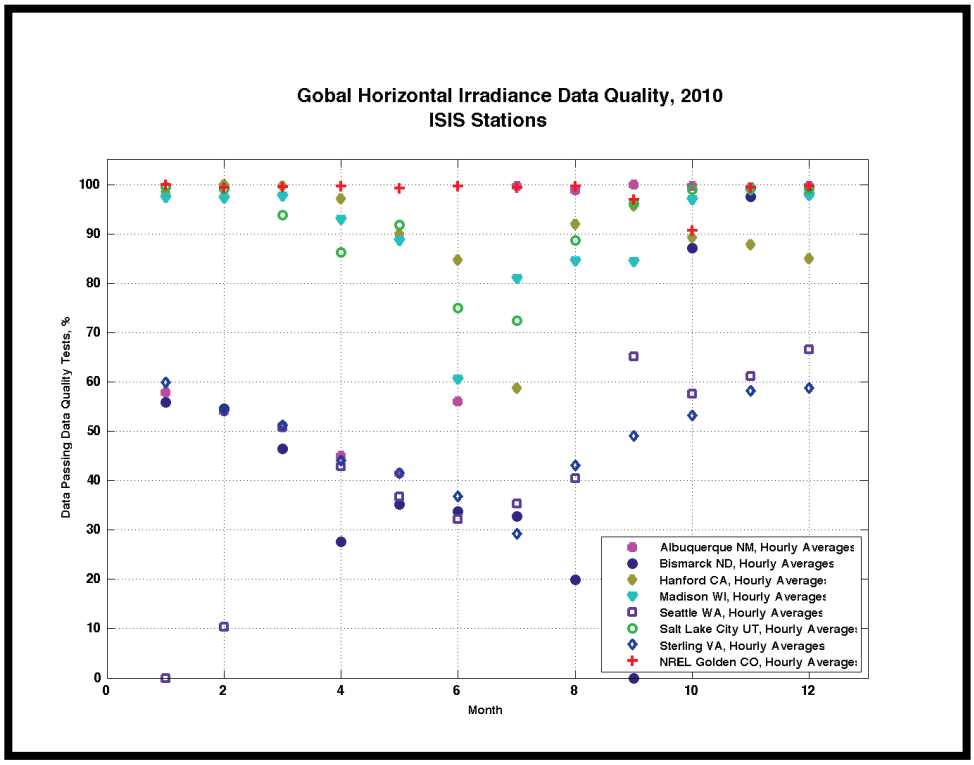


Figure 76. ISIS and SRRL-BMS 2010 hourly average GHI that passed data quality tests

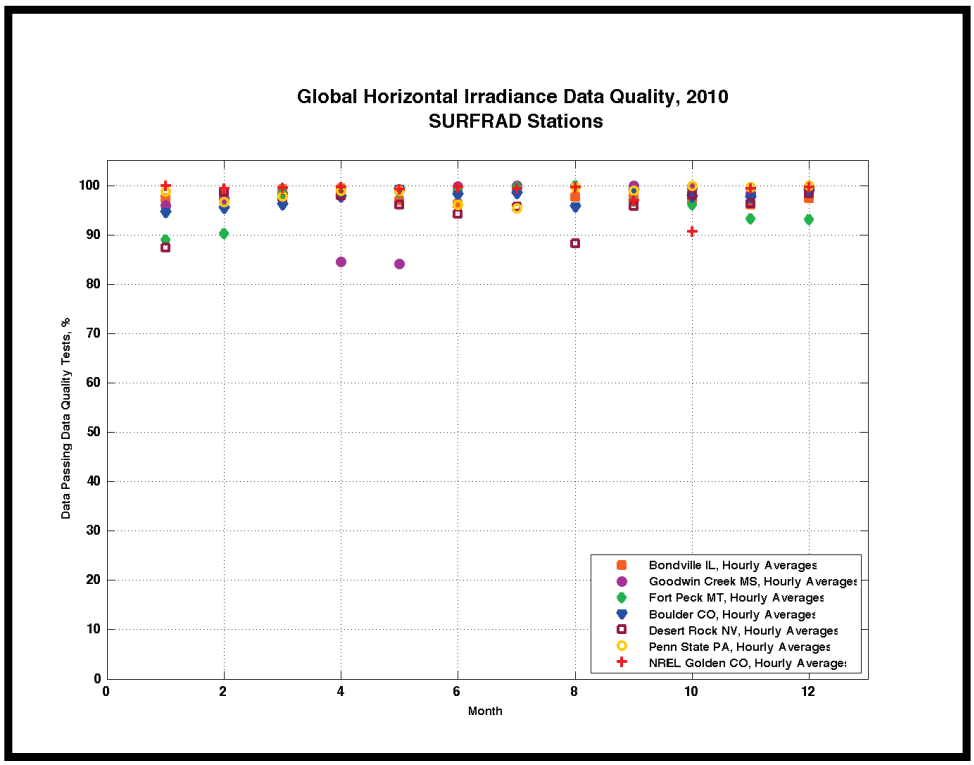


Figure 77. SURFRAD and SRRL-BMS 2010 hourly average GHI that passed data quality tests

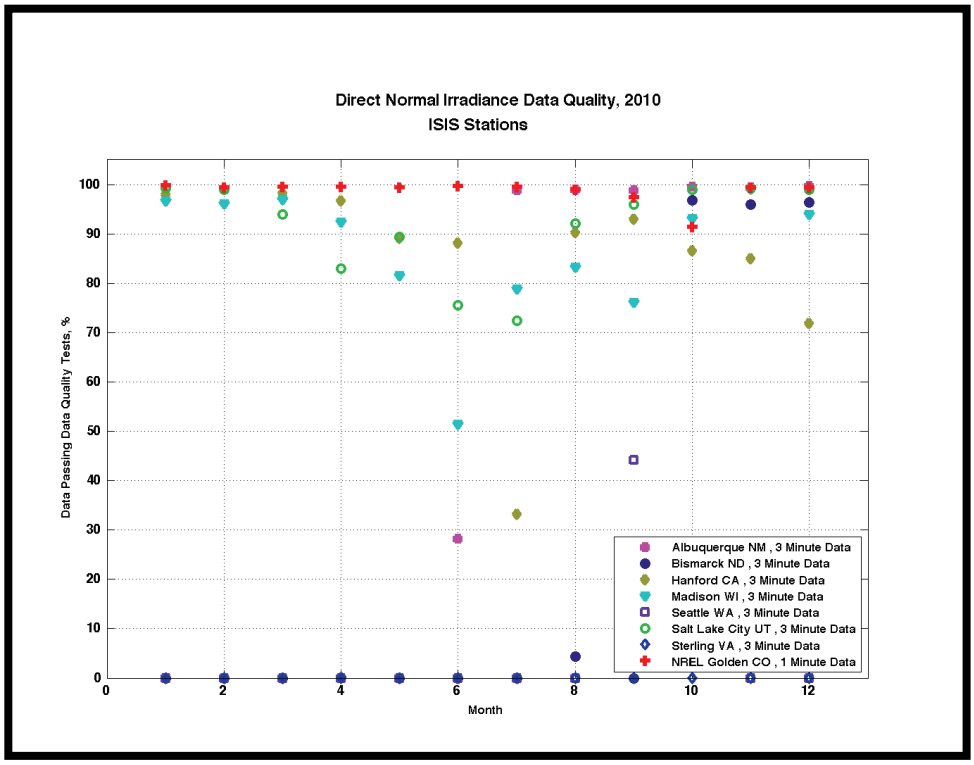


Figure 78. ISIS and SRRL-BMS 2010 DNI that passed data quality tests

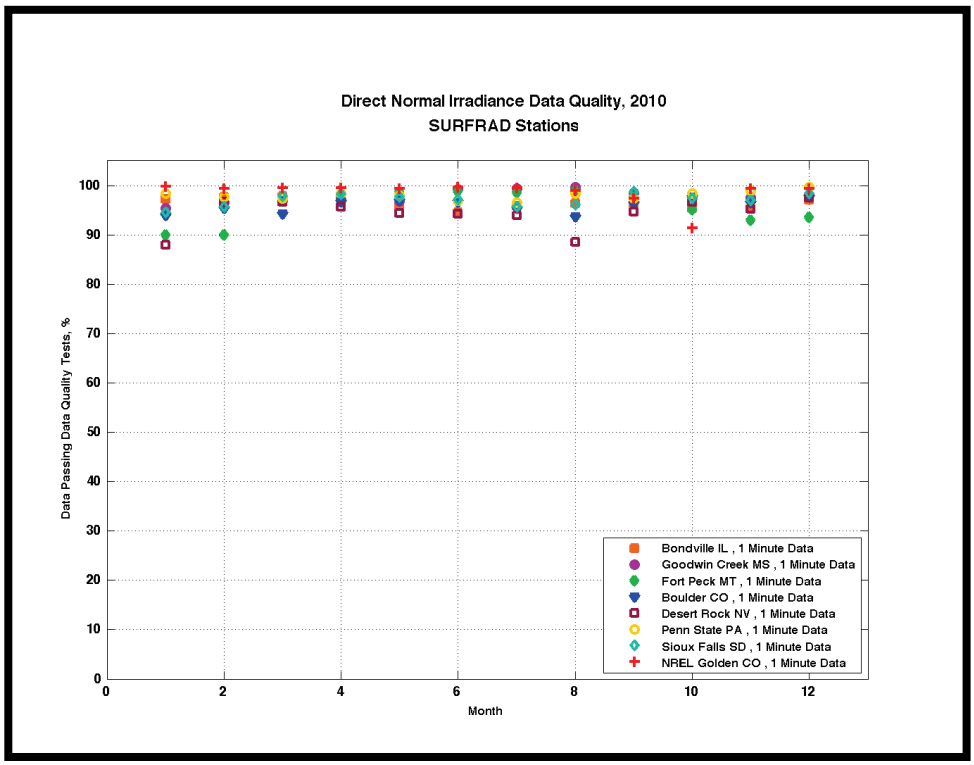


Figure 79. SURFRAD and SRRL-BMS 2010 DNI that passed data quality tests.

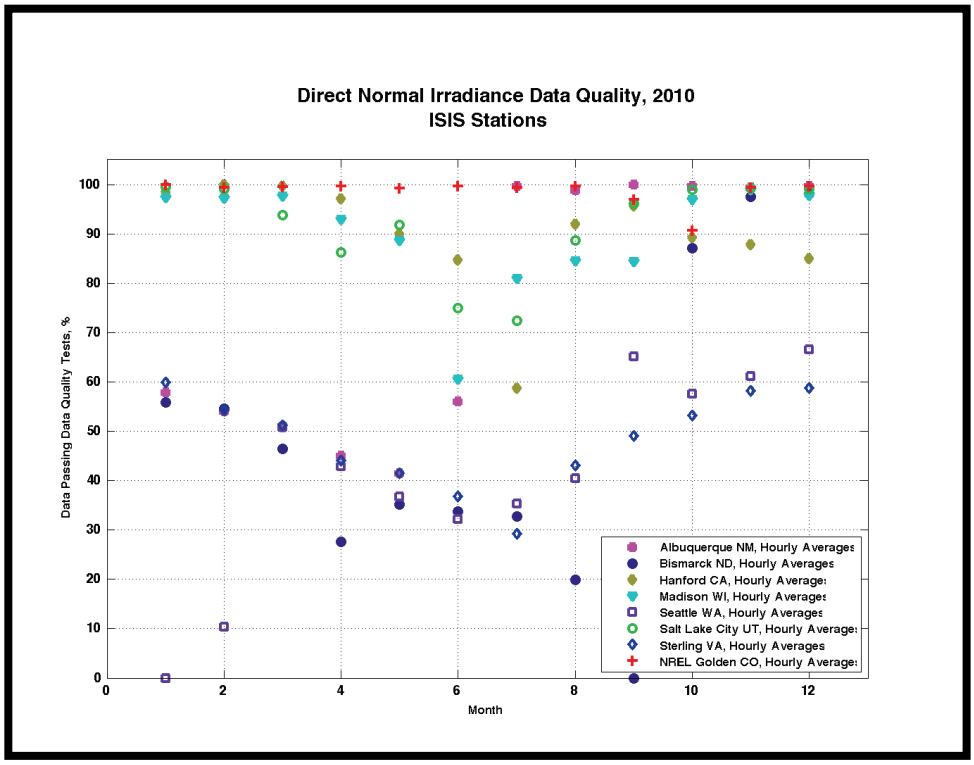


Figure 80. ISIS and SRRL-BMS 2010 hourly average DNI that passed data quality tests

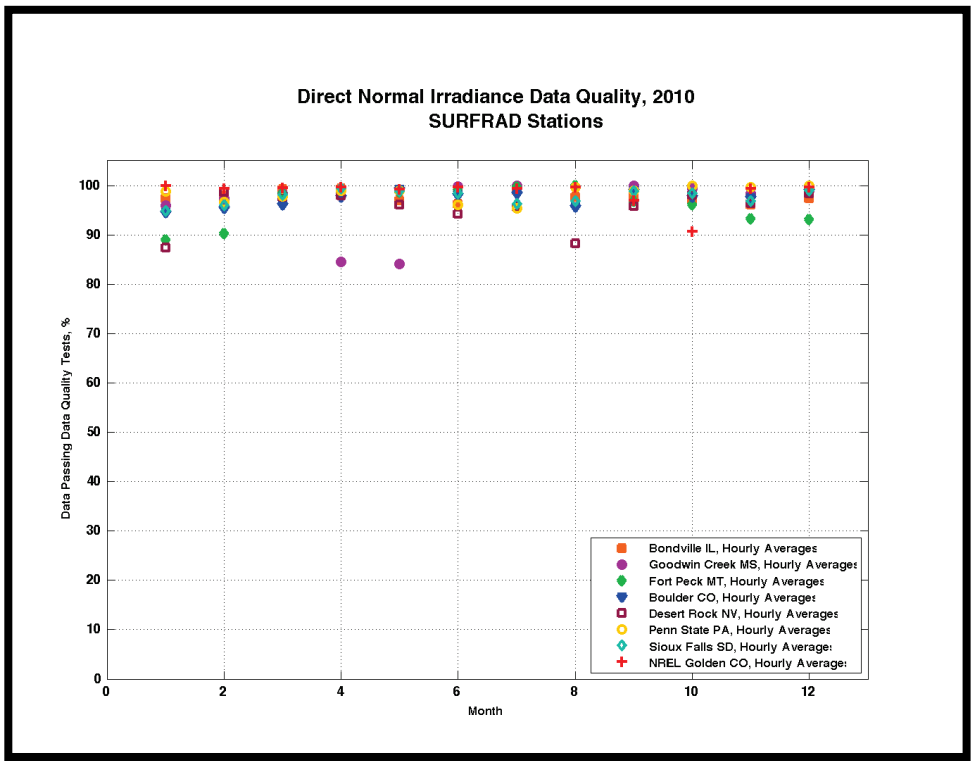


Figure 81. SURFRAD and SRRL-BMS 2010 hourly average DNI that passed data quality tests

