Development of integrated spectral sun-photometer based on embedded Linux OS

Qi Zhaoyang¹², Sun Fengying¹, Li Jianyu¹, Zhu Wenyue¹, Xu Wenqing¹*, Xu Gang and Huang Yao

¹ Key Laboratory of Atmospheric Optics, Anhui Institute of Optics and Fine Mechanics, HFIPS, Chinese Academy of Sciences, Hefei, 230031, China
² University of Science and Technology of China, Hefei, 230026, China
*Corresponding author’s e-mail: wqxu@aiofm.ac.cn

Abstract. Accurate detection of solar irradiance has important application value for theoretical research on climate change and atmospheric analysis, so this paper proposes the integrated spectral sun-photometer to enrich methods of obtaining the solar irradiance and entire atmospheric transmittance. With the ARM microprocessor as central processing unit and Linux OS as the software platform, the two-dimensional turntable and grating spectrometer are combined to construct sun-photometer which can measure continuous wavebands. This article advances the solution scheme to realize data transmission between microcontroller and turntable through CANopen communication. Meanwhile, the spectrometer based on USB communication protocol is used to obtain spectrum from visible to near-infrared band. In addition, both the multiple task operating system Linux and application framework Qt are employed to design friendly user-interface and display real-time process images, which would simplify and integrate the solar radiometer. After Langley calibration is used to calculate the constants to achieve calibration of instrument in spectral band, measured data of the radiometer and results of the DTF solar radiometer are compared and analysed, which confirms the reliability of integrated sun-photometer.

1. Introduction
The selective absorption and scattering of solar irradiation by atmospheric molecules affect the radiation distribution on the ground, and accurate assessment of solar irradiation will be helpful to the development of meteorological observation and environmental monitoring. Sun-photometer is an effective detection method for remote sensing to detect solar irradiance, aerosol and atmospheric transmittance[1]. With the establishment of several irradiance observation networks such as the SORCE project carried out by NASA [2-4], refined solar irradiation observations contribute to improving people’s understanding of the relationship between radiation budgets and climate change. Ground-based measurements have provided continuous and reliable radiance information, aerosol loading and optical properties in atmospheric detection[5]. In order to supplement the existing measurement methods, further research and investigate are required to conduct in on-site observations, which also promotes efforts to develop new radiometers in the Europe and Asia. At present, traditional sun-photometer adopts a master-slave control architecture, generally with bulky industrial computer as the main body, and functional modules are connected to industrial computer through various interfaces. As master-slave control gradually fails to meet the development needs of integration and intelligence, the appliance of integrated control architecture has become research focus for sun-photometers. Along with the rapid
development of embedded technology and on-chip technology, some studies have proved the effectiveness of optimizing radiometer based on the ARM platform [6]. The research team proposes design scheme of integrated sun-photometer and completes the manufacture of instrument. Section 2 introduces the instrument, mainly including the design of two-dimensional tracking turntable, acquisition of spectrum on ARM-Linux platform and design of human-computer interaction interface. Brief descriptions of calibration methods and results are given in section 3, section 4 presents analysis and comparison of measurement results.

2. System Design

2.1. The overall design of integrated radiometer

As shown in Figure 1, integrated control system is mainly composed of embedded microprocessor, two-dimensional turntable, spectrum measurement, human-computer interaction (HCI) unit and peripheral auxiliary modules (such as temperature control system and power supply system). The sun-photometer uses the i.MX6UL board with Linux system as the core microprocessor, which will be responsible for system scheduling, data storage and low-power management. Experiment has proved this development model is suitable for real-time radiation measurement systems and promotes application development based on multiple communication protocols (such as Controller Area Network (CAN) and universal serial bus (USB)). CANopen communication protocol is applied to realize communication between microprocessor and turntable; The spectrometer mounted on turntable obtains the solar spectral radiation, saves data in local or SD storage and realizes the mode configuration through the USB protocol; The human-computer interaction unit is responsible for parameter adjustment and instructing users to execute corresponding operation through interface written by QT/E on touch-enabled screen. Meanwhile, real-time status and spectrogram will be displayed on the interface to monitor the operation of the instrument.

