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Application note

USDA UV-B monitoring system: An application of centralized architecture

*Xinli Wang**, *Wei Gao*, *Jim R. Slusser*, *John Davis*, *Becky Olson*, *Scott Janssen*, *George Janson*, *Bill Durham*, *Roger Tree*, *Rita Deike*

USDA UV-B Monitoring and Research Program, Natural Resource Ecology Laboratory, Colorado State University, Fort Collins, CO 80523-1499, USA

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ABSTRACT

In order to determine the spatial and temporal variations of solar ultraviolet-B (UV-B) radiation reaching the Earth's surface and their effects on agriculture and environment due to the depletion of atmospheric ozone, the U.S. Department of Agriculture (USDA) UV-B monitoring system has been established to provide essential information of ground UV-B levels, along with other variables, to research communities, decision makers, and the public. This monitoring network of 39 sites was designed as a centralized system covering the U.S. domain with collaborating sites in Canada and New Zealand. Programmed data loggers and a central data server are employed to automate the work. The centralized architecture allows centrally processing the data from all sites on a 3 min basis and making daily updates available for the users. The system architecture, algorithms for data collection and data flow in the data processing procedures are presented in this article. Statistics show that the system is rather reliable with an overall data completeness of 98.14% since it began running in 1994. Main damages to the instruments are caused by the static electricity associated with severe thunderstorms, which result in a lower data completeness in summer months than in the others. The drawbacks of the centralized architecture, the possible remedies for the network failures, and our experiences with the system are discussed.

1. Introduction

The intensity of UV-B radiation reaching the Earth's surface is strongly influenced by atmospheric ozone. The observed depletion of atmospheric ozone (Farman et al., 1985; Stolarski et al., 1992) raises serious concerns about the concomitant increases in UV-B radiation at the Earth's surface (Cotton et al., 1988; Blumthaler and Ambach, 1990; Kerr and McElroy, 1993) and its detrimental effects on plants, humans, and the environment (Longstreth et al., 1998; Caldwell et al., 1998, 2003). Although recent measurements indicate the start of a turnaround in stratospheric ozone, its recovery will likely take decades and is influenced by many factors (Staehelin et al., 2001; Newchurch et al., 2003; Reinsel et al., 2005; WMO, 2007). Great uncertainties exist in the future surface ultraviolet (UV) radiation, since it will be additionally affected by changes in clouds and aerosols (McKenzie et al., 2007). Observations of ground solar radiation especially in the UV band will be always important for many purposes including monitoring the pace of ozone recovery and developing UV climatology. Initiated by

* *Corresponding author*. Tel.: +1 970 4913611; fax: +1 970 4913601.
E-mail address: xwang@uvb.nrel.colostate.edu (X. Wang).
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the USDA in 1992, the USDA UV-B Monitoring and Research Program (UVMRP) has set up a monitoring network in the United States to provide essential information for assessing the potential impacts of increasing UV-B levels on agriculture, environment, and humans (Bigelow et al., 1998).

The USDA UV-B monitoring system is the largest and the most comprehensive UV radiation monitoring system in the world in terms of its large-scale coverage and comprehensive measurements. It covers the United States domain, including Alaska and Hawaii, as well as parts of Canada and New Zealand, and has been successfully established and maintained for continuous and reliable data collection since it began running in 1994 (Bigelow and Slusser, 2000). Instruments are installed to measure spectral irradiances in both UV and visible wavelength regions along with erythemally weighted irradiances and photosynthetically active radiation (PAR). The system provides unique information to the national and international research communities and possesses the immense potential to contribute to a wide range of interdisciplinary researches in the areas of agriculture, ecology, environment, meteorology, atmospheric chemistry, satellite validation, and human health. Its successful operation provides a useful example for designers of similar systems.