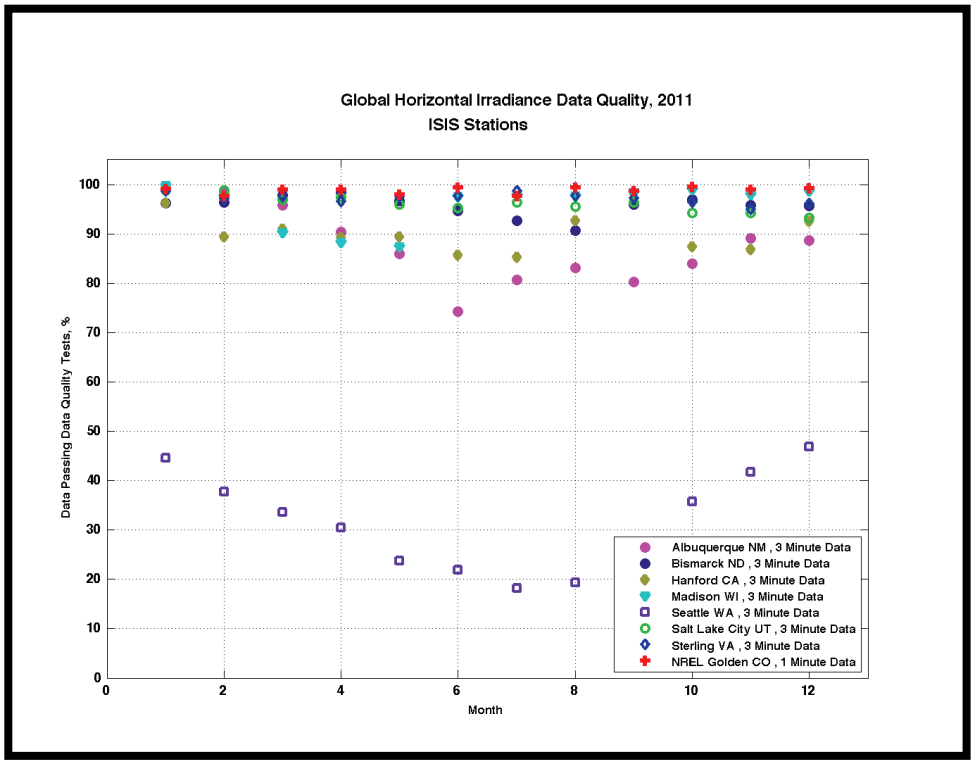


Figure 82. ISIS and SRRL-BMS 2011 GHI that passed data quality tests

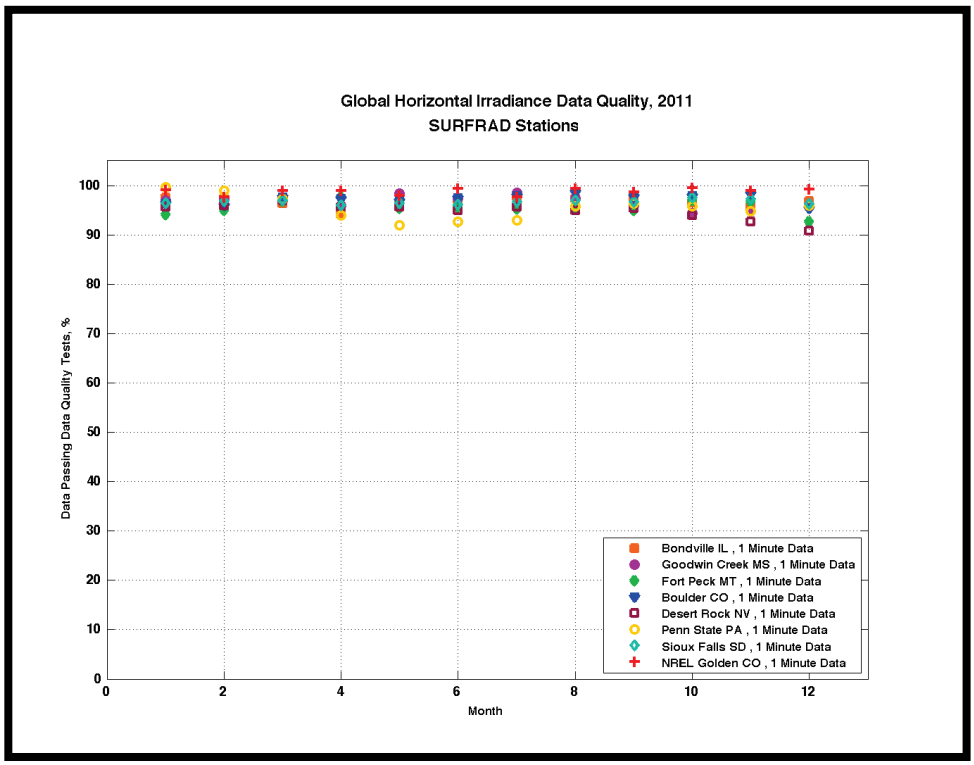


Figure 83. SURFRAD and SRRL-BMS 2011 GHI that passed data quality tests

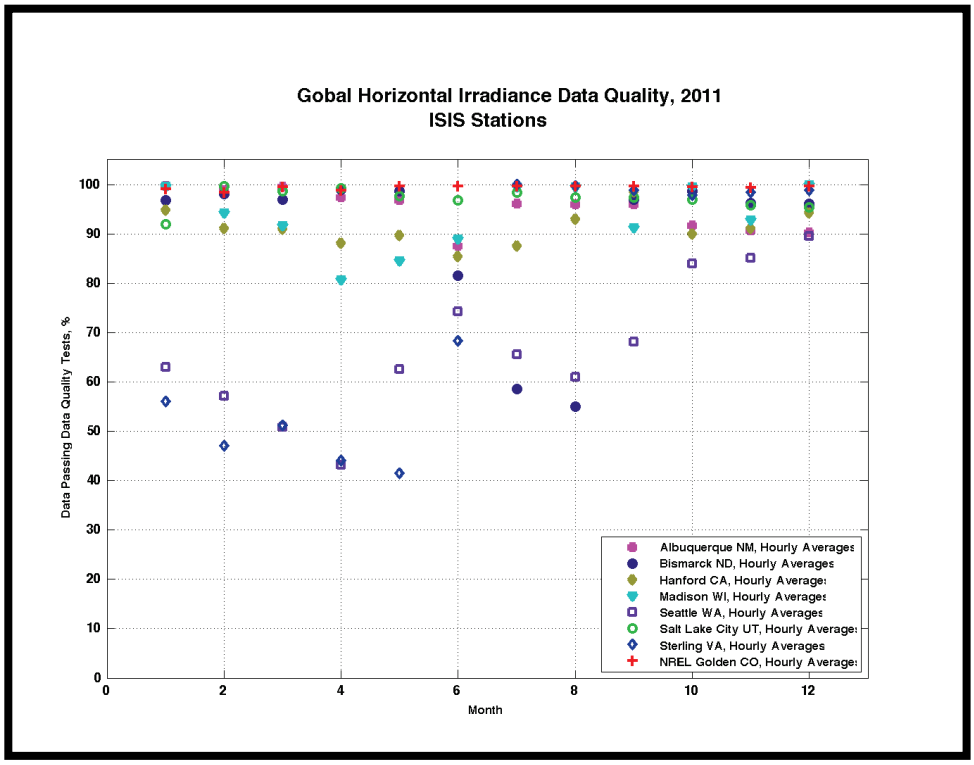
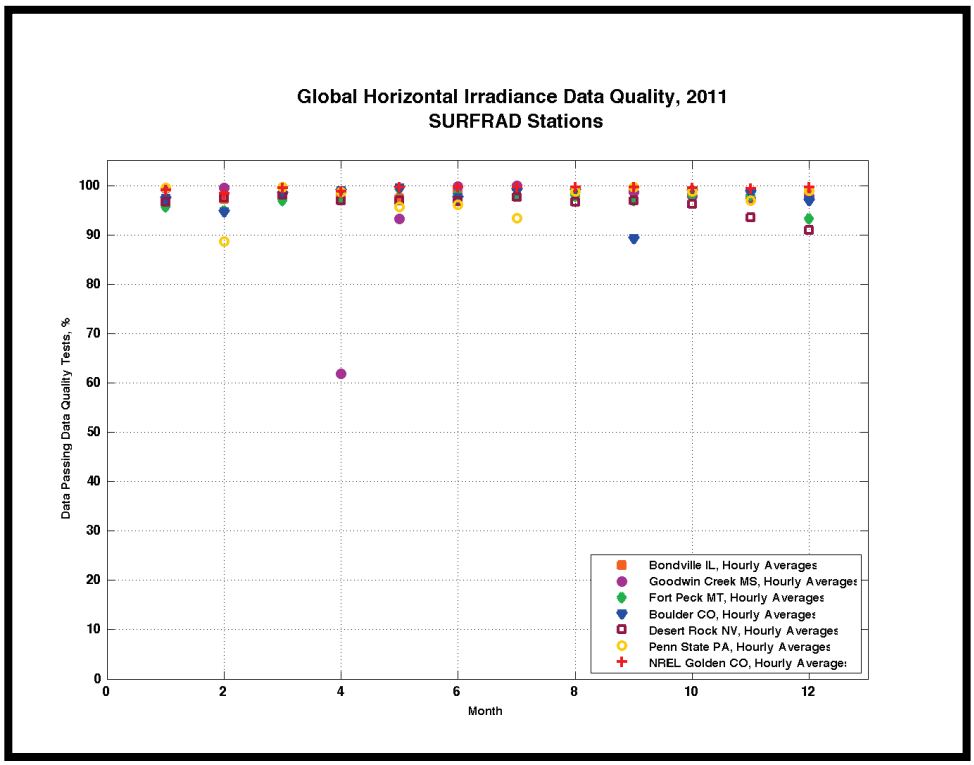


Figure 84. ISIS and SRRL-BMS 2011 hourly average GHI that passed data quality tests



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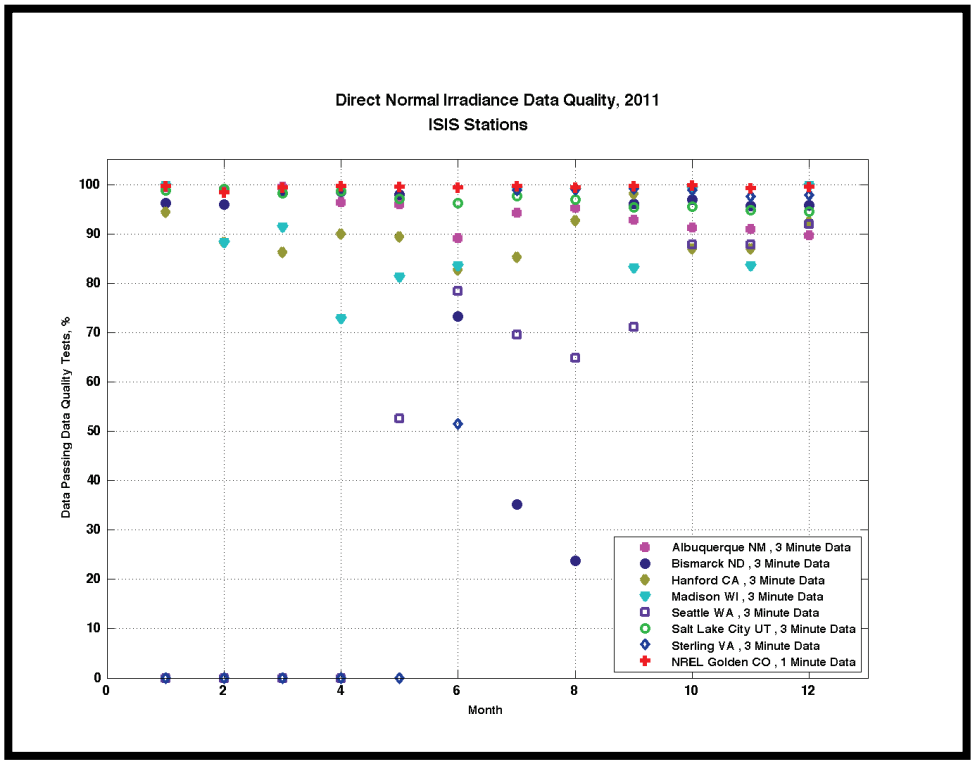


Figure 86. ISIS and SRRL-BMS 2011 DNI that passed data quality tests

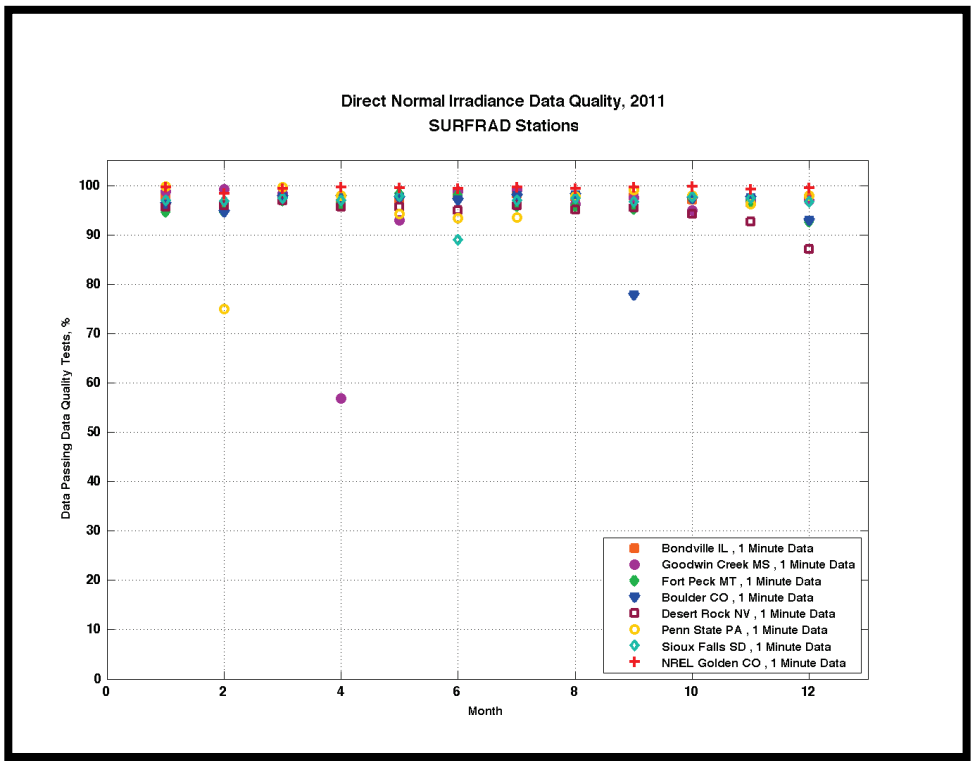


Figure 87. SURFRAD and SRRL-BMS 2011 DNI that passed data quality tests

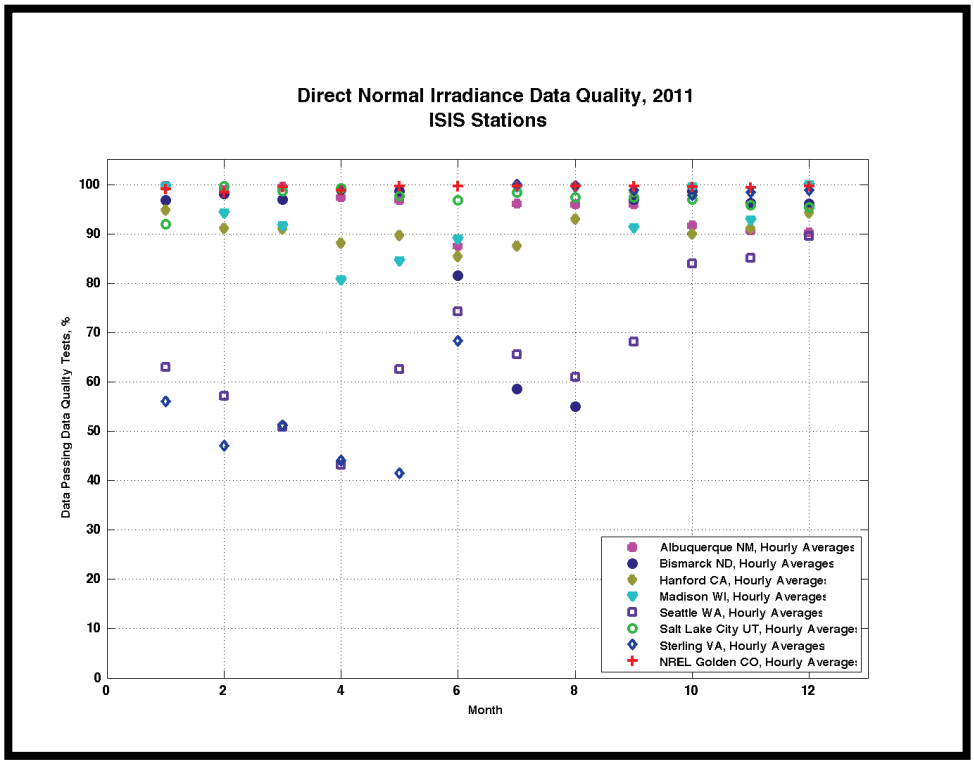


Figure 88. ISIS and SRRL-BMS 2011 hourly average DNI that passed data quality tests

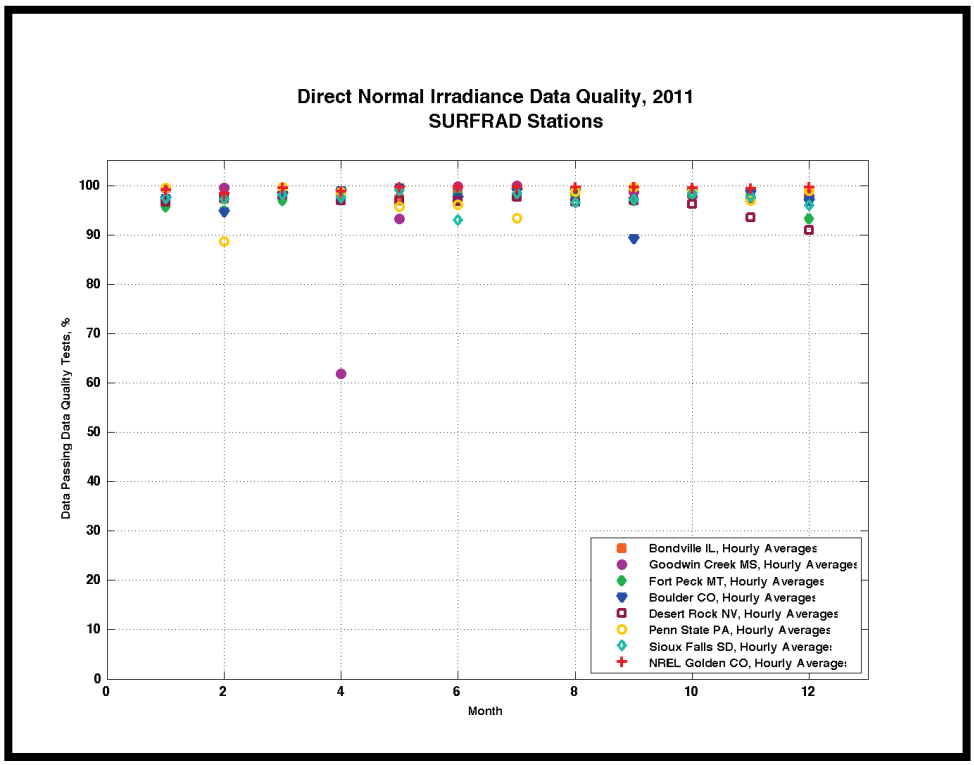


Figure 89. SURFRAD and SRRL-BMS 2011 hourly average DNI that passed data quality tests