Figure 1. Architecture design of Embedded platform.

The main structure of sun-photometer is composed of fixed base, a two-dimensional turntable and measuring probe, the overall structure is shown in figure 2. Optical probe of radiometer is supported and driven by U-shaped two-dimensional turntable, and can rotate in two orthogonal dimensions of pitch and horizontal axis. The touch-enabled screen provides operation interface for interactive tasks, and all functional modules are connected to embedded platform through communication interface to achieve centralized processing and control. Total weight and size of radiometer are optimized due to its compact
mechanical structure and lightweight design. The appliance of temperature control technology ensures constant temperature control and heat insulation protection of measuring probe under working condition of wide temperature from -20°C to +50°C.

Figure 2. Architecture design of Embedded platform.

2.2. Embedded Linux Platform

The prerequisite for controlling measurement components is that embedded systems have a series of characteristics, such as real-time communication, algorithm embedding, and data processing. From this perspective, the ARM-Linux platform with high processing speed and low energy consumption requirement is the frontier technology for developing measurement solution. With the development of system-on-chip and sensor detection technology, embedded systems are increasingly used in various environmental monitoring systems and atmospheric composition detection. On the basis of open-source 32-bit ARM (advanced RISC machine) as the core component and Linux operating system as a software platform, the embedded platform could flexibly develop application programs to control and communicate with peripheral modules. The ARM-Linux operating mode is suitable for real-time radiation measurement systems, and can meeting stable and flexible application requirements.

2.3. CAN communication mechanism

As a key system for accurately tracking the sun, the two-dimensional turntable uses grating encoders and drivers to obtain the absolute angular positions of two axes, and complete closed-loop control based on information feedback. In order to ensure the information transmission between microcontroller and turntable system, CAN communication is introduced into radiometer system, which can effectively support real-time control with a high security level [7]. With reference to Open System Interconnection model, the CAN bus just defines the layer 1(physical layer) and the layer 2(data link layer) of mode while the application layer protocol and communication profile are not introduced. Communication function cannot be realized by physical layer and data link layer, so we apply a set of network layer socketCAN protocols to the system according to the socket principle, thereby additionally defines the network layer of CAN bus [8]. Then CANopen protocol will be applied as application layer to achieve the complete master-slave node development and build a distributed control system on development platform.
As shown in figure 2, in order to increase the support for socketCAN in Linux, it is necessary to configure Linux kernel properly when compiling the kernel and complete the initialization of socketCAN by calling the socket creation function and binding function. After the connection is established, embedded microprocessor can communicate with motor driver by Read function and Write function. Through the socketCAN driver module, Linux system registers the device driver of the CAN controller as a network device into system network layer, and dynamically loads and unloads multiple transmission protocols. The CANopen protocol of the application layer is responsible for sending and receiving data to realize the communication between nodes, and increases the function that cannot be achieved only by the physical layer and the data link layer. Object dictionary of the CAN node, which is the core of CANopen protocol, stores node information, communication parameters and process data. Once the embedded board powers are on, MCU send NMT (Network Management) message to start up the nodes involved. Then the MCU transmits the SDO (Service Data Object) messages to send configuration information in network system by modifying the object dictionary of the node. After that, only when slave node of the drive is in operating state, PDO (Process Data Object) message can be used to achieve real-time data transmission. The RPDO of the object dictionary will be traversed to find the message matching the COB-ID and modify the parameters. After each PDO is given corresponding functional characteristics of slave node (COB-ID, data transmission type), the master node can use PDO to transmit control commands and real-time data.