As an application of a centralized distributed system, this network is automated by networked computers, data loggers, and sensors. Previous works (Bigelow et al., 1998; Bigelow and Slusser, 2000) have discussed the scientific problems and the rationale to establish the system as well as the scientific validity of the data for the domain of the United States. In this article, we present the system architecture, explain its design principle, give the algorithms for collecting and processing the data, describe the web page for publishing the products of the system, demonstrate the reliability of the system, and discuss our experiences with this system. The domain of the network coverage is given in the next section. Then the system assumptions and how they are managed in practice are explained. Algorithms for data collection and processing are presented in Section 4. Reliability of the system is demonstrated in the following section. Finally we argue the advantages and major drawbacks of the centralized design in Section 6. Our experiences with the system and possible remedies for network failures are also discussed.

2. Network coverage and instrumentation

The design goal of the network was to have a 5° latitude × 10° longitude equal-area representation of the continental United States with additional coverage of Alaska and Hawaii although the existing distribution of the observation sites is not quite ideal because of various reasons (Bigelow and Slusser, 2000). As of 2007, thirty-six observation sites in the United States, with two collaborating sites in Canada and one in New Zealand, are operating (Fig. 1). The observation sites in Canada and New Zealand were set up for the purpose of comparison between different geographical locations and cooperation with international scientists. Each site was set up either as a research site or as a climatologic site. High-resolution spectroradiometers are installed at research sites where key collaborative research allows interdisciplinary uses of the data. Instruments at a research site may be turned off and on at any time, and additional instruments can be installed and run for a certain period of time depending on the purpose of the research. The climatologic sites require less sophisticated instrumentation than the research site and the climatologic-site instruments operate continuously without intended interrupts except for routine maintenance.

A typical climatologic site in the monitoring network is equipped with two main instruments: a UV Multi-Filter Rotating Shadowband Radiometer (UV-MFRSR), which is used to measure the irradiances at the wavelengths centered around 300, 305.5, 311.5, 317.5, 325, 332.5, and 368 nm and a visible Multi-Filter Rotating Shadowband Radiometer (VIS-MFRSR), which is for the radiation measurements at the wavelengths centered around 415, 500, 615, 673, 870, and 940 nm (Harrison et al., 1994). Other instruments include a UVB-1 broadband pyranometer measuring the erythemally weighted UV irradiance from approximately 280–320 nm, a Licor Inc. LI-190SA quantum sensor to measure the downward (from the Sun) PAR in the 400–700 nm waveband, a Licor Inc. LI-210SZ photometric sensor to measure the upward (reflection) radiation, and probes for measuring air temperature and humidity. A barometer is installed at 14 sites to measure the atmospheric pressure. Two data loggers are installed at each site to scan data from the sensors and probes periodically. One data logger is used to collect the data every 15 s from the VIS-MFRSR, UVB-1, temperature/humidity sensors, and downward PAR sensor; and the other is for the UV-MFRSR, upward PAR sensor, and barometer on the basis of 20 s. The sampling interval for the VIS-MFRSR is shorter than the UV-MFRSR because of the design characteristics of the monitoring heads. The VIS-MFRSR devices are small, and at the late times of the day the shadowing band is able to rotate under the can, which takes about 15 s. On the UV-MFRSR device the can is much taller than on the VIS-MFRSR head, and the shortest sampling interval, which provides enough time for the shadowing band to rotate over the full path, was determined to be 20 s. As shown in Fig. 1, all of the instruments are mounted about 1.5 m above the ground and are connected to the onboard data loggers. The data loggers are programmed to collect the measurements and aggregate these real-time measurements to 3 min averages, which are stored on the memory chips attached to the data loggers. When they are polled, the data loggers communicate with the UVMRP central data server to transfer the stored 3 min averaged data through either a designated phone line or the Internet. The instruments and the data loggers are driven by AC power with rechargeable batteries in line to act as a backup in case the AC power fluctuates or outages occur for a short period of time.