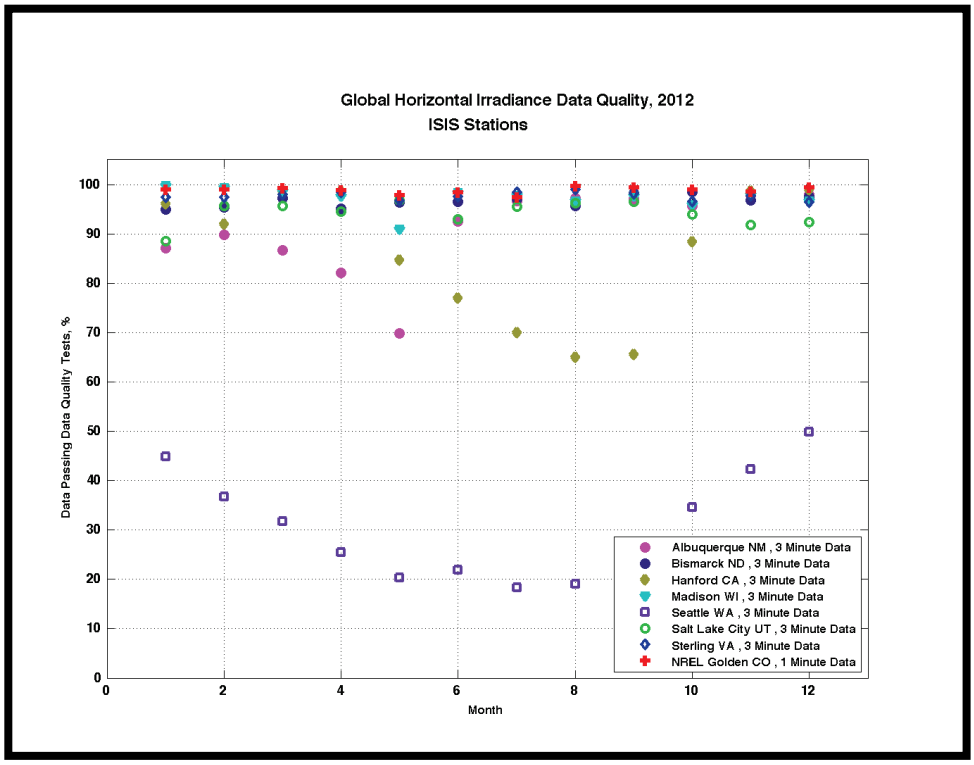


Figure 90. ISIS and SRRL-BMS 2012 GHI that passed data quality tests

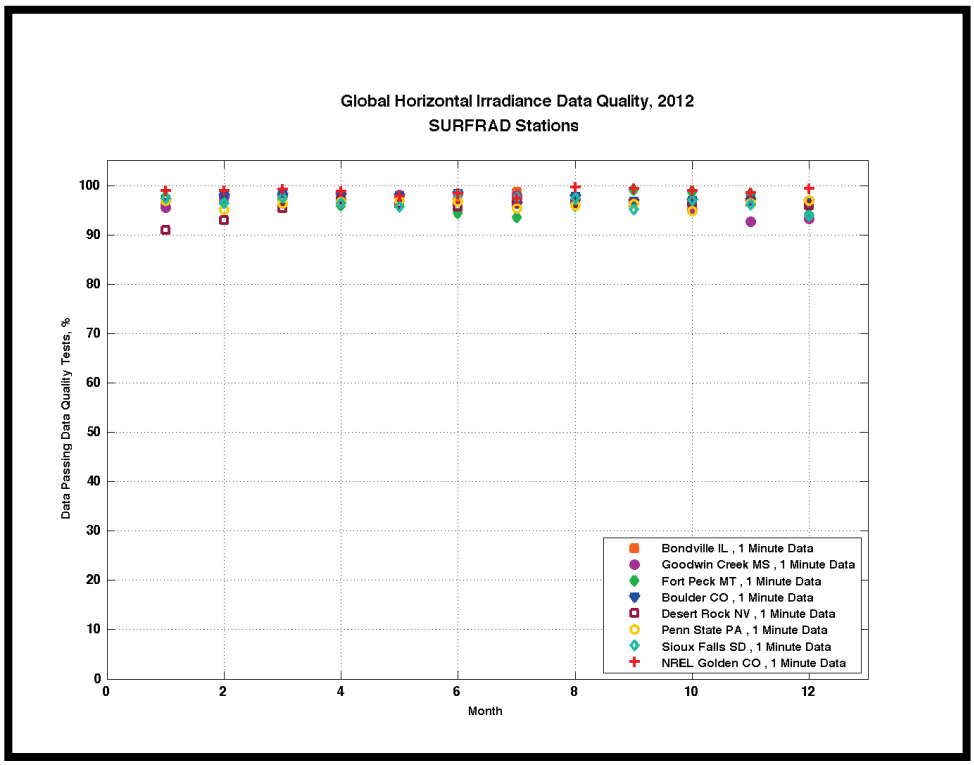
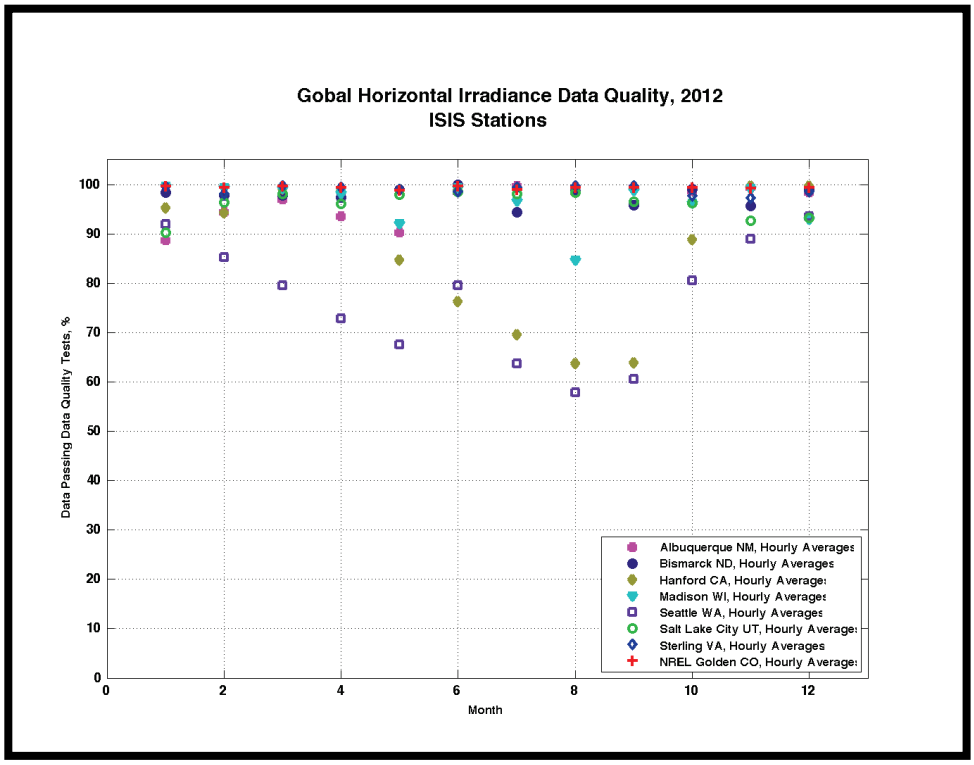


Figure 91. SURFRAD and SRRL-BMS 2012 GHI that passed data quality tests



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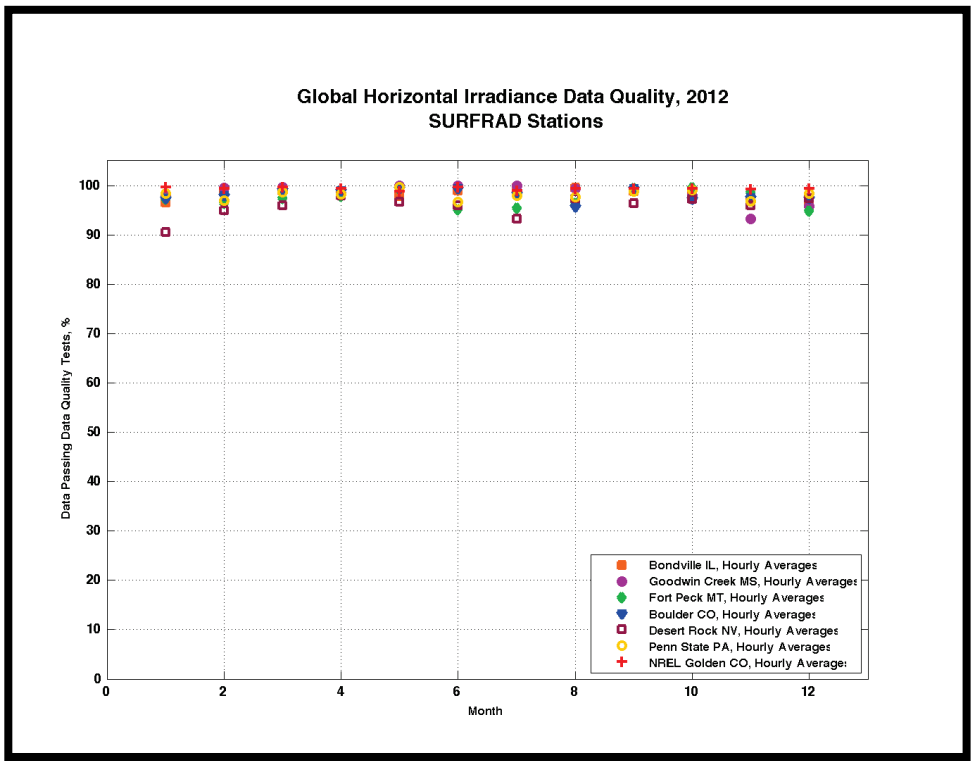


Figure 93. SURFRAD and SRRL-BMS 2012 hourly average GHI that passed data quality tests

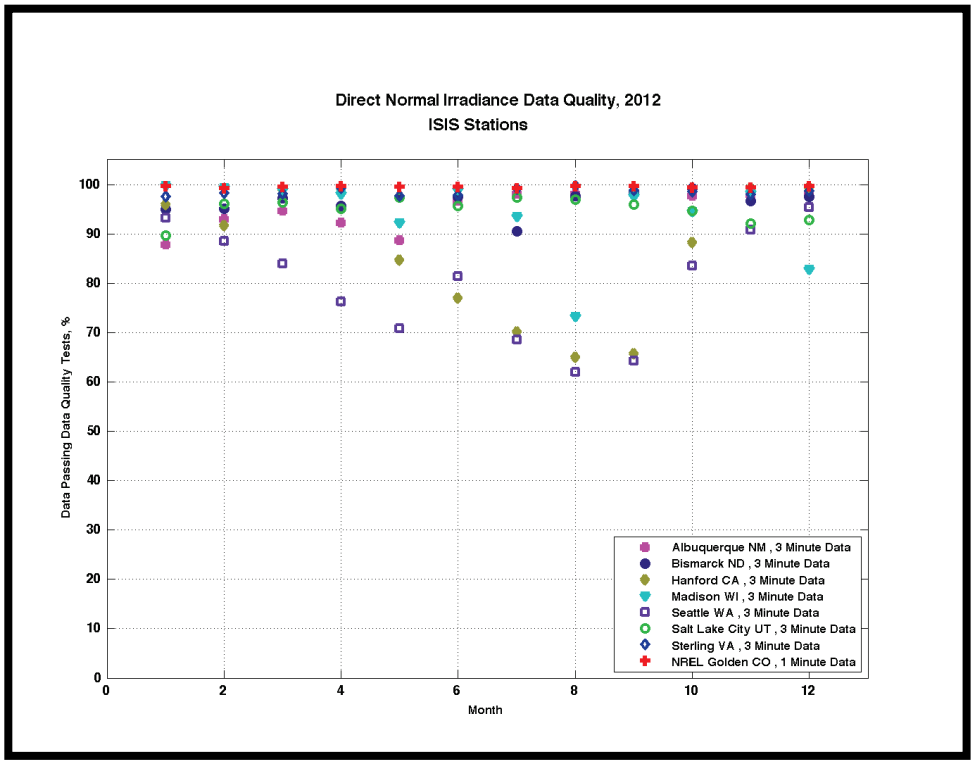


Figure 94. ISIS and SRRL-BMS 2012 DNI that passed data quality tests

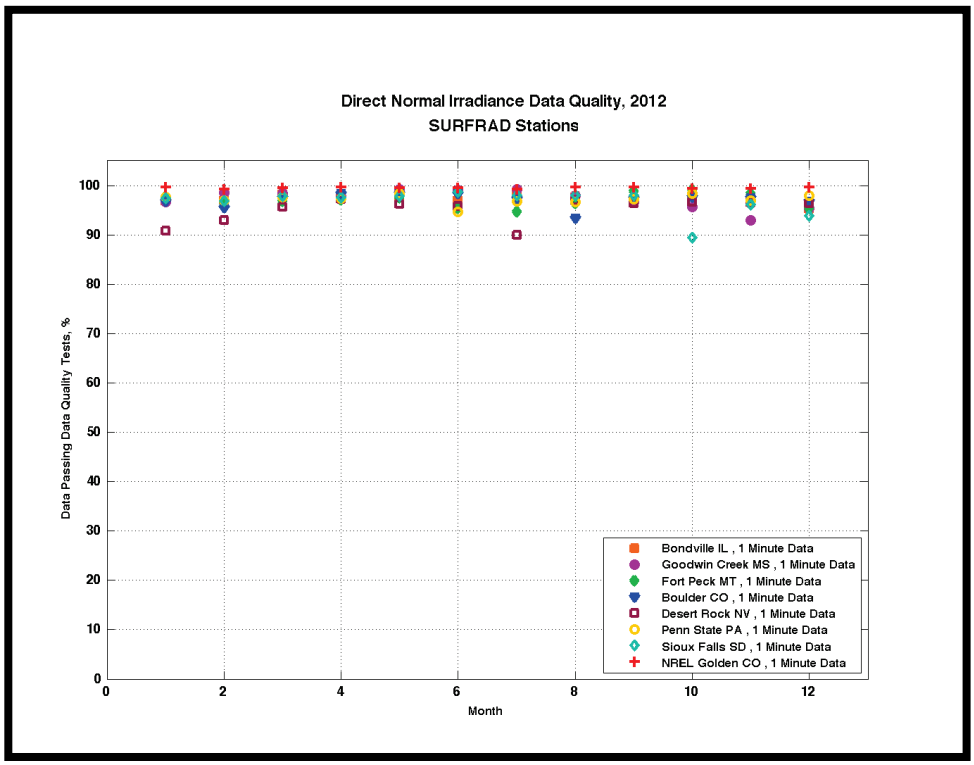


Figure 95. SURFRAD and SRRL-BMS 2012 DNI that passed data quality tests

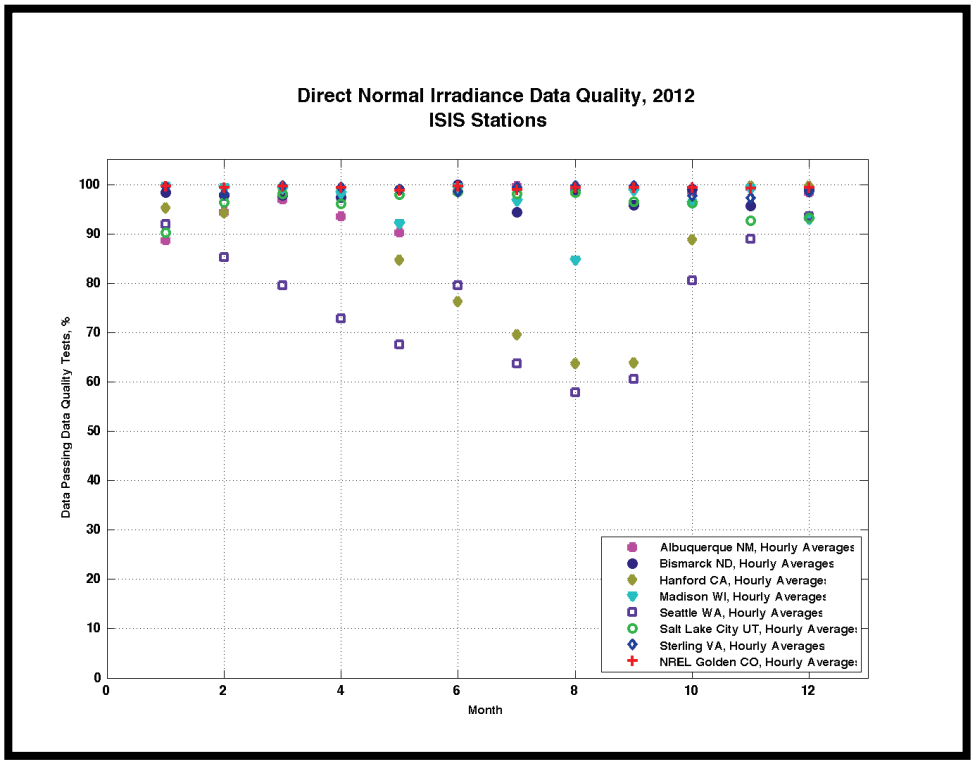


Figure 96. ISIS and SRRL-BMS 2012 hourly average DNI that passed data quality tests

