2. Instrumentation

All six sites of the NSF UV monitoring network are equipped with SUV-100 spectroradiometers manufactured by Biospherical Instruments Inc (BSI). All systems are accompanied by two ancillary radiometers from Eppley Laboratory Inc.; a short-wave pyranometer (Model PSP) and a broadband UV-A radiometer (Model TUVR). Two mobile spectroradiometers are also part of the network and are used for intercomparison campaigns and quality control purposes. One of these mobile instruments has similar specifications as the stationary SUV-100 spectroradiometers and was in use until 1996. In 1997, it was replaced by a new instrument, the SUV-150. It is the SUV-150 that will be deployed if new sites should join the network.

2.1. SUV-100 UV Spectroradiometer

The SUV-100 Spectroradiometer System is built for permanent installation and continuous 24-hour operation. The system is also designed for all-weather operation in any climate including polar regions. The fully automated system only needs operator attention for periodic manual calibrations, operational checks, data transmission, and occasional service.

2.1.1. Design, Specifications, and Installation of the SUV-100

The SUV-100 is based on a temperature-stabilized, scanning double monochromator coupled to a photomultiplier tube (PMT) detector. All basic components are shown in the figure below:

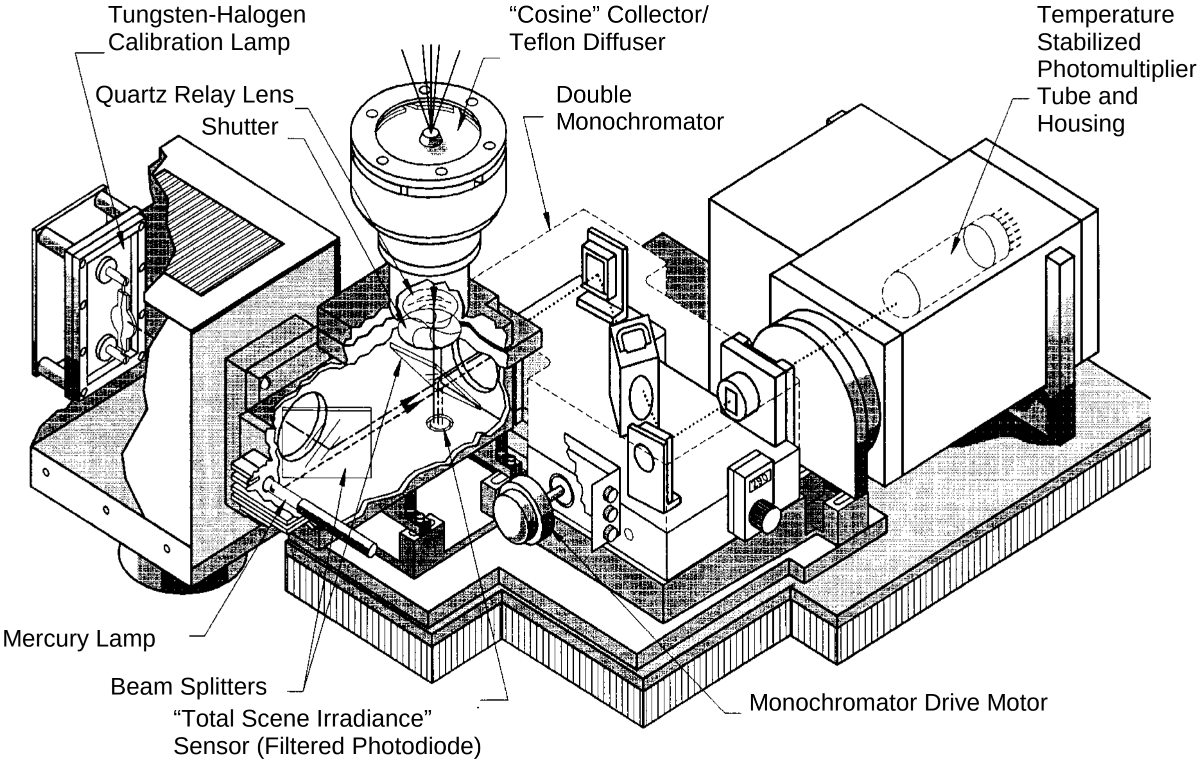

Figure 2.1. *Cutaway diagram of the SUV-100.*

The system is optimized for operation in the UV. A Teflon® diffuser serves as an all-weather irradiance collector (Figure 2.2.) and is conductively heated by the system to minimize ice and snow buildup. The instrument has internal wavelength (Hg) and irradiance reference (tungsten-halogen) lamps for automatic system characterizations at programmed intervals (typically once each per day). A data acquisition system and control instrumentation accompany the instrument. Starting in mid-1996, Pentium microprocessor-based personal computers (PC), using the Windows NT® operating system, were put into use for system control and data collection.