![Diagram](image.png)

**Figure 3.** The process flow of the CAN communication.

After system enters the program loop of communication, radiometer converts the displacement deviation obtained by the mixed tracking method of sun tracking algorithm and four-quadrant tracker into control parameters for turntable. The ARM board, the only active master node in the network, sends NMT management commands and SDO configuration messages to manage motor driver, then realizes tracking process by sending and receiving PDO. The motor driver, as the slave node, receives control command from master node and realizes position adjustment and status detection. With the circle of program running well, radiometer will acquire and track real-time central position of sun.
2.4. Spectrum acquisition
The main function of the spectrum acquisition system is to measure the intensity of target spectrum according to wavelength distribution, and obtain information such as component content. During the process of tracking the sun, optical fiber spectrometer mounted on turntable will measure spectral information of the scanning point. The installing of a filter wheel sequence equipped with attenuator with different attenuation coefficients in the optical path avoids the saturation of the spectrum signal and improves the measurement accuracy and dynamic range of instrument. At present, USB devices on the Linux platform can be operated by either the kernel-driven development method or the efficient Libusb-based driverless method. Since Libusb is an open-source project and there is no need to consider the compatibility issues of different kernel versions, this embedded platform adopts Libusb-based USB application design. When developing USB host-side driver in Linux operating system, linux_libusb can provide application programming interface (API) for operating hardware directly in user space [9]. The high-level API encapsulates the interaction between low-level kernel and the USB module, and provides a series of functions suitable for USB driver development in user space, so that it can contribute to realize the control of USB spectrometer by microprocessor.

2.5. HCI design
After internal algorithm loops normally, the human-computer interaction subsystem developed with Qt/E shows the process of detecting solar irradiance, as shown in figure 3. Parameters such as operation mode and integration time can be set in the upper left area of interface, the lower right of screen is the status monitoring area. Meanwhile, real-time spectrum during scanning is displayed on the right side of interface on the touch-enabled screen. This solution gets rid of the shackles of bulky industrial computers and provides reference value for the application of field measurement.

3. Calibration
Since the spectral response of any solar and sky radiometer is unstable, it is critically important for any Sun-photometer measurement to calibrate under stable, clean and cloud-free atmospheric conditions.

Figure 4. HCI supported by Qt/E.
According to the Bear-Bouguer-Lambert equation, with relative atmospheric mass as the abscissa and irradiance as the ordinate, extrapolated to the top of the atmosphere (TOA) solar irradiance (air mass = 0) in the Langley plot is the calibration constant used at different specific wavelengths [10,11]. The calibration time is selected on January 8, 2021, calibration curve of selected bands is shown in the figure 4 below:

![Figure 5. Calibration curve of selected bands including water vapor band.](image)

### Table 1. Calibration value, correlation coefficient and standard deviation of selected bands.

| Date       | Parameter | Selected seven wavebands |
|------------|-----------|--------------------------|
| Jan 8, 2021| InG0      | 400nm 11.4710 500nm 13.8964 610nm 14.2554 670nm 13.9838 780nm 13.2036 870nm 12.4030 940nm 12.0060 |
|            | R         | -0.9950 -0.9986 -0.9981 -0.9972 -0.9960 -0.9956 -0.9984 |
|            | SD        | 0.0058 0.0022 0.0019 0.0018 0.0017 0.0015 0.0021 |

The correlation coefficient of each waveband is above 0.995, and the standard deviation is very small. It indicates that this day is suitable to calibrate, and the calibration values of each band can be used as calibration constants.

### 4. Analysis

On January 12, 2021, simultaneous observation experiment is carried out between spectral sun-photometer and DTF solar radiometer in Hefei. The DTF, a proven and reliable solar radiometer, obtains direct solar irradiation in eight bands from visible to near-infrared, and inverts the total atmospheric transmittance and optical characteristics in real time [12].