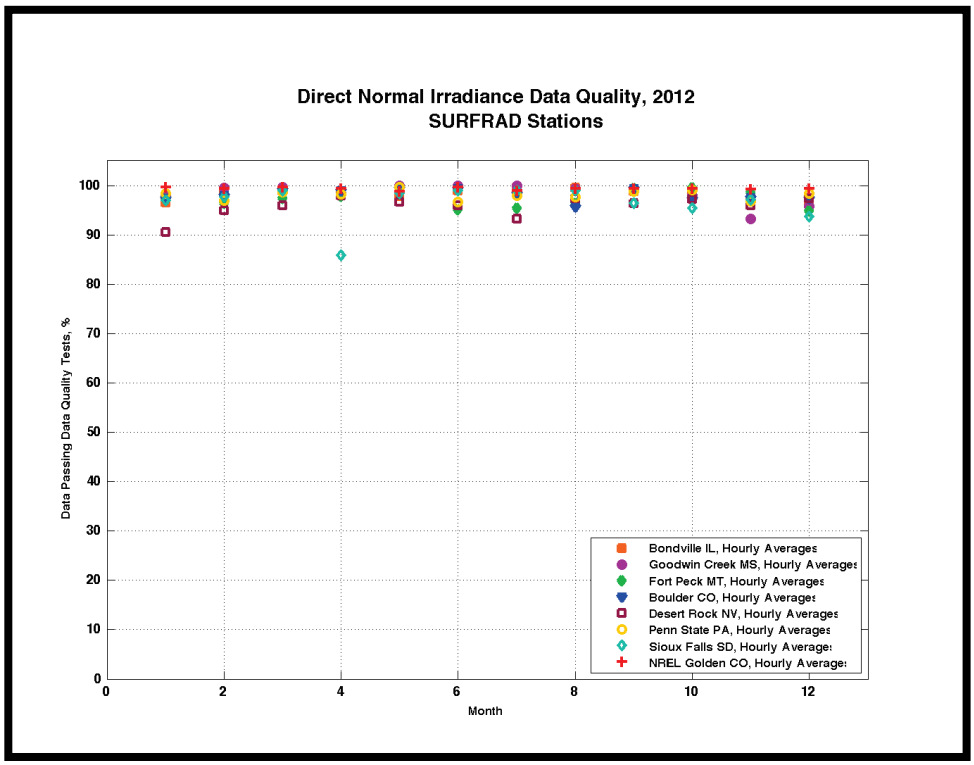


Figure 97. SURFRAD and SRRL-BMS 2012 hourly average DNI that passed data quality tests

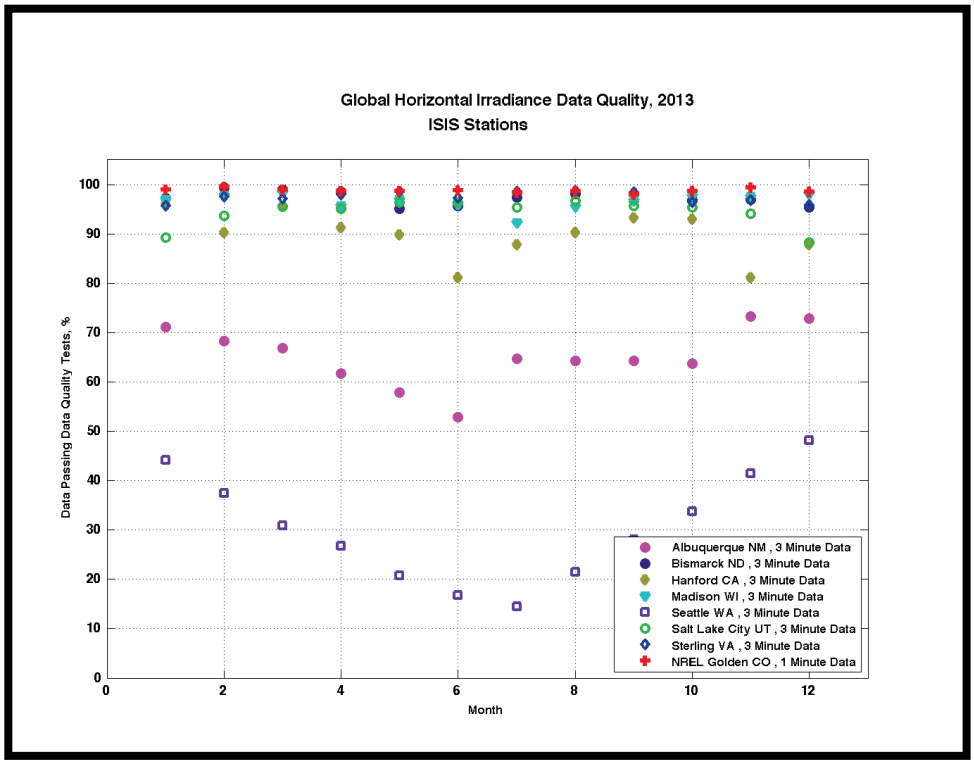
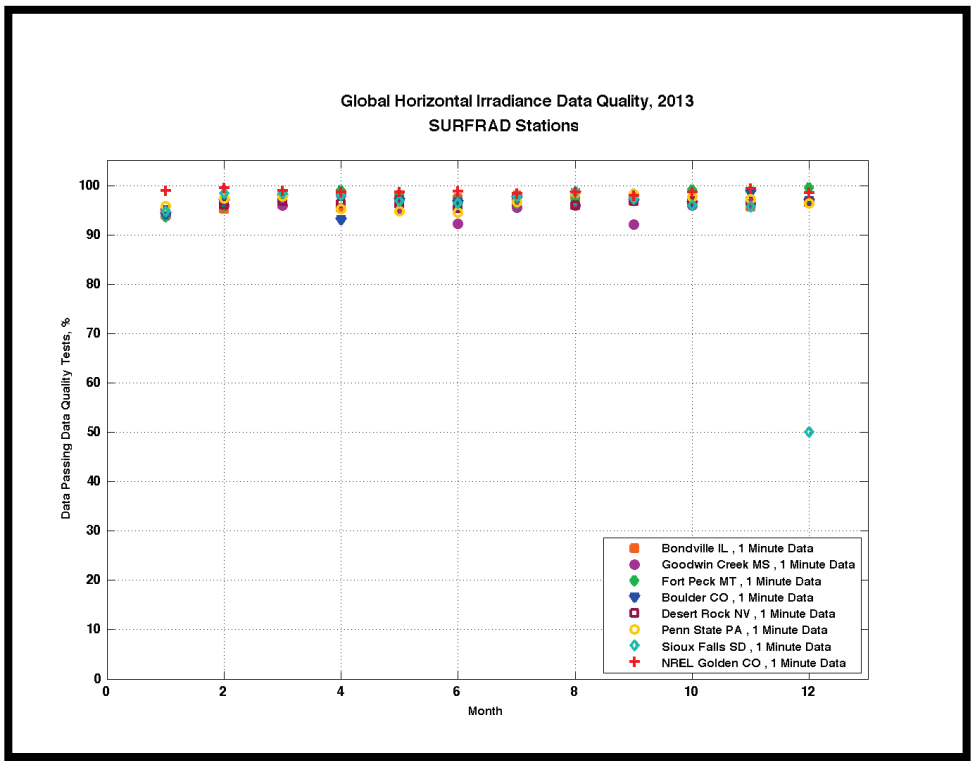


Figure 98. ISIS and SRRL-BMS 2013 GHI that passed data quality tests



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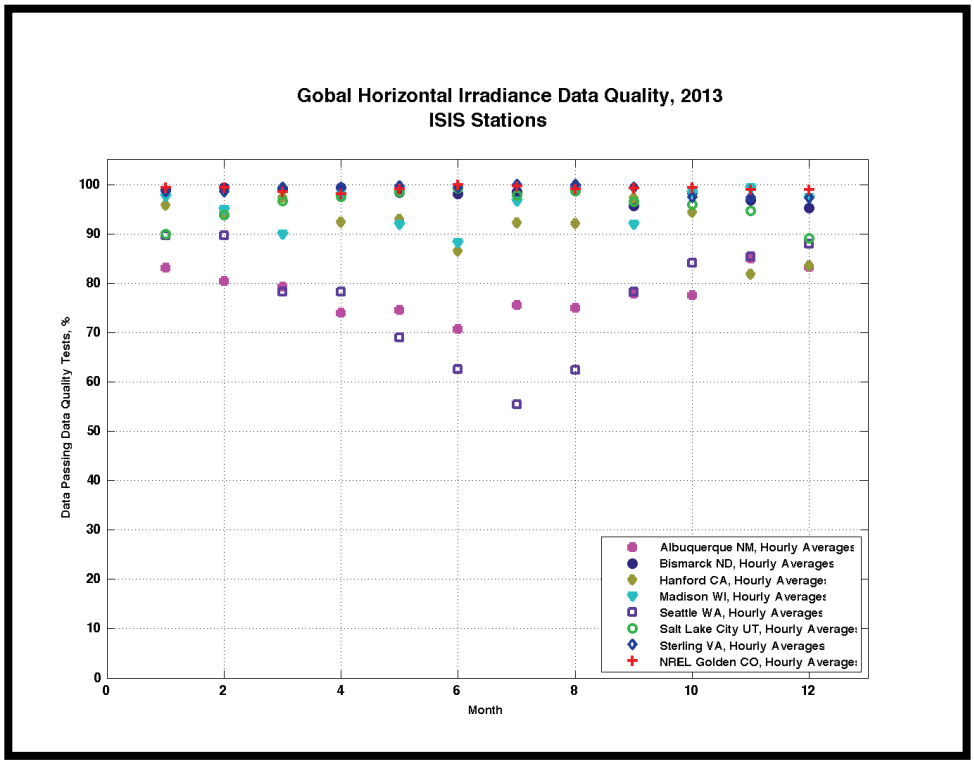

Figure 100. ISIS and SRRL-BMS 2013 hourly average GHI that passed data quality tests

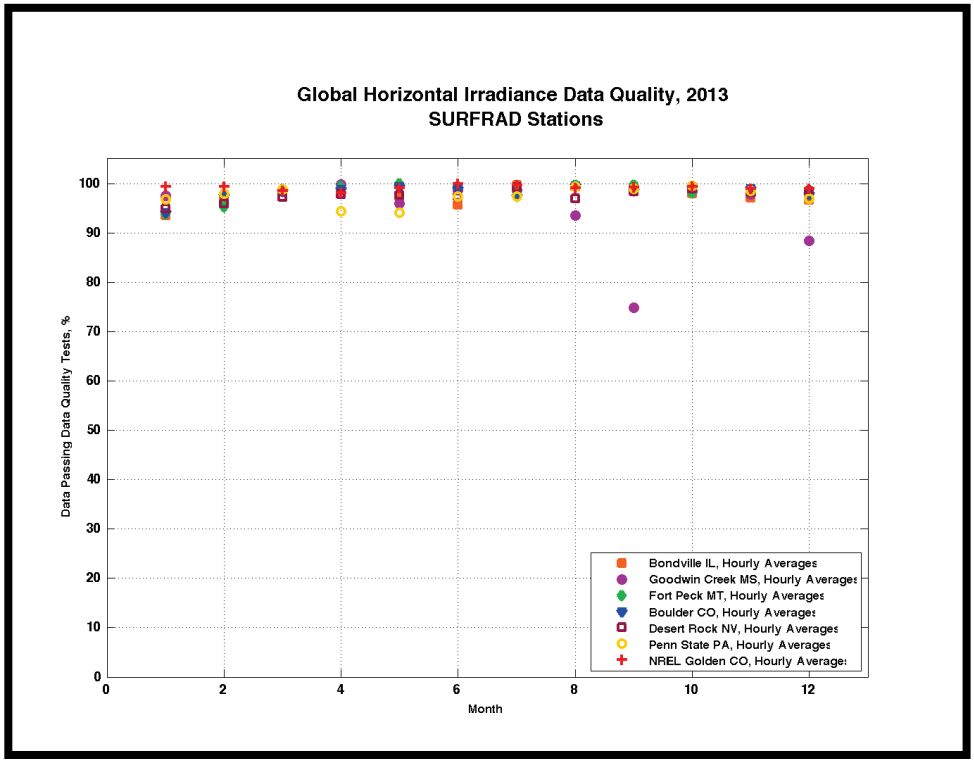

Figure 101. SURFRAD and SRRL-BMS 2013 hourly average GHI that passed data quality tests