The f/3.5 0.10 meter double monochromator is the heart of the system and is configured with 167-micron (10^{-6} Meter) wide input/output slits and a 250-micron wide intermediate slit. The monochromator's holographic gratings have 1200 grooves/mm, and are blazed at 250 nm. The resulting spectral bandwidth is nominal 1 nm full width at half maximum (FWHM). A stepping motor, with a minimum step size of 0.1 nm, drives the monochromator. The PMT is a 28-mm diameter, 11-stage device with a bialkali cathode and a quartz window. The PMT is housed in a Peltier-cooled enclosure that is maintained at approximately –2 °C to reduce dark current and noise. The temperature of the monochromator is carefully controlled and monitored. It is typically stable to ±1.0 °C. In addition to daily calibrations with the internal sources, the system is calibrated periodically (typically biweekly) using a 200-Watt tungsten-halogen Standard of Spectral Irradiance, traceable to the National Institute of Standards and Technology (NIST). All specifications of the system are detailed in Table 2.1.

Figure 2.2. *Top part of the SUV-100 spectroradiometer at the installation at Palmer Station. The irradiance collector is the black ring with the white Teflon® diffuser in the middle. At the left of the collector is a connector for the external calibration fixture.*

A typical instrument installation is shown in the Figure 2.3. The system hardware is divided into two main sections. The first section—the irradiance collector, monochromator, PMT, data acquisition unit, thermal management components, and internal reference sources—are housed in the roof box. This insulated, weatherproof enclosure is designed to be built into the roof of an existing building, trailer, or other portable structure. The remainder of the system (Figure 2.4.), consisting of power supplies, temperature controllers, electronic interfaces, and a PC, is located up to 15 meters away. A calibration fixture is provided for periodic manual calibrations.