3. System model

Although the sensors and probes are connected to the data loggers, they are not programmed. We consider the data loggers and computers only in the system. These data loggers and the data server work on their own tasks independently, sharing no memory or clock. Cooperation between them is done solely through message passing. As a result, the monitoring network can be modeled as an asynchronous static distributed

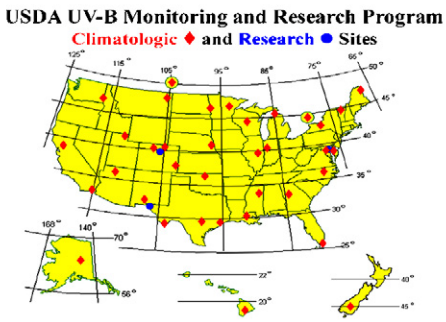

Fig. 1 – The UV-B monitoring network coverage (left) and the layout of instruments at a climatologic site (right). As of 2007, there are 39 observation sites operating in the network, three research sites and 36 climatologic sites. Two climatologic sites are located in Canada, one in New Zealand, and the rest are in the United States.

system of seventy-nine processes. Let $SYS = \{p_0, p_1, p_2, \ldots, p_{78}\}$ denote the process set with p_0 being the central data server and $p_1, p_2, \ldots, p_{78}$ representing the data loggers, which are distributed at the 39 sites. While the basic task for p_i, $i = 1, \ldots, 78$, is to collect data from the attached sensors and to process the raw real-time measurements primarily, process p_0 is programmed to muster data from all other processes and manipulate the data for products of different levels. In addition, all of the processes are considered not faulty.

The network topology can be considered as a centralized system of a star architecture with p_0 as the designated master and the others as slaves. A virtual link exists between p_0 and p_i for $i = 1, 2, \ldots, 78$. Process p_0 is running on the UVMRP data server, which is physically located at Colorado State University at Fort Collins, Colorado, USA. The connection between p_0 and $p_i \in SYS$ is through either a designated phone line or the Internet connection. Seven of the sites are on the Internet. In this case, a local computer is set up to download data from the data loggers periodically and to communicate with the central server for data transfer when polled. However, we consider only the server and the data loggers in this configuration for simplicity because the computer between them does nothing more than to provide communication between the server and the data loggers.

While the Internet protocol is exploited for data transfer over the Internet, the xmodem and VT100 protocols are adapted for the communications using designated phone lines. Communications between the server and the data loggers are assumed reliable in the sense that each of the communicated messages is not corrupted. No spurious message is inserted into the data flow, messages are not duplicated, and each message is eventually delivered to the intended destination.

In the operation, the membership of a process may change, especially the data loggers. Some old or damaged data loggers need to be replaced with new ones. New data loggers may be added and data loggers at old observation sites may exit the system. However, these faults are detected manually and the replacements are planned in advance. The system is reconfigured when changes have been made. Consequently, the system can still be considered as being static during the period when no changes are made. Processes may also be faulty during the operation due to unpredictable reasons. For example, data loggers may be damaged or wires may be chewed by mice. The communication network may be down. These faults are detected manually by the staff of the project and are fixed immediately when they are identified. For simplicity, the system is not designed to tolerate faults except necessary backups for the data on the server and duplicates for the polling server. Furthermore, the system may do nothing with a damaged data logger without replacing it. It will be more expensive or impractical to duplicate the instruments for fault tolerance.

4. Algorithms and data processing procedures

Data collection, data processing, and product publication are the major missions of the monitoring system. In this section, we will present the protocols for data collection and processing as well as the data flow in the following data processing procedures. The web page for product publication will be also introduced.

4.1. *Data collection*

Two algorithms have been developed for data collection at different levels. One (the data logger program) is implemented on the data loggers for them to scan attached sensors periodically and to aggregate the raw measurements. The other (the data polling protocol) is designed for the UVMRP data server to collect measurements from the data loggers. These two programs cooperate tightly to collect and process the signals from the sensors.