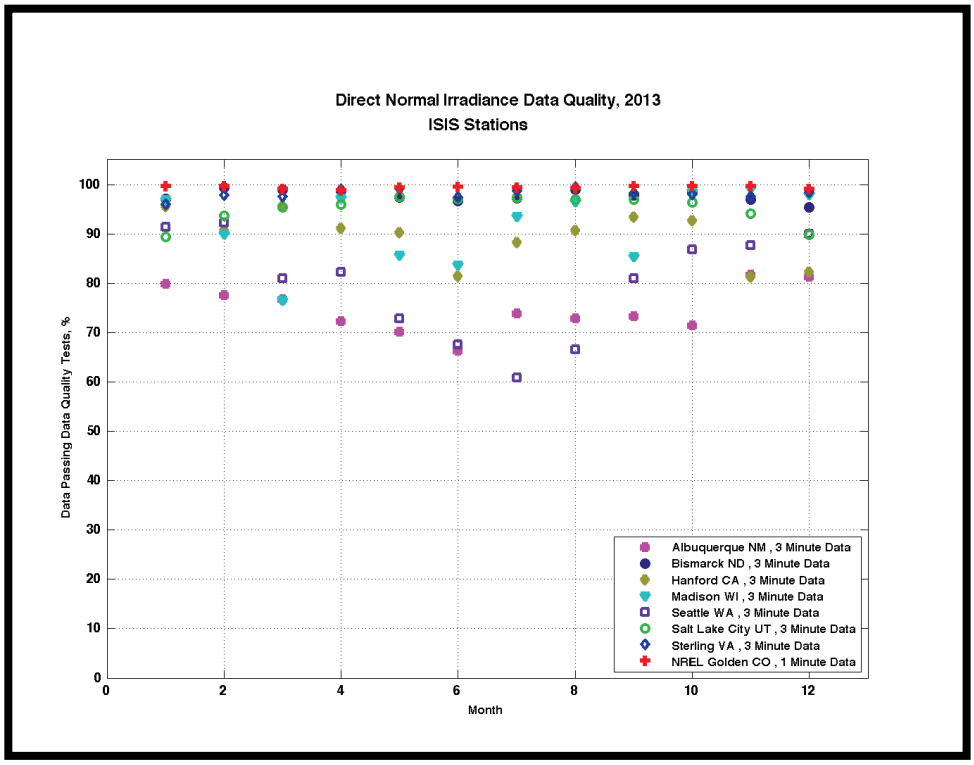

Figure 102. ISIS and SRRL-BMS 2013 DNI that passed data quality tests

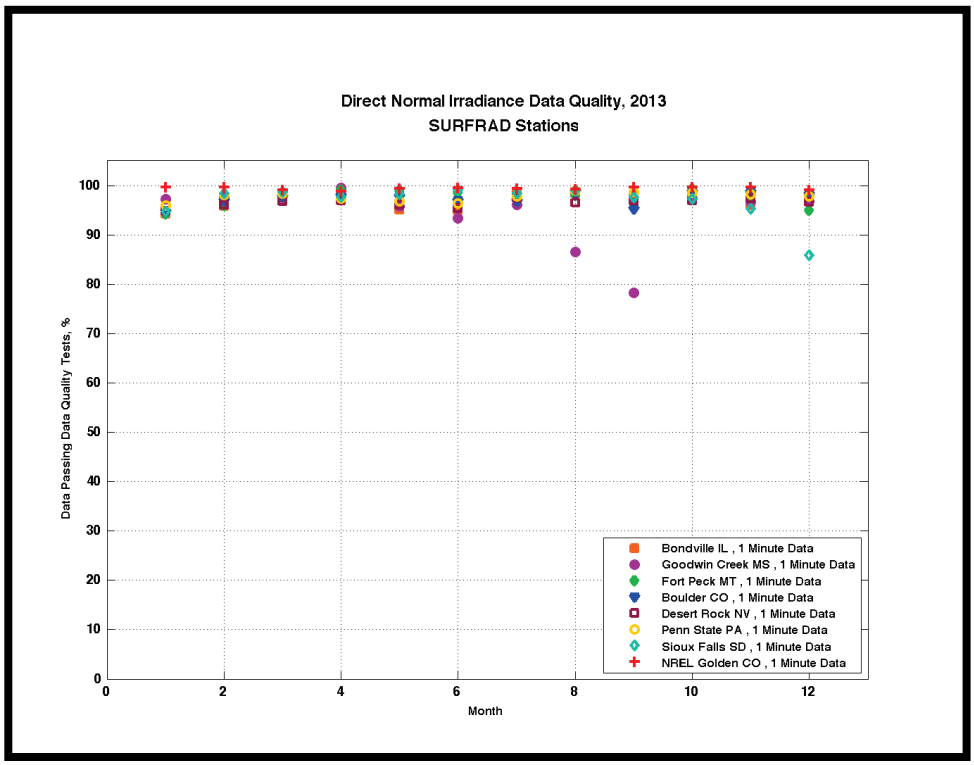

Figure 103. SURFRAD and SRRL-BMS 2013 DNI that passed data quality tests

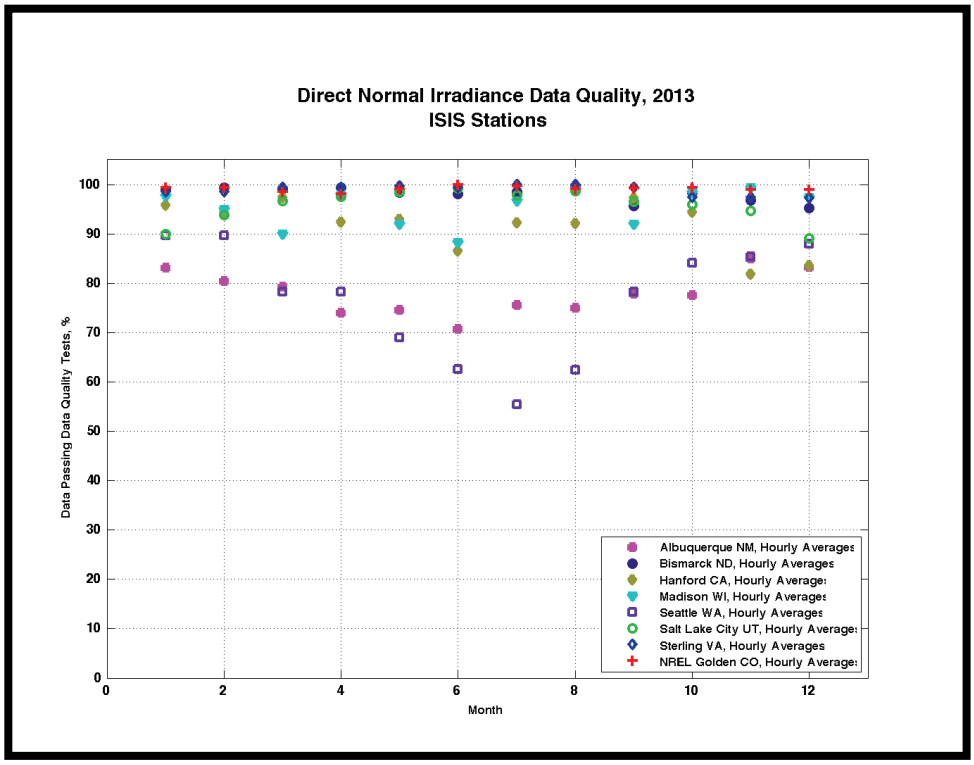

Figure 104. ISIS and SRRL-BMS 2013 hourly average DNI that passed data quality tests

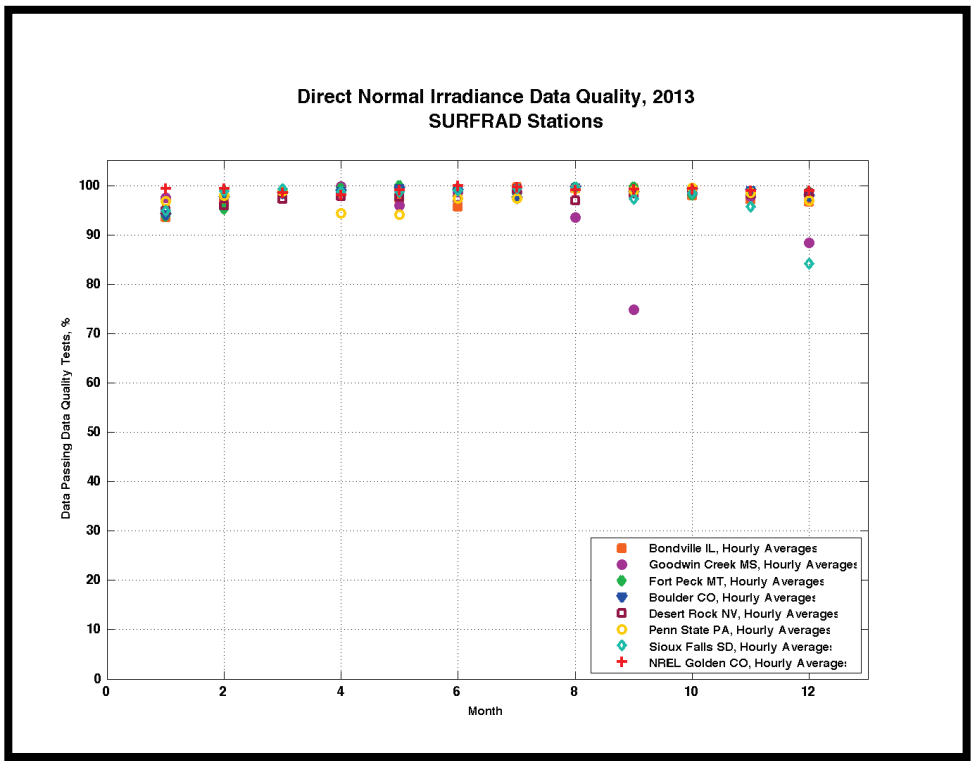

Figure 105. SURFRAD and SRRL-BMS 2013 hourly average DNI that passed data quality tests

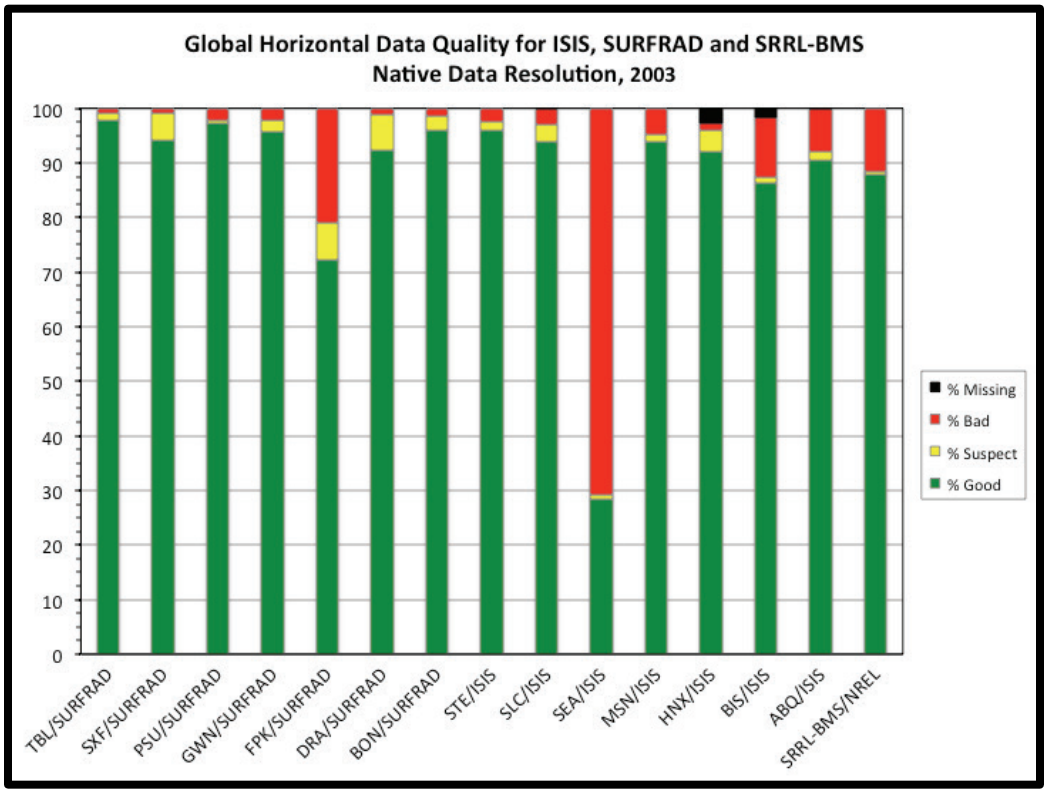

Figure 106. ISIS, SURFRAD and SRRL-BMS 2003 GHI data quality (See text for data resolution.)

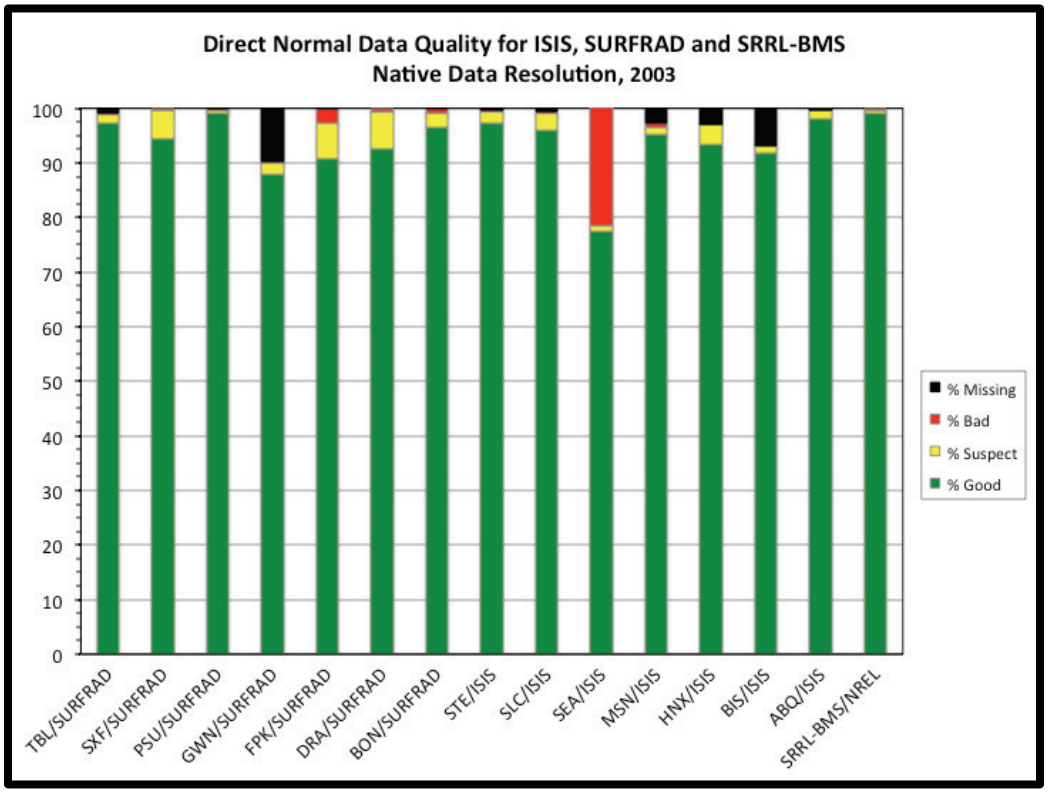

Figure 107. ISIS, SURFRAD, and SRRL-BMS 2003 DNI data quality (See text for data resolution.)

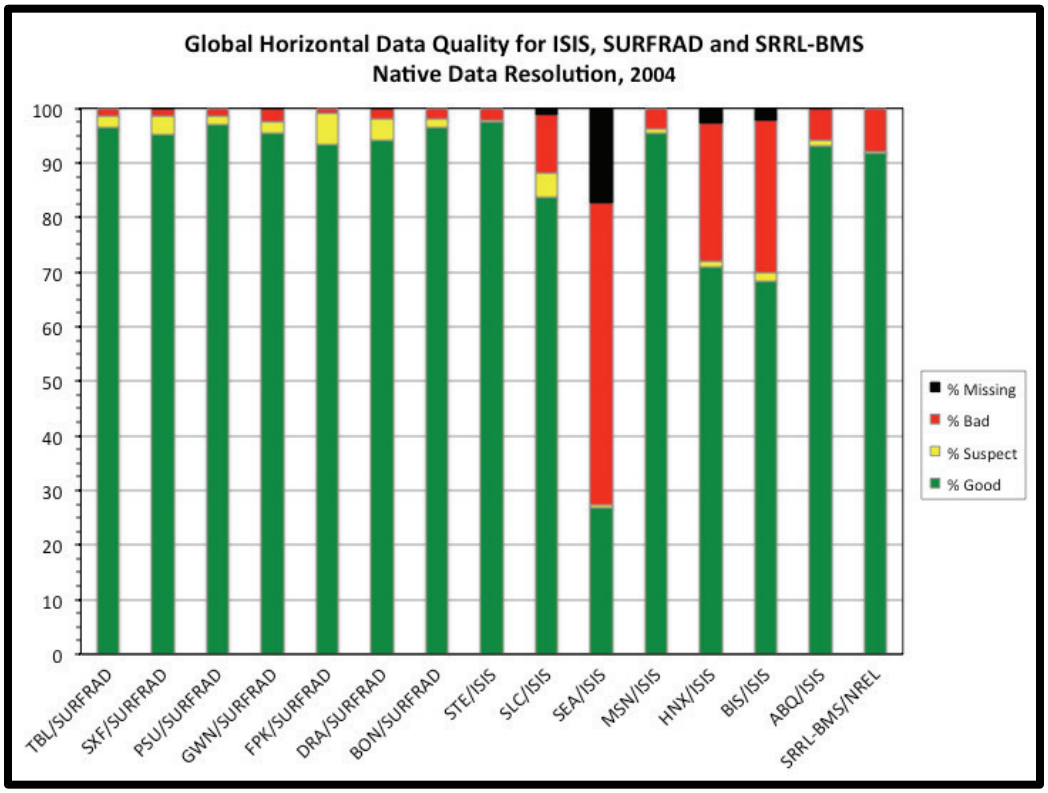

Figure 108. ISIS, SURFRAD, and SRRL-BMS 2004 GHI data quality (See text for data resolution.)

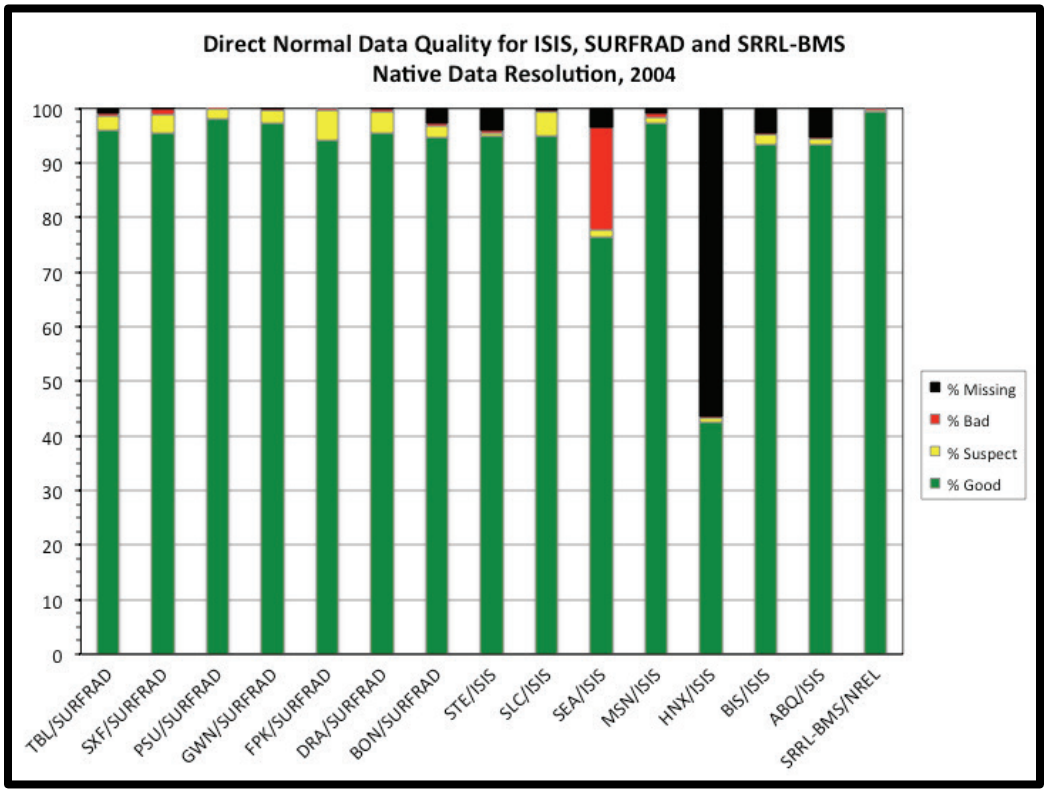

Figure 109. ISIS, SURFRAD, and SRRL-BMS 2004 DNI data quality (See text for data resolution.)