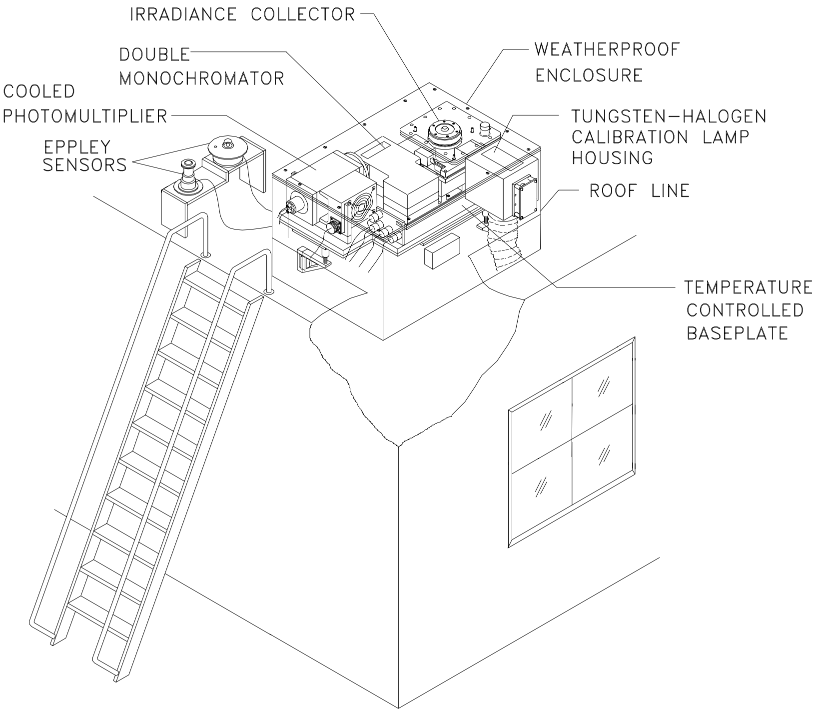

Figure 2.3. *The spectroradiometer shown in a typical installation.*

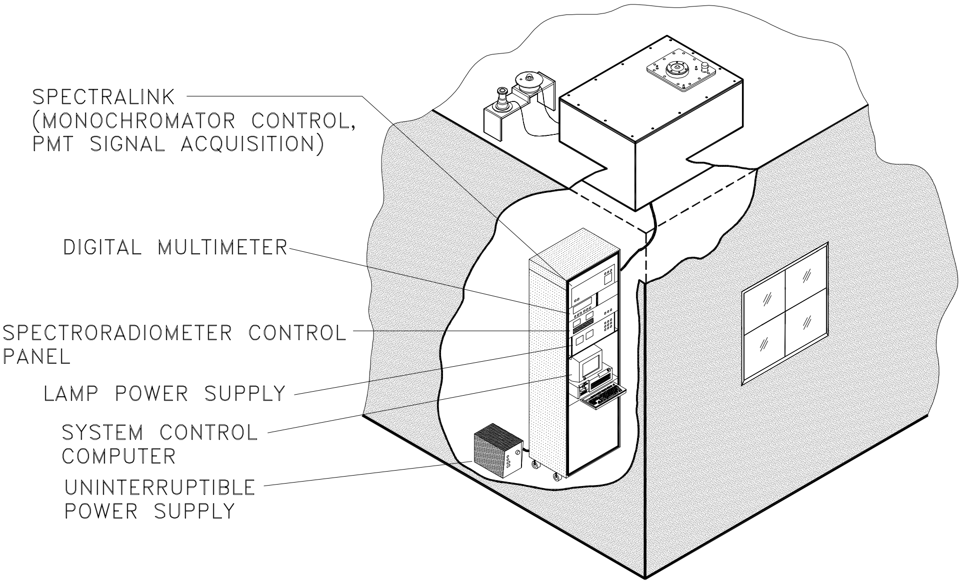

Figure 2.4. *Diagram of electronic components and computer. Access to the instrument mounted on the roof is typically provided above the installation.*

Table 2.1. SUV-100 spectroradiometer specifications, revision 1998/99.

Quantity Measured	Global spectral irradiance
Spectral Range	250-750 nm; 280-610 nm is range used for solar measurements
Monochromator	ISA DH-10UV, 0.10-meter double monochromator with focal ratio f/3.5, equipped with holographic gratings, 1200 grooves/mm 250 nm blaze wavelength (Note 1)
Bandwidth	1.0 nm ±0.1 nm (bandwidth varies from instrument to instrument; individual instruments are stable to ±0.015 nm). (Note 2)
Stray Light	Out-of-band rejection determined with a HeCd laser at 325 nm: $1x10^{-6}$. (According to specifications of the monochromator's manufacturer, out-of-band rejection is $2x10^{-9}$ at 8 band passes from a HeNe laser line at 632.8 nm.)
Wavelength Calibration	Based on combination of internal mercury discharge lamp measurements and post-correction with a Fraunhofer-line correlation method. See Section 4.2.2.2. for details.
Minimum Useable Wavelength Increment	0.1 nm
Wavelength Precision	±0.025 nm (±1σ) (Note 3)
Wavelength Uncertainty	±0.04 nm (±1σ) (Note 4)
Detector	11-stage photomultiplier tube R269 from Hamamatsu with bialkali photocathode; thermoelectrically cooled
Measurement Mode	PMT operated in DC mode. PMT anode-current converted to frequency with variable integration time; 10^6 count maximum; 1 MHz count rate maximum.
Integration Times	0.1 – 10 seconds under software control, typically set to 0.2 to 0.5 seconds
Dynamic Range	10^6, defined by the digitization scheme
Detection Limit	0.0005 $\mu W\ cm^{-2}\ nm^{-1}$ for SZA > 70°, 0.001 $\mu W\ cm^{-2}\ nm^{-1}$ for SZA < 70°; values refer to a signal-to-noise ratio of one (Note 5)
Offset Stability	Typically 10^{-5} relative to full scale, plus the contribution of PMT dark current
System Responsivity Stability	Depending on site and time period, see Section 5.
PMT High voltage	0-1000 Volts under software control
Irradiance Collector	Teflon®-covered quartz with cosine respone
Operating Temperature Range	+40° to –80° C outside environment
Utility Requirements	115 VAC, 15 Volt-Amps, telephone line (Note 6) and/or Internet access, uninterruptable power supply provided for 1 hour minimum operation in the event of power failure.
Internal Standards and Time Source	45-Watt Tungsten-Halogen Lamp, Hg discharge lamp, and GPS.
Primary System Calibration Sources	200-Watt tungsten-halogen Standards of Spectral irradiance, NIST traceable
Signal Range	Maximum 250 microwatts $cm^{-2}\ nm^{-1}$, minimum limited by noise level. (see above)
Monitored System Parameters	Monochromator temperature, enclosure temperature, TSI, monochromator wavelength position, and lamp current.
Ancillary Sensors	Shortwave (0.3 µm-3 µm) Pyranometer (Eppley PSP), UV-Pyranometer (Eppley TUVR), and temperature and humidity sensors.
Data Formats	Data recorded in Microsoft Visual Basic® native binary format. Separate Programs for conversion to ASCII MS-DOS/Windows format with full application of calibration data. Normal retrieval of data via modem and/ or Internet.

