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The study on the spectral irradiance responsiveness calibration for UV-VUV solar spectrometer

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ABSTRACT

The monitoring of the solar spectral irradiance has important scientific significance and application value. This paper describes the principle, structure and performance of the UV-VUV solar spectrometer. The calibration principle and the calibration method of the spectral irradiance responsiveness are emphatically discussed, based on synchrotron radiation. The spectral irradiance responsiveness calibration of UV-VUV solar spectrometer in the 165 nm–320 nm spectral range is realized under vacuum environment with PTB transfer standard deuterium lamp as standard source. The results of the calibration are achieved, factors affecting the accuracy of the calibration are analyzed. The synthesized uncertainty of the calibration is 5.1 %.

1. Introduction

The monitoring of the solar spectral irradiance has important scientific significance and application value for solar physics research, atmospheric physics research and environment science research etc. Solar spectrometers are usually adopted to monitor the variation of the solar spectral irradiance.

Since the 1970s, SBUV(Solar Backscatter Ultraviolet Spectrometer) [1], SUSIM(Solar Ultraviolet Spectral Irradiance Monitor) [2], SOLSTICE(SOLar-Stellar Irradiance Comparison Experiment) [3,4], SIM(Solar Irradiance Monitor) [5] and SOLSPEC(Solar Spectrum) [6] were in succession developed and successfully used for on-orbit long-term monitoring of solar spectral irradiance. A great deal of valuable information about the solar spectral irradiance and its long-term change are achieved.

In addition to hardware, one of the key problems is the spectral irradiance responsiveness calibration during the solar spectrometer development. The classification description of the calibration methods for the above mentioned payloads is as follows:

(1) Before the solar spectrometer is launched, a ground calibration is carried out and the spectral irradiance responsiveness of solar spectrometer obtained by the ground calibration is directly used for on-orbit measurement. Such as SBUV, SBUV/2 and CSBUV [7,8].
(2) The solar spectrometer is equipped with standard sources for the on-orbit calibration. The spectral irradiance responsiveness of the solar spectrometer obtained in space is adopted for the solar spectral irradiance measurement, such as SUSIM and SOLSPEC.
(3) Bright blue stars are adopted as transfer standard sources for the on-orbit spectral irradiance responsiveness calibration of the solar spectrometer, such as SOLSTICE I and SOLSTICE II.

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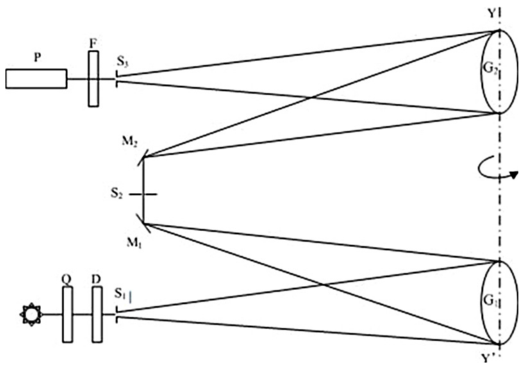

Fig. 1. The optical layout for the UV-VUV solar spectrometer.

The solar spectral irradiance spectrometer developed by this Institute consists of four spectrometers. It covers 165 nm–320 nm spectral range by two same UV-VUV solar spectrometers, 285 nm–700 nm spectral range by VIS spectrometer and 650 nm–2400 nm spectral range by IR spectrometer. The groupware of UV-VUV, VIS and IR spectrometers is placed on the platform of a solar tracker with pointing accuracy 0.1°to track the sun and measure the solar spectral irradiance. Among the four solar spectrometers, the spectral irradiance responsiveness calibration of two UV-VUV solar spectrometers adopts the first kind of the above mentioned calibration method.

This paper describes the principle, the structure and the performance of the Engineering Proto of UV-VUV solar spectrometer. The spectral irradiance responsiveness calibration of the UV-VUV solar spectrometer in the 165 nm–320 nm spectral range is realized under vacuum environment with PTB transfer standard deuterium lamp. The results of the calibration are achieved and the factors affecting the accuracy of the calibration are discussed. The synthesized uncertainty of the spectral irradiance responsiveness calibration for UV-VUV solar spectrometer is 5.1 %.

2. The engineering proto of UV-VUV solar spectrometer

UV-VUV solar spectrometer consists of quartz plate Q, pre-diffuser D, entrance slit S_1, concave grating G_1, turning plane mirror M_1, middle slit S_2, turning plane mirror M_2,concave grating G_2, exit slit S_3, filter wheel F, R2078 photon counter type photomultiplier and photon counter P, wavelength scanning driver and computer for the control of UV-VUV solar spectrometer, shown in Fig. 1. UV-VUV solar spectrometer employs IV type aberration correction concave holographic gratings with ruling density 3600 g/mm, curve radius 96.3 mm, operating spectral range 165 nm–320 nm, and diffraction efficiency 30 %. Plane turning mirrors were coated with Al + MgF_2, which improved the reflectivity of the turning plane mirrors in ultraviolet spectral range. The detector of UV-VUV solar spectrometer is R2078 photon counter type photomultiplier of Hamamatsu [9], which is thermally controlled to ± 0.6℃. It has Cs-Te cathode and fused quartz window.