4.1.1. *Data logger program*

An algorithm is designed to implement the required functionality of a data logger (Table 1). It is essentially a loop. The

Table 1 – The algorithm of data logger program

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Loop:
   scan sensors for their voltages every 15/20 s;
   buffer the real time measurements;
   compute averages every 3 min and store them;
   reset states for next 3 min.
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Table 2 – The data polling protocol

protocol for the master (p_0):	protocol for a slave (p_i, i = 1, 2,. . .,78):
when scheduled; for each p_i, i = 1, 2, . . ., 78 do request p_i for data; store the data in a buffer on arrival; send local time to p_i;	when requested for data from p_0: send previous day's 3-min averages to p_0; when receives time from p_0: check difference between the local clock and the received time, set local clock with the received time if ≥4 s;

data logger scans attached sensors periodically for their voltages and dumps the signals into a buffer. Since the system stores 3 min mean values only, the averages are computed periodically and are stored on the memory chip. For safety, the storage is designed for an accommodation of 2–3 days of 3 min averages. In case the data are lost or corrupted during the transportation in the communication network, they can be recovered from the data logger's storage. In order to compute the 3 min averages, the data logger needs to reset its state variables every 3 min.

4.1.2. *Data polling protocol*

The functionality of the data polling protocol is to collect data from the data loggers through the underlying network. The UVMRP data server polls data from each data logger every day at about the same time and verifies the data logger's clock. If the data logger's clock has drifted more than 4 s, it will reset the clock to synchronize it to the system time and subsequently purge the historical data since the clock and data time stamps have changed. At the other end, a data logger transfers the 3 min averages from its storage when it is demanded.

As described in Table 2, the protocol for p_0 itself is a loop, while the protocol for a slave is a signal-driven event. Process p_0 runs on the UVMRP data server at night. When it is scheduled, p_0 polls the data loggers one by one for collecting data. The protocol for a data logger is straightforward. Whenever a request is received, it sends the 3 min averages that are stored in the memory chip on the data logger. At the sites with phone line connections, the clock on the data logger is verified with the time from the UVMRP data server every day when data have been transferred. The clock is synchronized with a local Internet time server at the sites with an Internet connection. The clock on the UVMRP data server is also synchronized with a local Internet time server using the NTP protocol. If any of the data logger clocks have drifted more than 4 s, their clocks will be reset and the contents of the memory chip on the data logger will be purged. This is to ensure that the high quality of the data is maintained. In the future, most of the clocks on the data loggers will be automatically synchronized with a local Internet time server when they are connected to the Internet network. Note that the simplicity of the data polling protocol and its correctness are achieved by the non-faulty assumption.

4.2. *Data processing*

The UVMRP data server collects raw voltage measurements from the data loggers. Various data processing algorithms have been implemented to convert these voltages to irradiances and generate products of different levels. Instead of presenting the scientific algorithms, here we describe the data flow in the procedures of data processing only.

As shown in Fig. 2, the data processing procedures start with raw voltage measurements. For the purpose of safety, two copies of raw voltages are made on the UVMRP data server. One copy resides in a temporary buffer for the use in the following processing procedures, while the other is stored in a permanent storage, which may be a hard disk, a magnetic tape, a CD, or a DVD. These two copies of raw data are necessary for improving the system performance as well as preventing the original measurements from permanent loss. Before converting voltages to irradiances (the processed data), necessary corrections are made, including nighttime bias corrections and cosine (angular) corrections. The former is generated by electronics of the observation system, including the data loggers, the amplifiers, the circuits, and the connection wires, in the absence of solar radiation since the system is operated by an AC power supply. The latter is the correction for the deviation of the senor response from an ideal cosine regulation. Sensors of UV-MFRSR and VIS-MFRSR are calibrated every year. Based on our recent research results, higher level products of daily column ozone (Gao et al., 2001), optical depths (Harrison and Michalsky, 1994), and continuous synthetic spectra (Min and Harrison, 1998) are derived from the measurements.