Note 1: Monochromator is modified and temperature stabilized.

Note 2: Testing indicates that the bandwidth, as measured with a HeCd laser or an external Hg lamp, completely illuminating the cosine collector, is approximately 1.0 nm. The specification on bandwidth stability was derived from all internal mercury scans of Volume 7.

Note 3: Wavelength *precision* specifies the change in the registered position of the 296.73 nm mercury line within one day. The value is the standard deviation of the difference in the position derived from two consecutive wavelength scans, which are performed on a daily basis. The wavelength precision is similar for all sites, see Chapter 5.

Note 4: Wavelength *uncertainty* is the square-root-sum of two components: The first component (±0.035 nm (±1σ)) is the standard deviation of the wavelength offset (measured minus target wavelength position) after the solar data have been corrected for wavelength errors. The residual offset was determined with the "Fraunhofer-line correlation method" described in Section 3.3.1.2. The second component (±0.02 nm (±1σ)) is the estimated uncertainty of the correlation method.

Note 5: Detection limit is defined as the standard deviation of the measured spectral irradiance at 285 nm. At this wavelength, all solar radiation is filtered out by the Earth's ozone layer. The measured value at 285 nm therefore reflects the magnitude of instrument noise, which causes the detection limit. At large solar zenith angles, the PMT is operates at a higher voltage, leading to better sensitivity and a lower detection limit.

Note 6: At Antarctic continent locations, the computers are locally networked and established as FTP servers, allowing for direct data access from San Diego and/or transmission by operators - limited only by satellite windows.

2.1.2. Ancillary Sensors

The SUV-100 installations are equipped with several ancillary sensors, including broadband radiometers, filtered photodetectors (integral part of the SUV-100), several sensors for monitoring instrument parameters, and a GPS receiver. Typically, ancillary sensor data are recorded during the high-resolution spectral scans (several sets of readings per minute) and between the scans at an operator-selected rate ranging from a reading every one to sixty minutes. Since all sensors are directly interfaced with the SUV-100, data sets are fully synchronized without the need for additional data recording or handling.

Eppley Radiometers

Two independent radiometers are mounted alongside the SUV, the Eppley Laboratory, Inc.'s Precision Spectral Pyranometer (Model PSP with WG7 hemisphere) and the UV Radiometer (Model TUVR), see Figure 2.5. Calibration coefficients of both instruments are provided by Eppley Laboratory. The PSP measures short-wave (0.3 – 3 µm) solar irradiance. The TUVR is sensitive in the 295-385 nm range. The output of these sensors is collected automatically with the *SUV-100 System Control Software*, and a Biospherical Instruments designed pre-amplifier. Raw data is converted to irradiance units (mW/cm²) and published together with the spectral measurements. Calibrated values of the TUVR agree to within ±20% with spectral measurements of the SUV-100, integrated over the UV-A (320-400 nm). TUVR data are less accurate than integrated spectral data and should therefore not be used as a surrogate for SUV-100 measurements. However, TUVR measurements are valuable for quality control purposes. For example, by comparing time-series of TUVR and SUV-100 measurements data that might be affected by snow accumulation on one of the sensors can be detected. The TUVR is not heated and is therefore much more affected by snowfall and ice buildup on its diffuser than the SUV-100.