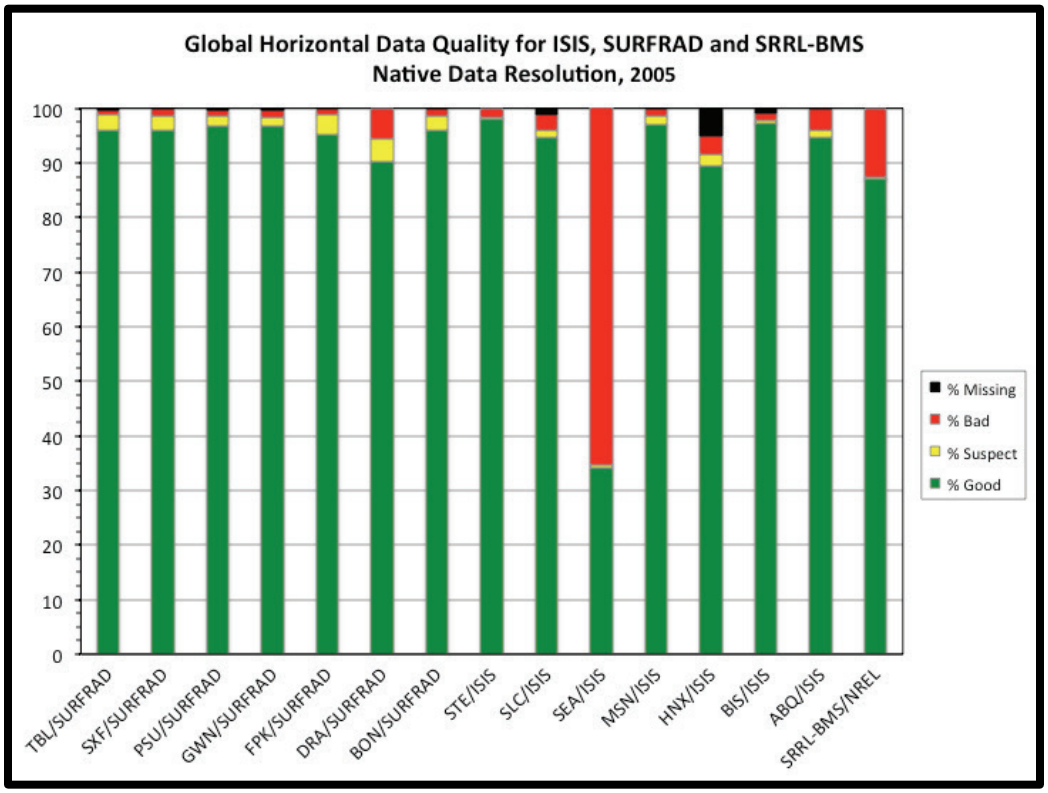

Figure 110. ISIS, SURFRAD, and SRRL-BMS 2005 GHI data quality (See text for data resolution.)

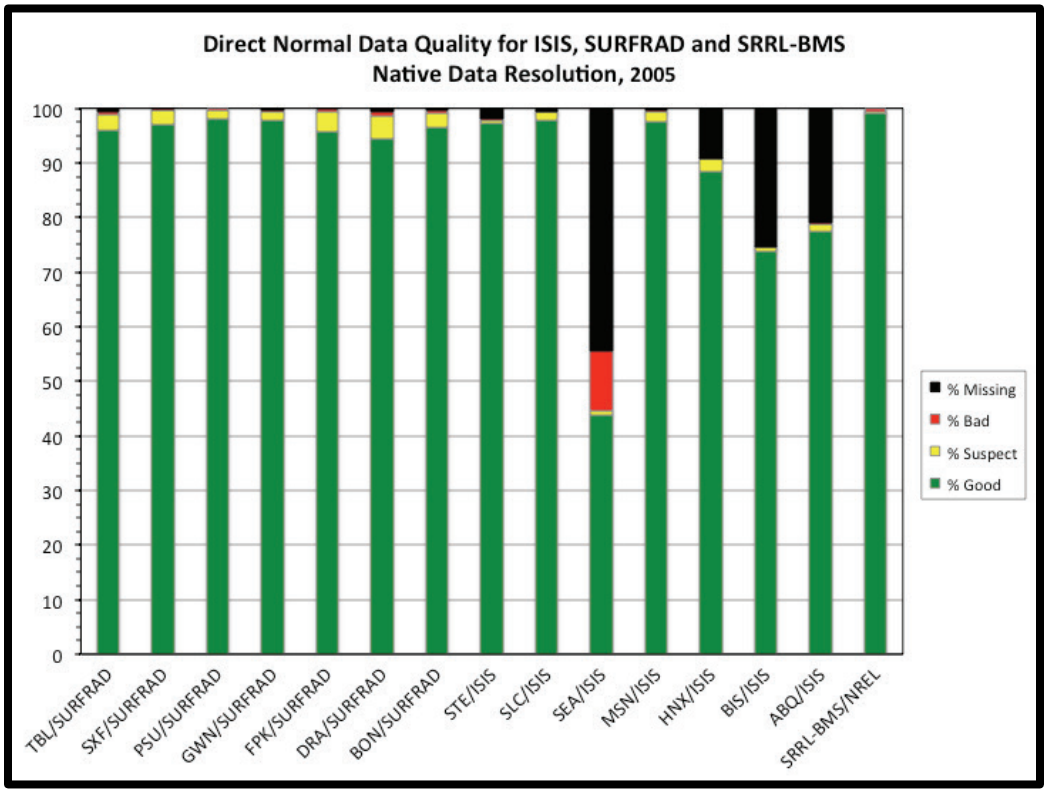

Figure 111. ISIS, SURFRAD, and SRRL-BMS 2005 DNI data quality (See text for data resolution.)

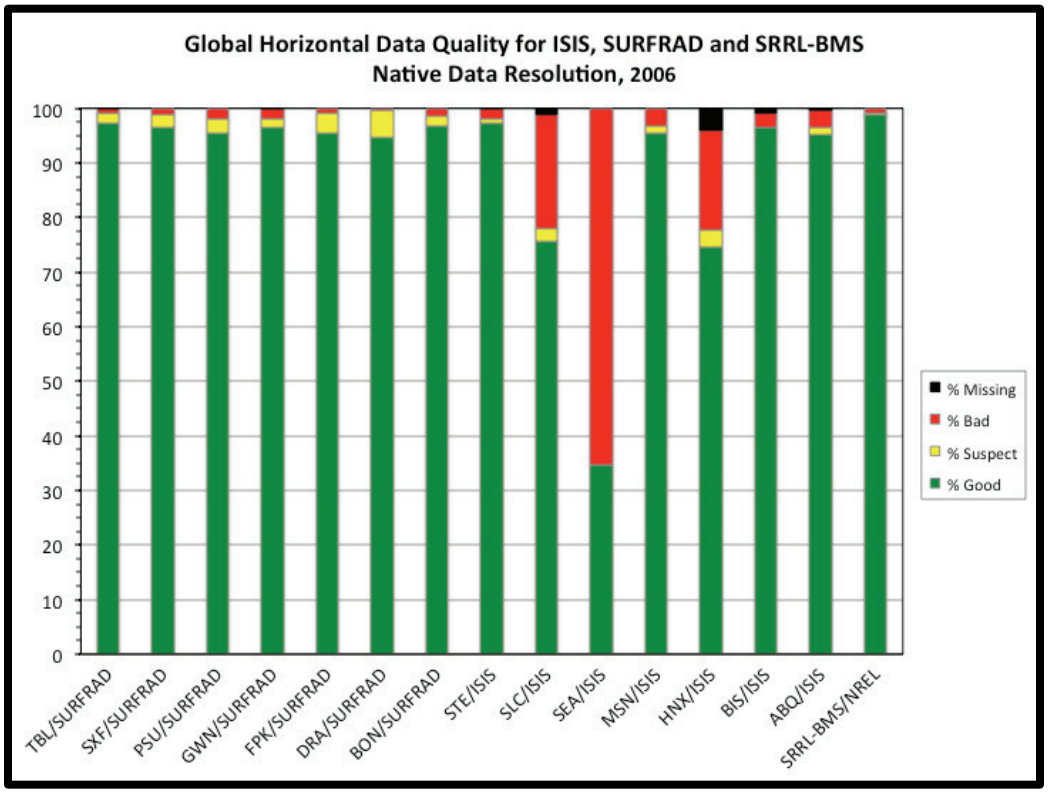

Figure 112. ISIS, SURFRAD, and SRRL-BMS 2006 GHI data quality (See text for data resolution.)

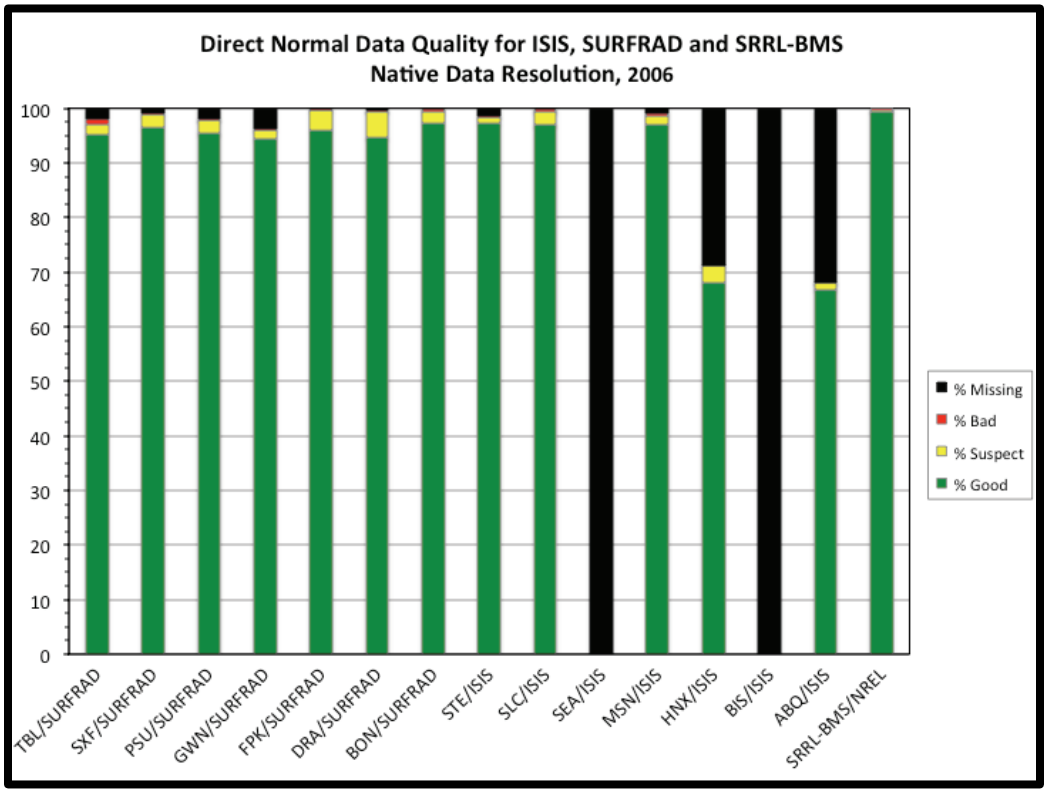

Figure 113. ISIS, SURFRAD, and SRRL-BMS 2006 DNI data quality (See text for data resolution.)

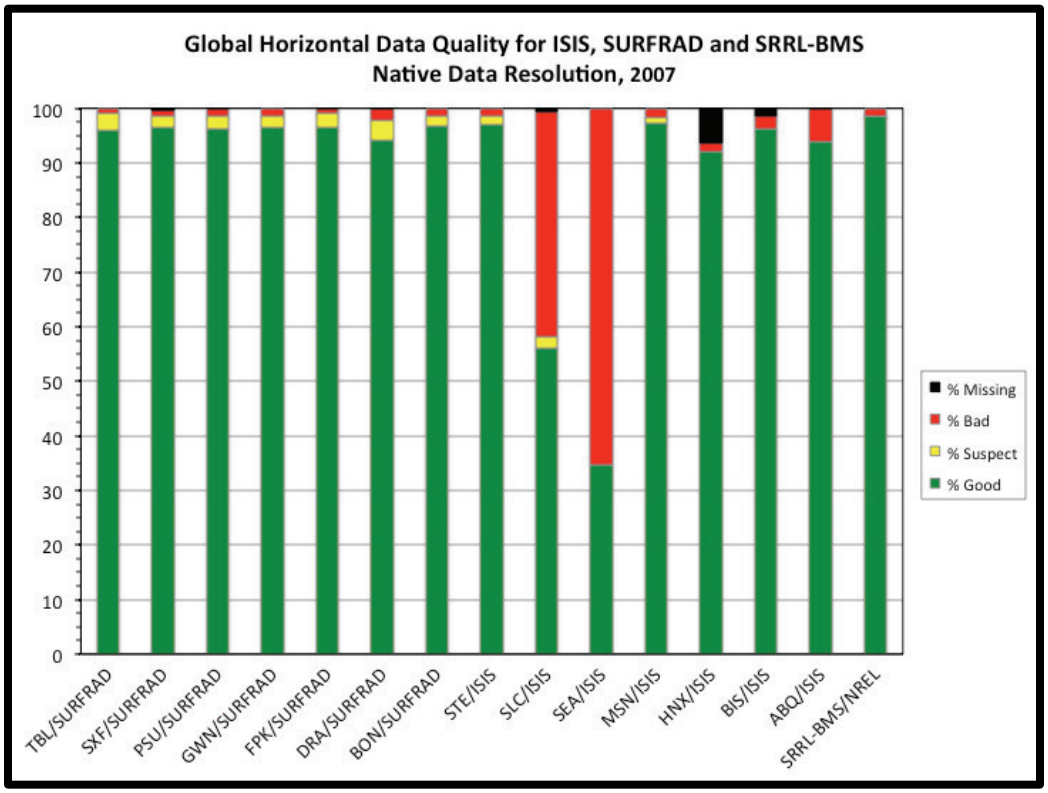

Figure 114. ISIS, SURFRAD, and SRRL-BMS 2007 GHI data quality (See text for data resolution.)

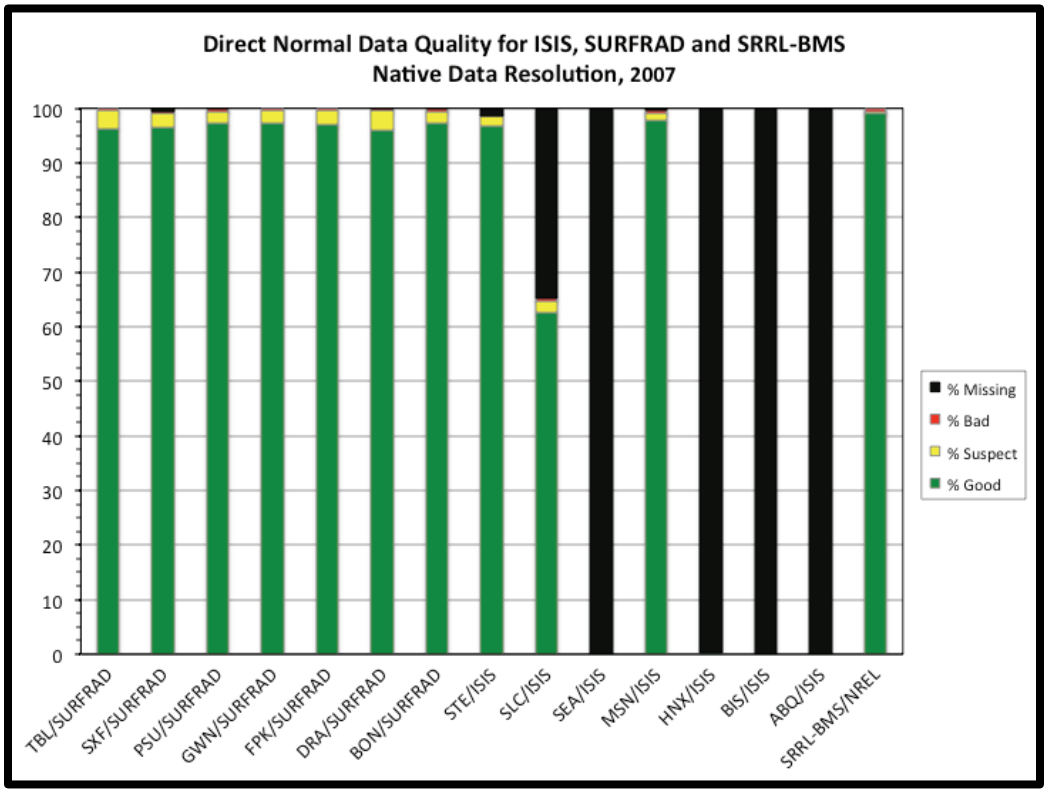

Figure 115. ISIS, SURFRAD, and SRRL-BMS 2007 DNI data quality (See text for data resolution.)