Note that the processed data and higher level products are not stored. Instead, all of the irradiance data and derived products are processed on the fly while requested by a user. This may degrade the performance of the system. However, this design is to save the storage space. At present, the sys-

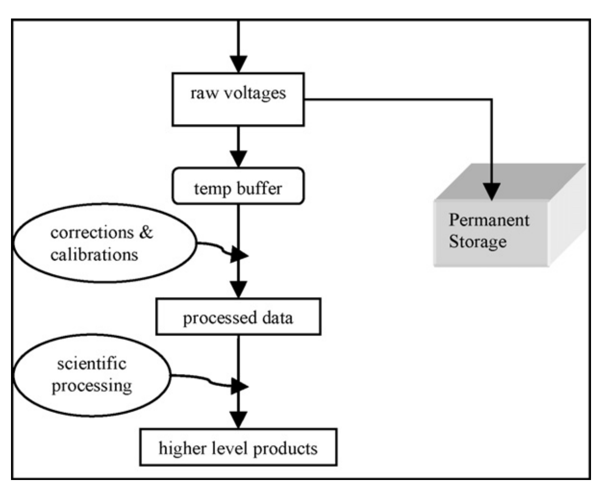

Fig. 2 – Data flow in the data processing procedures.

tem performance is satisfactory since most users from the public view only a few days' data. Massive data requirements are processed on a special request basis by the project staff.

4.3. Product publication and the users

The data and products are published on a World Wide Web site (URL: http://uvb.nrel.colostate.edu/UVB). From the main web page, a user may go to "Station/Data" and then "Data Plots", where the user can see a brief introduction to the processed data. By clicking on the self-explainable buttons, a user can either view plots of the data or download the data that are used to generate the plots through the Internet. A user can also find links to the detailed information about the data, products, instrumentation, the site location, and the methodology and the techniques to process and calibrate the data and to generate the products.

This Web page/database is designed under the client-server paradigm. All data reside on the UVMRP data server and a Web service daemon is running continuously to provide various services for any client requests. The Web page publishes only commonly used data and products. Requirements can also be directed to UVMRP staff for special services.

Numerous users (nationally and internationally) from, among others, the research communities, government agencies, industries, and the public have been using the data and the products, especially in recent years. There may be hundreds or thousands of people visiting our web site on some days. Our statistics show that several gigabytes data could be downloaded from our data server on a busy day. A special request may include tens of gigabytes of data. The data accessed by users fall in various categories for different purposes, including the raw voltage measurements, the angular corrections, the irradiances, the auxiliary measurements, the continuous spectral irradiances, and the derived higher level products. The research communities are in the fields of, among others, agriculture, environment, meteorology, plant sciences, animal sciences, human health, biology, and ecology.

5. Maintenance and reliability

In the operation, the system is maintained with a centralized technical staff/local operator approach. The running status of the system is monitored by a technician all the time. Whenever a fault is identified, the technician will call and guide a local helper to go to the site and fix the problem. In our experience, the instruments and data loggers are rather stable. Damages to the instruments are mainly caused by severe natural events such as static electricity from thunderstorms and other types of extreme weather conditions. These damages and maintenance activities lead to data losses.

The system reliability can be demonstrated by the data completeness, which is defined as follows:

$$\text{comp} = \frac{D_{\text{act}}}{D_{\text{tot}}} \times 100,$$

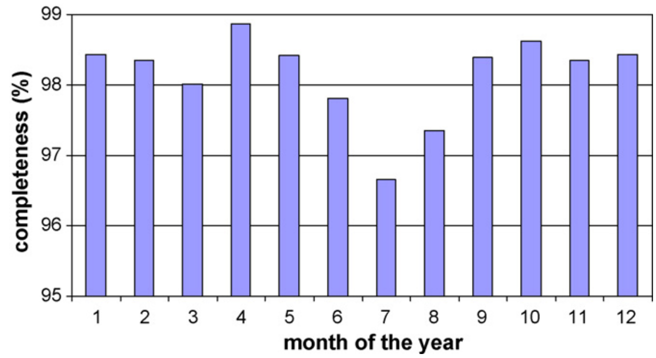

Fig. 3 – Data completeness in each month. Data are averaged over all years and all sites.

where *comp* represents the data completeness in percentage, D_{act} and D_{tot} are, respectively, the actual number of the 3 min periods at which the data is collected and the total number of the 3 min periods acquired during the period of time the system is running. For example, assuming that there are exactly 24 h in a day, which results in a possible 480 3-min intervals, the completeness will be 90% if 432 measurements of 3-min average are correctly collected.