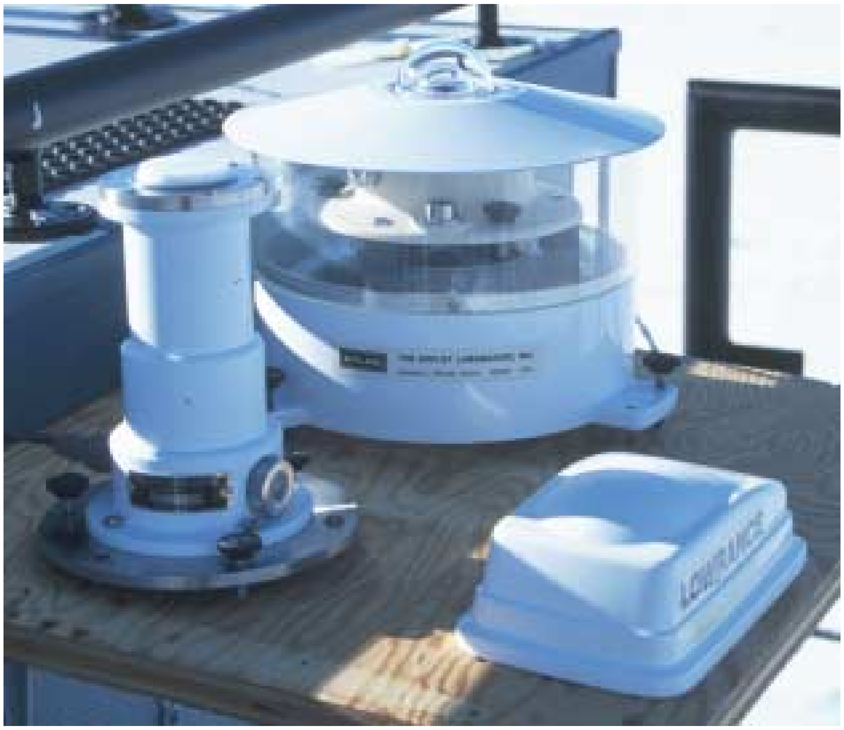

Figure 2.5. *Eppley radiometers and GPS receiver. The PSP is shown in the background and is equipped with a ventilator that continuously blows air over the instrument case and its dome, keeping the hemispheres clean from frost and snow buildup. The TUVR radiometer is on the left; the GPS receiver is on the right.*

Total Scene Irradiance Sensor

For quality control purposes, a stable filtered photo diode with response in the UV-A, called “Total Scene Irradiance sensor” (TSI), is integrated into the system (see Figure 2.1.). It serves several functions. First, the sensor is used to monitor changes in the system’s internal irradiance reference lamp on a daily basis. Similarly, the TSI is used to track changes in the 200-Watt calibration standards that are used biweekly for the instrument’s irradiance calibration. Third, the TSI provides an indication of changes in irradiance that may occur during a solar scan (e.g., due to changes in cloud cover). Finally, the TSI provides an independent measure of UV-A solar irradiance that can be compared with long-term spectral solar measurements of the SUV-100. The ratio of solar TSI measurements and spectral measurements, weighted with the spectral response function of the TSI (Figure 2.6), is a very useful tool to detect system drift. The TSI is not a calibrated sensor, but is used referentially; results are expressed in Volts. TSI readings from one season to another, or from one site to another, are not directly comparable.