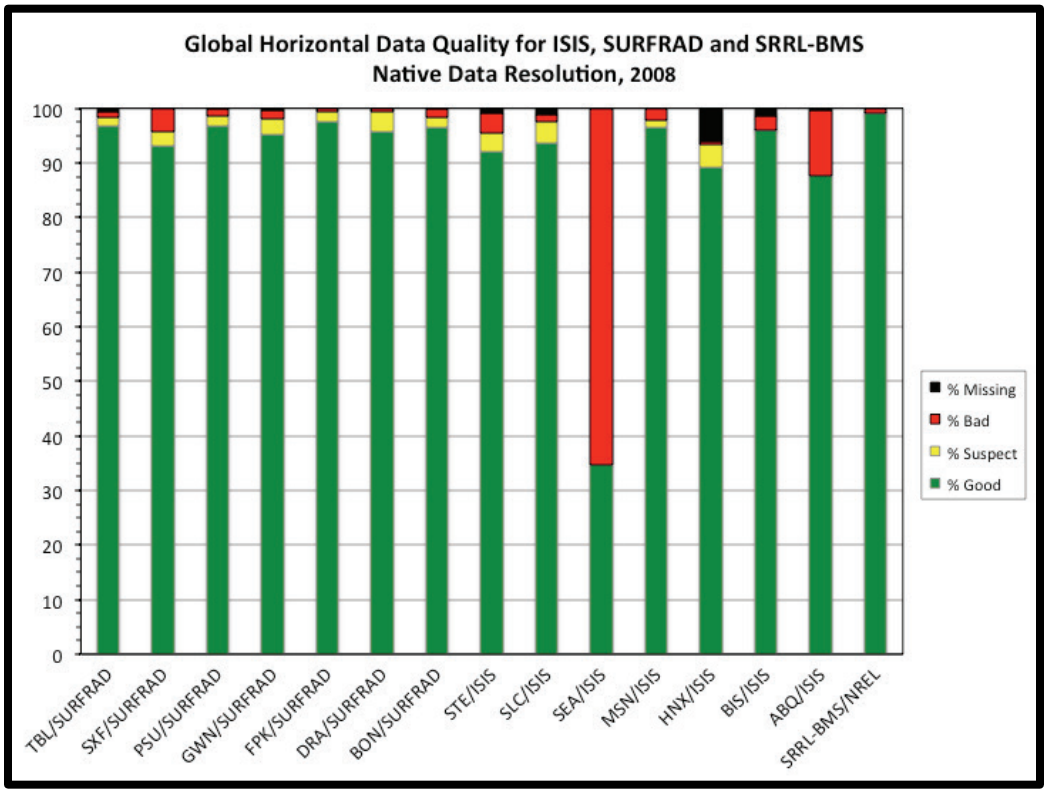

Figure 116. ISIS, SURFRAD, and SRRL-BMS 2008 GHI data quality (See text for data resolution.)

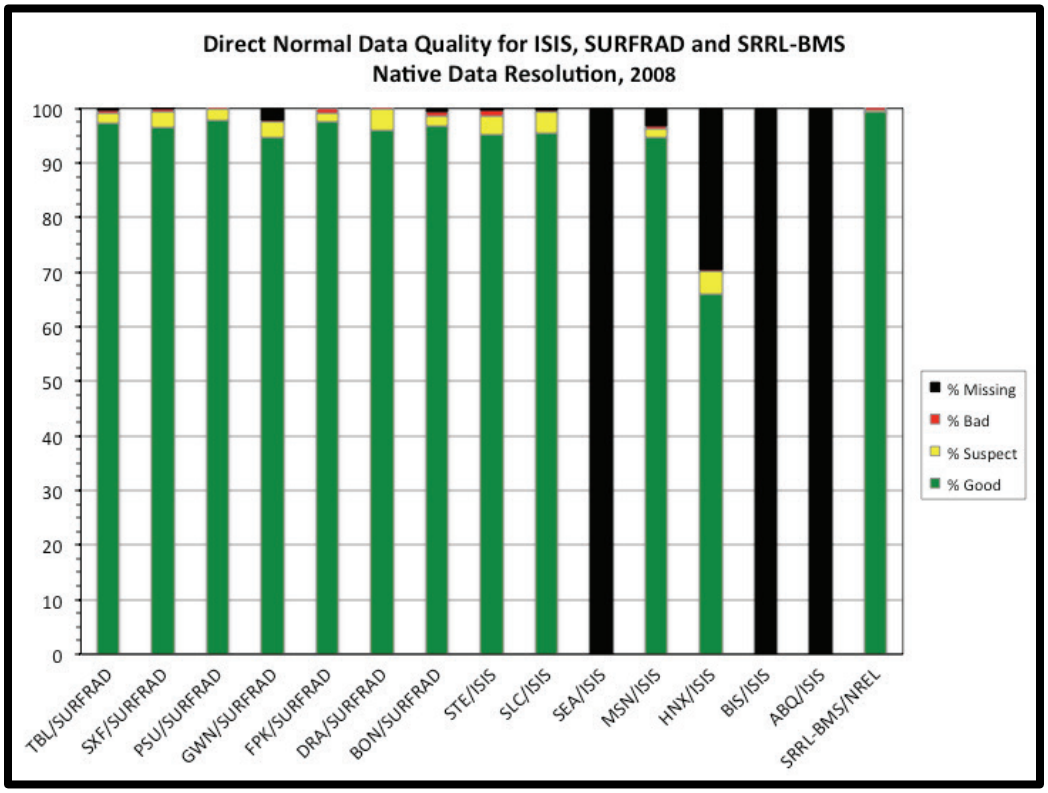

Figure 117. ISIS, SURFRAD, and SRRL-BMS 2008 DNI data quality (See text for data resolution.)

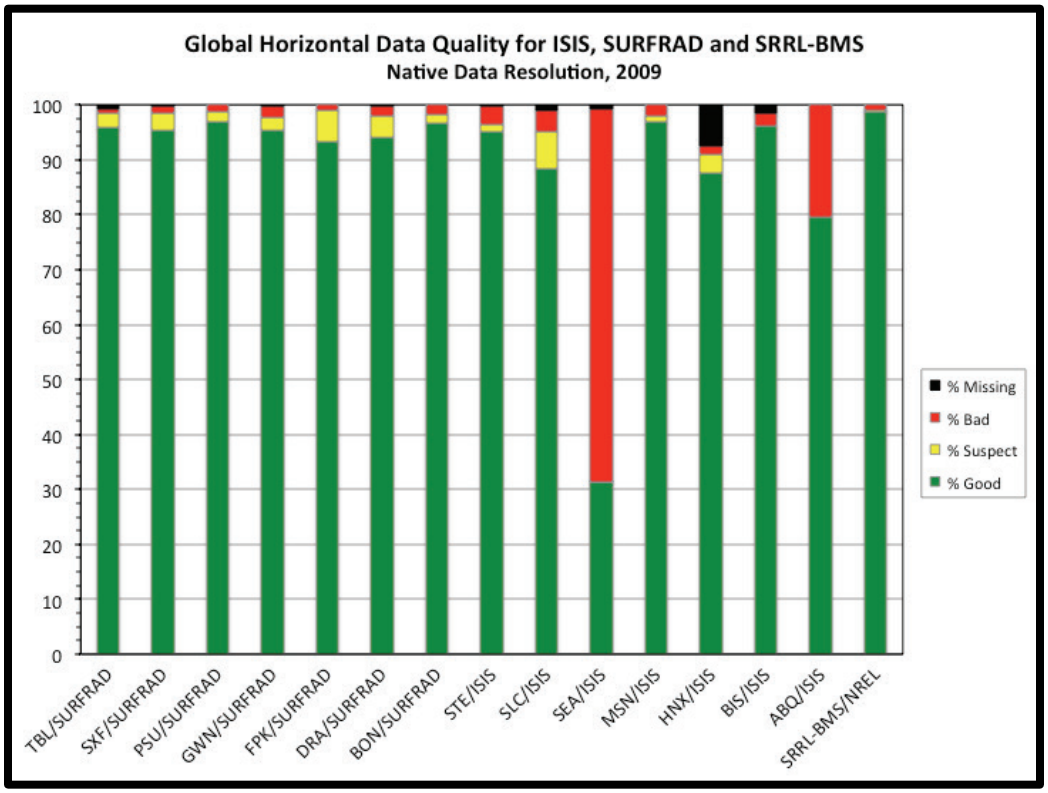

Figure 118. ISIS, SURFRAD, and SRRL-BMS 2009 GHI data quality (See text for data resolution.)

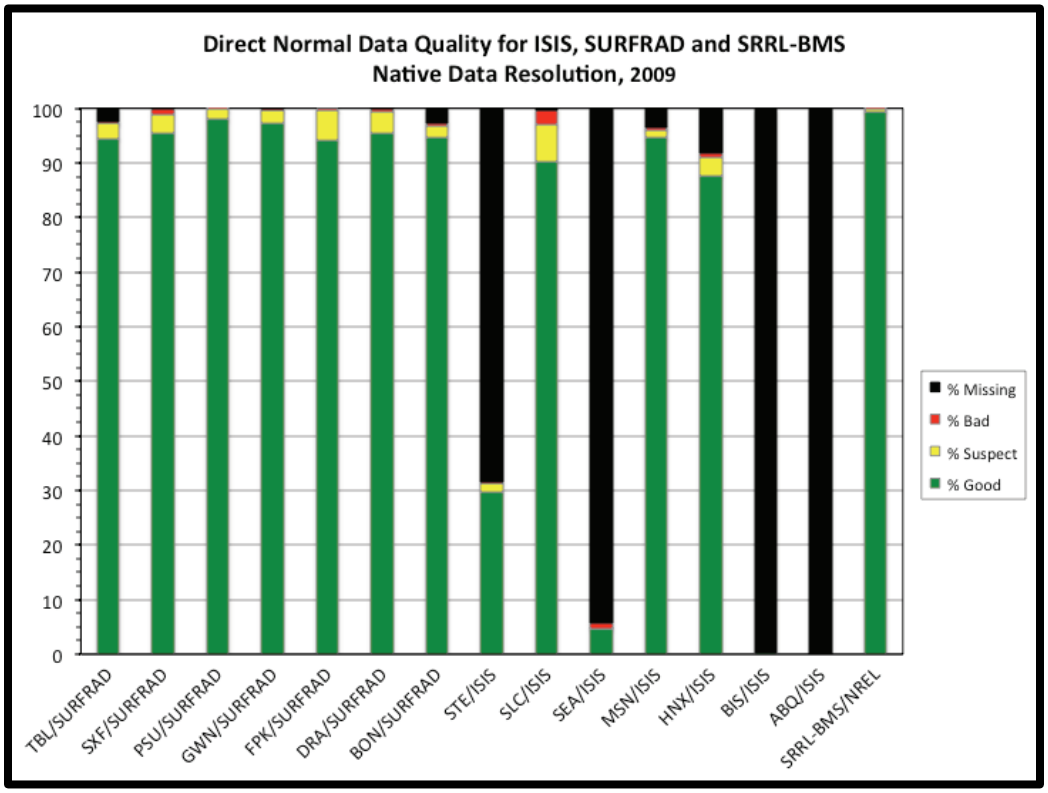

Figure 119. ISIS, SURFRAD, and SRRL-BMS 2009 DNI data quality (See text for data resolution.)

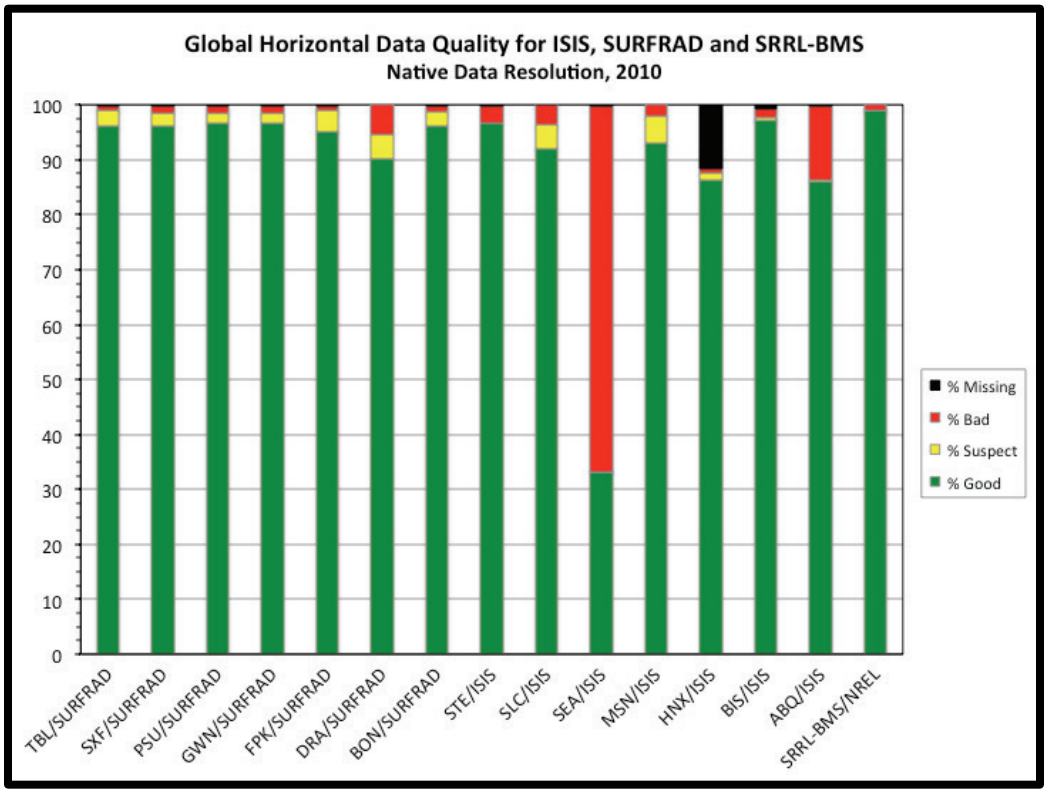

Figure 120. ISIS, SURFRAD, and SRRL-BMS 2010 GHI data quality (See text for data resolution.)

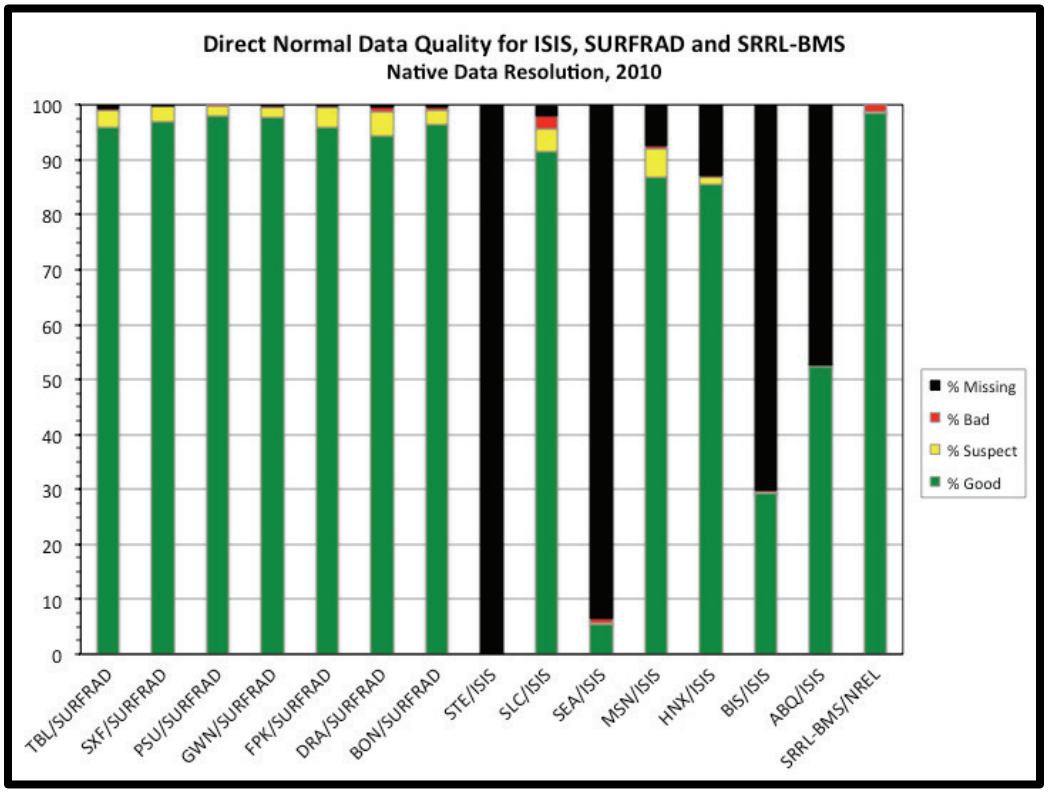

Figure 121. ISIS, SURFRAD, and SRRL-BMS 2010 DNI data quality (See text for data resolution.)