Figure 4 shows the changes in the atmospheric transmittance measured by the integrated sun-photometer (identified as: sun-photometer) and the DTF sun-photometer (identified as: DTF) at four typical wavelengths throughout the day. From the comparison results of typical bands, it can be seen that the change trends of the two radiometers in the corresponding bands over time are very consistent. This figure also presents that the relative error of four transmittance curves does not exceed 12%. The measurement result of integrated sun-photometer is reliable, and it is feasible to acquire atmospheric transmittance with integrated sun-spectrometer.
5. Conclusion
In this paper, the experiment has shown that embedded Linux combined with sun-photometer measurement module has great feasibility and stability to acquire the solar irradiance and entire atmospheric transmittance. By introducing communication protocol family, the system realizes the real-time control of two-dimensional turntable and spectrometer. Meanwhile, real-time solar spectrum can also be displayed on the page supported by QT graphics system. This solution completes the transformation of integrating the solar radiometer and gets rid of shackles of industrial computer and transmission cable. The comparison and analysis between the data of sun-photometer and the results of the DTF radiometer also confirmed the reliability of system. This design scheme provides important technical supports for measuring solar radiation, and provides measurement methods for meteorological observation and remote sensing research. In the following work, aerosol optical thickness, water vapor and other atmospheric parameters can be further inversed by using radiation information of characteristic wavelengths.

Acknowledgments
The authors wish to appreciate Cheng J. for his guidance on data analysis and Huang Y. for his help in mechanical structure design. This paper is supported by 173 key projects.

References
[1] Bergstrom, R.W., Pilewskie, P., Pommier, J., et al. (2004) Spectral absorption of solar radiation by aerosols during ACE-Asia. J. Geophys. Res., 109, D19S15.
[2] Anderson, D.E., and Cahalan, R.F. (2005) The Solar Radiation and Climate Experiment (SORCE) mission for the NASA Earth Observing System (EOS). Solar Physics, 230, (1-2), pp. 3-6.

[3] Che, H.Z., Zhang, X.Y., Chen, H.B., et al. (2009) Instrument calibration and aerosol optical depth validation of the China Aerosol Remote Sensing Network. J. Geophys. Res., 114, D03206.

[4] Holben, B.N., Eck, T.F., Slutsker, I., et al. (1998) AERONET - A federated instrument network and data archive for aerosol characterization, Remote Sensing of Environment, 66, (1), pp. 1-16.

[5] Schmid, B., Ferrare, R., Flynn, C., et al. (2006) How well do state-of-the-art techniques measuring the vertical profile of tropospheric aerosol extinction compare? J. Geophys. Res., 111, D05S07.

[6] Mera-Romo, D. E., et al. (2019) Low Power and Miniaturized Back-End Processing System for an L-Band Radiometer based on ARM Embedded Microprocessor. In: 2019 IEEE Radio and Wireless Symposium. New York. pp. 220-223.

[7] Wang Y., Yu Z., Bao C. and Shao D. (2014) Development of field control system of automated guided vehicle based on wireless local area network and CAN bus. Key Engineering Materials, vol. 2633, pp. 792-797.

[8] Sun X., Qin L., Shi C. and Wu G. (2012) The application of CANopen protocol in monitoring and control system of greenhouse microclimate, In: Proceedings of the 31st Chinese Control Conference. Hefei. pp. 5675-5678.

[9] Shen Y. (2015) USB Bridge Driver and Firmware Design for Test and Measurement Instruments [D]. University of Electronic Science and Technology of China.

[10] Shaw, G. E., et al. (1973) Investigations of atmospheric extinction using direct solar radiation measurements made with a multiple wavelength radiometer. Journal of Applied Meteorology, 12(2): 374-380.

[11] Zhou N. and Liu M. (2011) Total column water vapor retrieval methods and results comparison by using sun photometer. Journal of Remote Sensing, 15(3): 568–577.

[12] Li J., Wei H., Xu Q., Zhan J. (2012) Atmospheric aerosol optical characteristics measured at several typical zones at China. Optics and Precision Engineering, 20(06): 1166-1174.