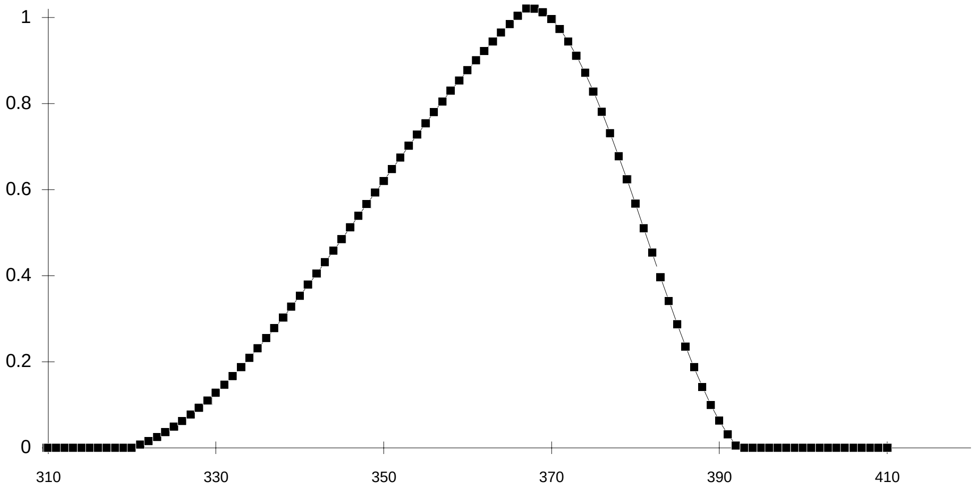

Figure 2.6. *Spectral response of the TSI sensor (typical).*

Sensors Monitoring Instrument Parameters and GPS

Several sensors are part of the SUV-100 systems at all sites. System parameters recorded include temperatures (ambient temperature, and temperatures of the monochromator housing and instrument enclosure temperature), and monochromator position. Humidity sensors to detect possible leaks in the roofbox are installed at Barrow, San Diego, and Ushuaia. In addition, the current during lamp scans is monitored with a high-precision digital multimeter. During the 1992-1993 season’s site visits, a Global Positioning System (GPS) receiver was added to the ancillary sensor system. The GPS is principally used as an automatically updated, high-accuracy time base for the system control computer clock.

2.1.3. Maintenance and Calibration of the SUV-100

During the 1998-99 season, the instruments at South Pole, McMurdo, and Palmer Stations were operated year-round by personnel from Antarctic Support Associates (ASA). The Ushuaia site is maintained by the Centro Austral de Investigaciones Cientificas, Argentina. The installation in Barrow operational assistance is provided by personnel from the Climate Monitoring and Diagnostics Laboratory (CMDL) of the National Oceanic and Atmospheric Administration (NOAA). Operator duties include the performance of data transmission, daily verification of the system operation, inspection/cleaning of the irradiance collector, biweekly calibrations with Standards of Spectral Irradiance, and routine and emergency service. Daily maintenance activities typically require 5 minutes; the biweekly system calibration takes about 1-2 hours. In addition to the routine maintenance, each site is visited annually by personnel from Biospherical Instruments. During these site visits, the on-site irradiance standards are validated and the spectroradiometers are serviced, cleaned, upgraded, and repaired if needed. The results of the site visit are a necessary prerequisite for the processing and the quality control of final data.

For the purpose of an irradiance calibration with the NIST-traceable 200-Watt standard, the operator mounts a specially designed fixture (or stand) on top of the instrument (see Figure 2.7). To reduce systematic errors in the process, the stand is designed so that it can only be mounted onto the system in one configuration. The lamp holders are keyed to the calibration stand and can only fit in one orientation. The lamp is then energized and, after a 10-minute warm-up period, a spectrum of the lamp is measured by the SUV-100. This measurement is then used to determine the spectral responsivity of the system. The whole procedure is described in more detail in Chapter 4.

In order to maximize the accuracy of calibrations, each SUV system includes an IEEE-488 controlled power supply (PS) and a high-precision digital multimeter (DMM) for monitoring the applied currents used to operate both the internal 45-Watt and external 200-Watt lamps. In addition, calibrations with "traveling" Standards of Spectral Irradiance are performed during the annual site visit. Thus, drifts of the lamps kept on-site are determined with an independent calibration standard. Since the same travelling standard is used at all network sites this helps to ensure consistent calibrations at all locations.

Figure 2.7. *Calibration stand with the 200-Watt lamp mounted on top of the. The lamp power is connected to the roofbox immediately below the fixture. Baffles limit stray light. During operation, an internally-blackened barrel covers this fixture.*

2.1.4. Software for Instrument Operation and Data Reduction

Network operation software is comprised of three major elements: *SUV-100 System Control*, *SUV Read*, and software tools to organize processed data into databases.