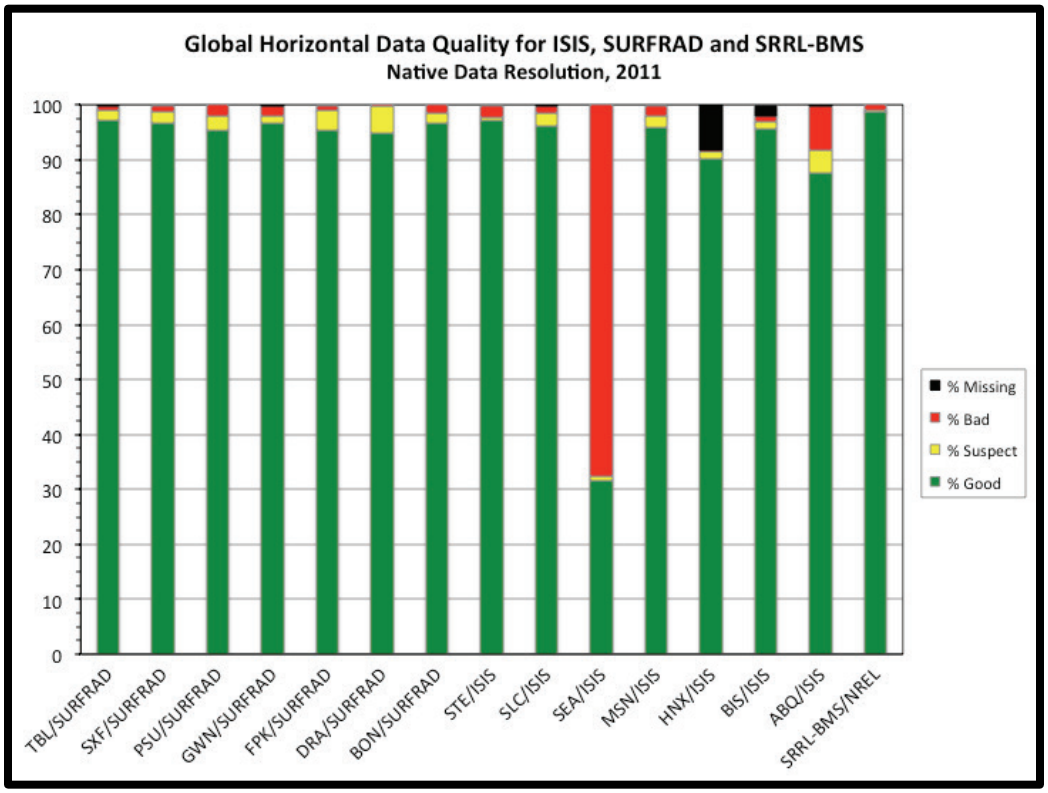

Figure 122. ISIS, SURFRAD, and SRRL-BMS 2011 GHI data quality (See text for data resolution.)

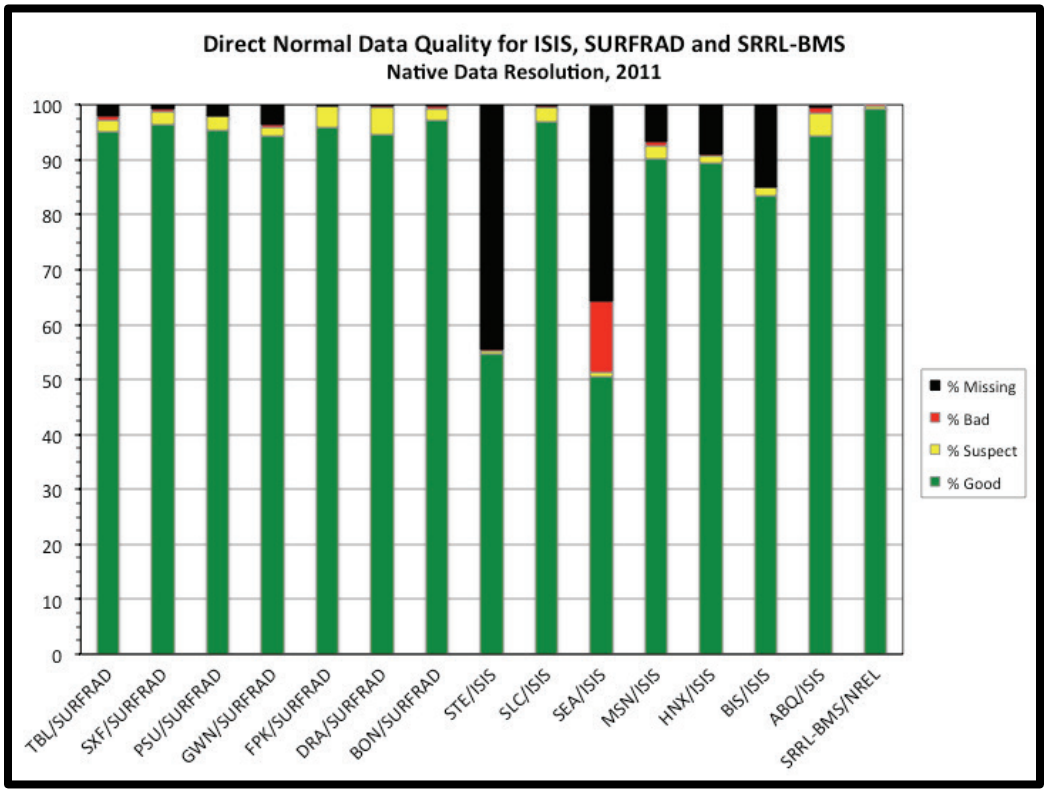

Figure 123. ISIS, SURFRAD, and SRRL-BMS 2011 DNI data quality (See text for data resolution.)

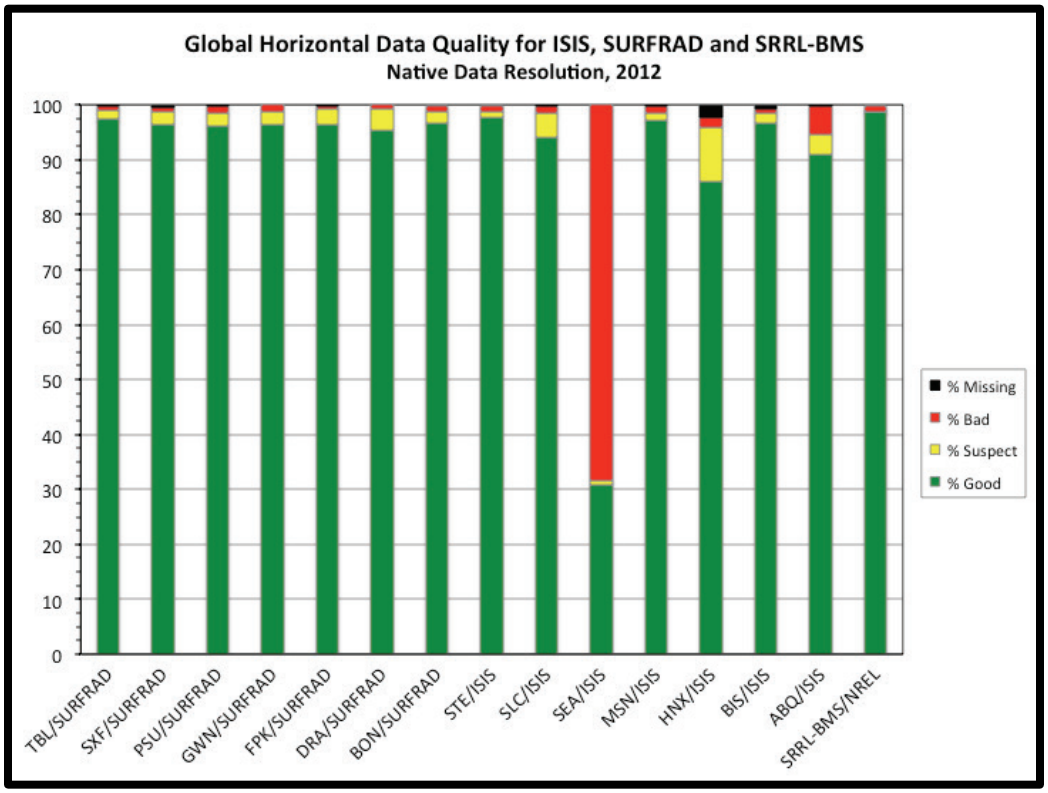

Figure 124. ISIS, SURFRAD, and SRRL-BMS 2012 GHI data quality (See text for data resolution.)

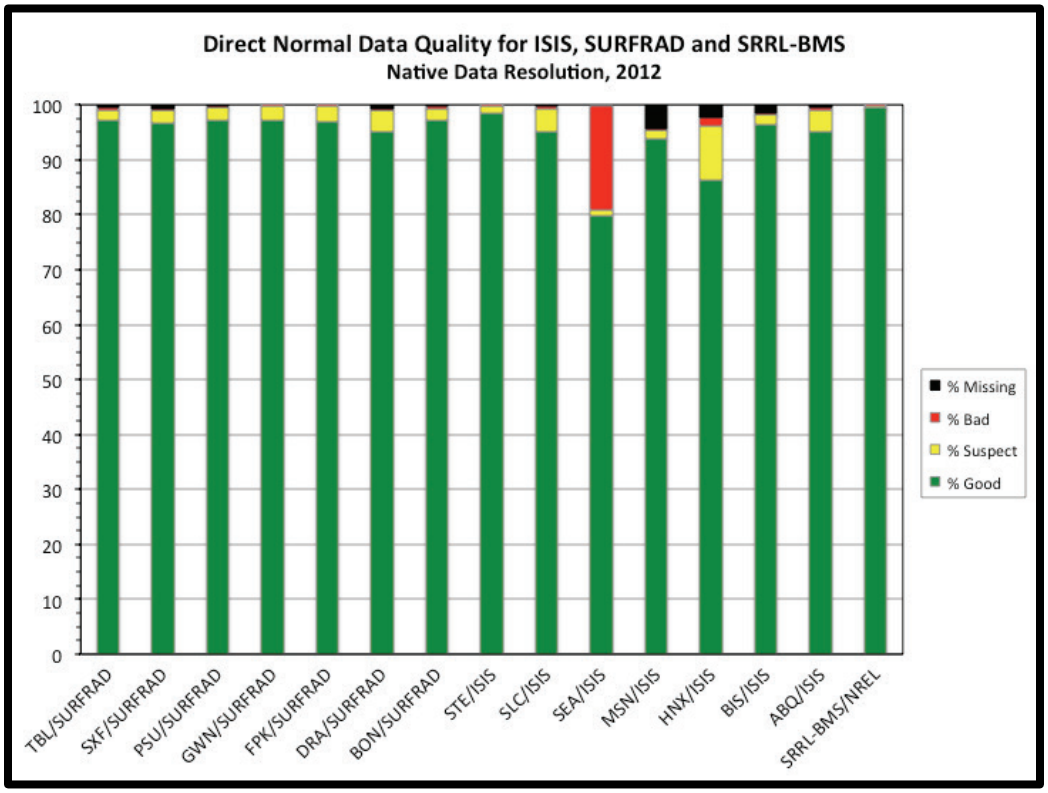

Figure 125. ISIS, SURFRAD, and SRRL-BMS 2012 DNI data quality (See text for data resolution.)

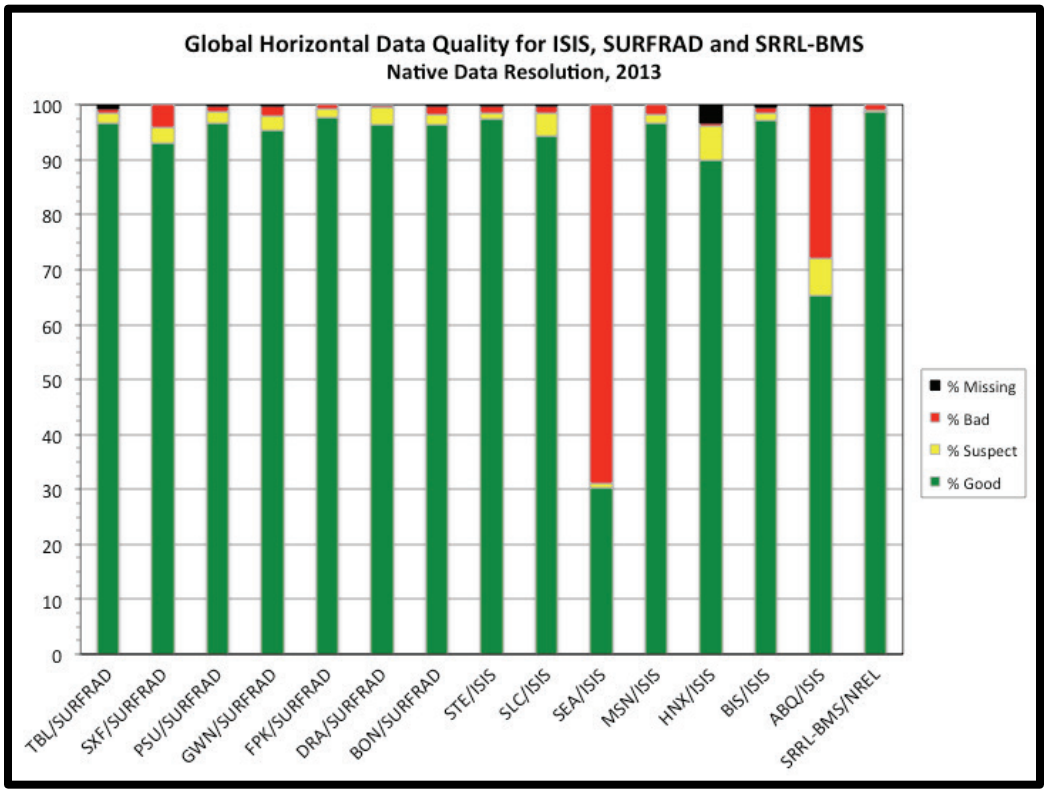

Figure 126. ISIS, SURFRAD, and SRRL-BMS 2013 GHI data quality (See text for data resolution.)

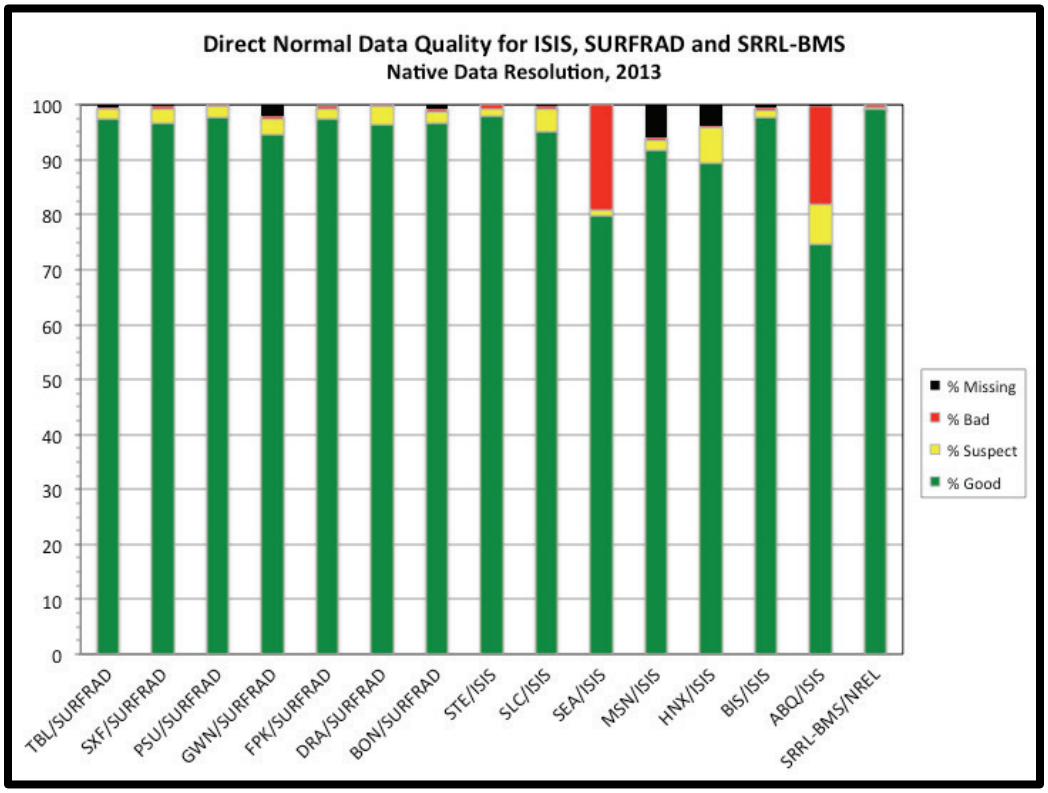

Figure 127. ISIS, SURFRAD, and SRRL-BMS 2013 DNI data quality (See text for data resolution.)