Statistics of the data from 1994 to 2005 at all sites show that the monitoring system is rather reliable. Although data completeness was low when the system began collecting data, more than 98.19% of the data have been correctly collected after 1998. Fig. 3 shows the data completeness for each month when the data are averaged over all years from all sites. Lower completeness in summer months (June, July, and August) implies again that the major interruptions to the system are associated with thunderstorms and lightning during the summer time. Data completeness is over 98% in the other months.

6. Discussion

One of the advantages of a centralized architecture is its simplicity. The hardware is cost-efficient to build the system and the software is less complex due the simplicity of the structure. The software to call all the sites and load the raw voltage measurements into our database is a Perl script of less than 300 lines of code. After the program was developed and debugged, it has been very stable. As in any other external monitoring systems, failures of instruments, data loggers, and communication lines can happen at any moment of time due to natural disasters, human activities, or animal actions. The centralized architecture allows us to monitor the status of the system manually and detect any faults and fix them in a short time.

Some care has been taken in designing the p_0 server to help remediate the problem of single point failure, which is the main weakness of a centralized system. The server was designed with RAID (Redundant Array of Inexpensive Disk) ADG (Advanced Data Guarding). This allows any two physical hard drives to fail without experiencing data loss. The server was also designed with multiple/redundant CPU's and power supplies to allow the machine to continue to function if either or both of those single components were to fail. As a secondary backup, all of the data are backed up to AIT3 magnetic tapes with a full/incremental/differential scheme. This allows the limited backup time window and tape space to be minimized. Currently specific data from any day of the prior year could be restored with short notice. In the future, we would like to upgrade the tape infrastructure to a storage technology with more capacity and higher speeds, such as an LTO library. As a tertiary backup, all of raw voltage data has been archived to CD and DVD media and is stored at a number of sites around the country. In addition, the p_0 server is actually comprised of a number of different computers each with their own specialized purpose. The raw data files are actually stored in multiple locations/formats on different members of the p_0 server. This helps to ensure data quality and high availability.

In the data logger design, a memory chip that is capable of holding 2–3 days' data is essential to prevent data loss. While phone lines are primarily the only choice for data transfer at the sites where there is no Internet access, periodically we are unable to connect when it is polled. This can be caused by numerous conditions, such as a busy phone line at the time when it is polled or it could experience line noise and subsequently disconnected while the data is being transferred. In this case, we can re-poll the site the next day without losing data because the data is stored in the data logger.

We physically store and backup the raw voltage measurements and the raw voltage data after nighttime bias and cosine corrections. Other data and products are derived and calculated on the fly when they are requested. This design not only saves the media storage, but also simplifies the data updates and modifications. For example, the algorithms for calculating optical depths are likely to be improved in the future, and at that time the improved algorithms can be plugged in without updating or reloading the database, because the optical depths are calculated on the fly. The same thing happens when the calibration factors are changed. One of the drawbacks of this design is that it may take a longer time to access the data. However, this delay of data retrieval is almost ignorable with the advances in computing speed.

Although the communication over the Internet is more reliable than over the Telco system, not all sites will be able to be connected to the Internet because some of the sites are too remote. Over the years, reliability of the Telco system and its components has been the most problematic in the data transfer. Telco components that are in incipient failure tend to have troubles during the colder nights when the data polling occurs and seem to work fine during the daytime when we task the Telco technicians to investigate the problem. As a result, we usually struggle along for days or weeks until the Telco component actually fails and then the Telco technician can find and fix it. Other longer duration outages have occurred occasionally when the Telco interface had problems. As such, the Internet connection for data transfer is preferred over the Telco system when this is possible.

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