- The *SUV-100 System Control Software* is installed on the system control computers at every site and automatically controls the instruments and records data. Compiled in Visual Basic®, the software offers ease of control, is intuitive to use, and runs under the Windows NT® operating system. The latest version of the *SUV-100 System Control Software* was installed at all sites over a period of seven months, beginning in June 1996 at the Barrow, Alaska, site. The software features Windows®-based menu operation, user-selectable graphic and numeric display of raw data in real-time, and alarms with an indicating status bar. Displayed error conditions include failures in specific system operations and functions. A "front panel" scrollable event log informs the operator of system malfunctions (achieved by defining a series of different alarms utilizing settable limits). This program also offers real-time display of data from the suite of ancillary sensors, an has built-in capability for additional sensors.

- *SUV Read* is used at Biospherical Instruments Inc., and occasionally by site operators to decode binary raw data from the instruments and apply wavelength and irradiance calibrations. The software allows the user to display both calibration and data results graphically. It can also be used to calculate solar zenith and azimuth angles, spectral integrals, weighted doses, and column ozone.

- In 1999, processed network data have been organized in Microsoft®-Access databases. Tools to maintain these databases are the third software component. This allows to display time-series spanning multiple years of data, and administer important performance measures for all network instruments. With the new tools, the quality control of data is more efficient leading to a shorter latency period between the recording and publication of data.

2.2. Mobile Spectroradiometers

Mobile instruments were developed for the purpose of research as well as quality control. One of these mobile instruments, the "portable SUV-100," has the same specifications as the stationary SUV-100 spectroradiometers and was in use until 1996. In 1997, it was replaced by a new instrument, the SUV-150. Both instruments have been active participants in national and international intercomparison activities.

In August 1994, the portable SUV-100 participated in an international intercomparison campaign, which took place at the Fraunhofer Institute for Atmospheric Environmental Research (IFU), located in Garmisch-Partenkirchen, Germany (Seckmeyer, et al., 1995), see Figure 2.8. The instrument also participated in three annual NOAA/NIST North American Intercomparisons of Ultraviolet Monitoring Spectroradiometers in 1994 through 1996 (Thompson et al., 1996, 1997).

The new SUV-150 was developed to take advantage of 10 years of advancements in optical, electronic, data acquisition, and computer technologies, with the end goal of deployment at one of the existing network sites and at new sites that may join the network in future. Figure 2.9 shows a diagram of the instrument. The design of the SUV-150 is based on a double scanning monochromator coupled to a photomultiplier tube (PMT) detector that is housed in a temperature regulated semi-hermetic enclosure. The temperature is maintained within ±1°C by a thermoelectric heater/cooler, driven by a PID controller. The heart of the system is a 150 mm, f/4.4 Czerny-Turner double monochromator optimized for recording UV-B and visible wavelength solar irradiance.

Significant effort has been expended to achieve outstanding cosine response that is free of asymmetry and spectral distortion over the full operational range. The SUV-150 utilizes a quartz window with vacuum-formed Teflon® diffuser at the entrance port of an integrating sphere with center baffle. The diffuser is heated to minimize ice and snow buildup and evaporate other moisture that accumulates. The most important specifications of the instrument are compiled in Table 2.2.

The SUV-150 instrument was first employed at the European Communities (EC) SUSPEN Campaign, an international instrumentation and standards intercomparison organized in Thessaloniki, Greece in July 1997 (Figure 2.10). After several engineering improvements following the experience at SUSPEN, the SUV-150 was then deployed at the NOAA/NIST North American Intercomparison at Boulder, Colorado in September 1997. The fourth in a series of annual NOAA/NIST North American Intercomparisons of Ultraviolet Monitoring Spectroradiometers, culminated in the reduction of uncertainties in measurements and standards, and has also led to the development of standards and apparatus for the purpose of "field" characterizations of this type of instrumentation. A report on the results of this intercomparison campaign is currently being prepared by NOAA.

Figure 2.8. *Instruments at an international intercomparison of UV spectroradiometers organized at the Fraunhofer Institute for Atmospheric Environmental Research (IFU), located in Garmisch-Partenkirchen, Germany. The portable SUV-100 is the instrument on the left. An Eppley PSP radiometer is placed on a tripod in front of the instrument. The stationary IFU spectroradiometer is located in the container on the right side. The apparatus to the far right is the suntracker of this instrument. Mountains of the Alps can be seen in the background.*

The SUV-150 spectroradiometer was operating in 1998 and 1999 next to the SUV-100 network instrument on the roof platform of Biospherical Instrument Inc. Data from the period August to December 1998 were evaluated and presented at the XXIV General Assembly of the European Geophysical Society that took place in The Hague, The Netherlands in April 1999 (Viewgraphs of the presentation are available on the BSI website). Compared to the SUV-100, it was shown that the SUV-150 has superior characteristics with respect to angular response, wavelength resolution, and detection limit. In addition, it has a smaller bandwidth and features a compact design, which facilitates installation, maintenance, and calibration. Instrument measurements were compared with model calculation. The agreement was in the range of ±5%, even for wavelengths below 300 nm (at high sun) and solar elevations as low as 2°. As of this writing, the

SUV-150 is under long-term evaluation at San Diego to further the understanding and definition of its performance envelope, stability, and reliability.

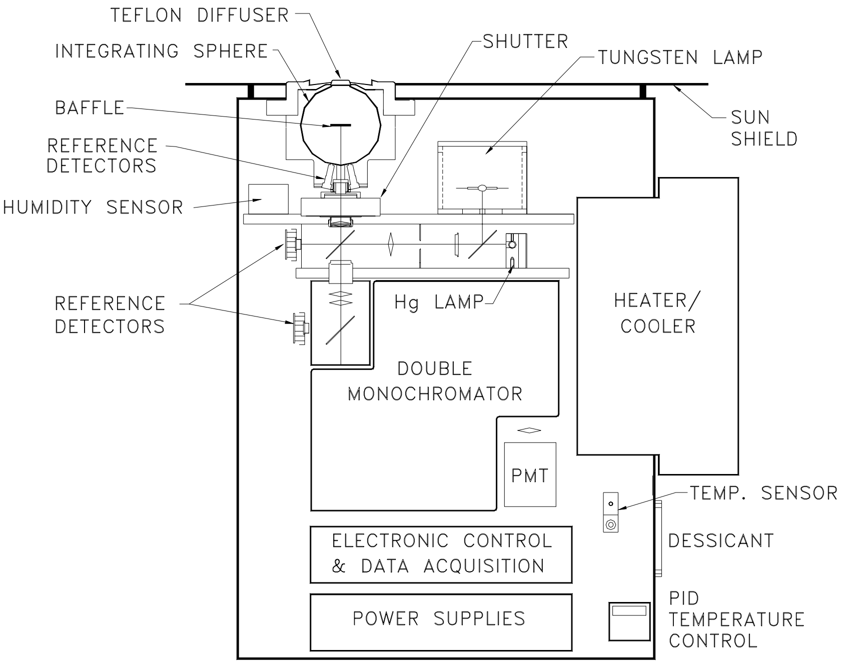

Figure 2.9. *Diagram of the SUV-150.*

Table 2.2. Selected SUV-150 spectroradiometer specifications

Spectral Range	280-600 nm
Monochromator	0.15-meter Czerny-Turner double monochromator with focal ratio f/4.4, equipped with ruled gratings, 2400 grooves/mm, 240 nm blaze wavelength.
Bandwidth	0.7 nm FWHM
Entrance optics	Vacuum-formed Teflon® diffuser at the entrance port of an integrating sphere with center baffle; cosine error <±2% up to 60° incidence angle, <±4% up to 80°; collector asymmetry and spectral Effects: <1%.
Detector	Type R1414 from Hamamatsu, low noise; 9 stage dynodes; mounted in shielded housing with built-in high voltage power supply.
Typical scan time	0.6 sec/wavelength point
Noise equivalent irradiance at 300 nm	2×10^{-10} W/cm^2 nm

Figure 2.10. *SUV-150 spectroradiometer at the SUSPEN intercomparison campaign held in Nea Michaniona, Greece in July 1997.*