The solar radiation irradiates the pre-diffuser of UV-VUV solar spectrometer following the normal direction of the pre-diffuser. Solar radiation passes through UV-VUV solar spectrometer and finally forms a spectral image of the entrance slit on the plane of the exit slit. The stepping motor under the control of the computer synchronously rotates the two gratings through sinusoidal mechanism and executes the spectral scanning with wavelength accuracy 0.05 nm and wavelength reproducibility 0.01 nm. The monochromatic radiation with different wavelength in succession is detected by the photomultiplier and converted by photon counter to the electronic output signals which finally form a solar spectrum.

In order to reduce the influence of the view field direction inhomogeneity of UV-VUV solar spectrometer on its spectral irradiance responsiveness direction performance, a transmission pre-diffuser is placed in front of the entrance slit.

3. The deuterium lamp calibration and intercomparison

Since synchrotron radiation is accurately calculable and stable, therefore it has been used as a radiation standard source at short wavelength since the 1970’s. In 1984 PTB established BESSY I synchrotron electron storage ring and went on the investigation on BESSY I synchrotron characteristics. Based on BESSY I synchrotron radiation, PTB calibrated deuterium lamps with MgF_2 window in 115 nm–350 nm. The uncertainty of the spectral intensity of the calibrated deuterium lamps is about 5% [10,11].

The deuterium lamps calibrated by PTB, based on synchrotron radiation of BESSY I, were intercompared under the spectral radiance mode by means of VUV spectral radiometer. The VUV spectral radiometer consists of pre-optics vacuum chamber, 3 m VUV McPherson monochromator with a grating of ruling density 1200 g/mm and curvature radius 3 m, photomultiplier detector R1689-02, Keithley 6485 electrometer, McPherson wavelength scanning driver and computer. The luminous point of the deuterium lamp is imaged onto the entrance slit of McPherson monochromator by a concave mirror with the curvature radius 1 m and a plane mirror. A precision entrance aperture with the diameter 0.9 mm is placed in front of the entrance slit. The pre-optics vacuum chamber and McPherson monochromator are vacuumized by turbo molecular pumps to 2×10^{-3} Pa. The intercomparison results of the spectral radiance of the deuterium lamps (lamp number V0195, V0248, V0250 and V0251) in spectral range 165 nm–300 nm reveal that the

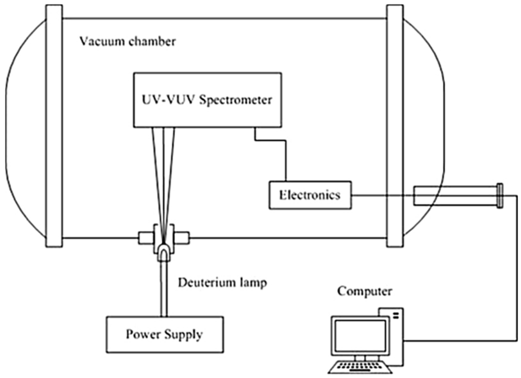

Fig. 2. The calibration system for the spectral irradiance responsiveness of UV-VUV solar spectrometer.

agreement of within 1%.

4. The calibration of UV-VUV solar spectrometer engineering proto and the uncertainty analysis

The equipment for the spectral irradiance responsiveness calibration of UV-VUV solar spectrometer is shown in Fig.2. Due to the atmospheric absorption, the calibration in UV-VUV spectral range was carried out in vacuum chamber. The outline dimension of the chamber is diameter 1200 mm × length1500 mm. It is vacuumized by a 5000 l/s low temperature condensation pump and the vacuum degree in the chamber is about 1.3×10^{-3}Pa. The standard lamp of the spectral irradiance responsiveness calibration for UV-VUV solar spectrometer is transfer standard deuterium lamp with MgF_2 window calibrated by PTB using synchrotron radiation. In the vacuum chamber the deuterium lamp irradiates the pre-diffuser of UV-VUV solar spectrometer and the spectral irradiance of the deuterium lamp is measured to obtain the spectral irradiance responsiveness of UV-VUV solar spectrometer.

The spectral irradiance responsiveness $R(\lambda)$ of UV-VUV solar spectrometer can be expressed as follows:

$$R(\lambda) = S(\lambda)/E(\lambda) = S(\lambda).\ d^2/I(\lambda) \quad (1)$$

Where $I(\lambda)$ for the spectral intensity of the deuterium lamp at the wavelength λ calibrated by PTB, $E(\lambda)$ for the spectral irradiance of the deuterium lamp at the wavelength λ, $S(\lambda)$ for theoutput signals of the photon counter of UV-VUV solar spectrometer.

The calibration data of the spectral irradiance responsiveness of UV-VUV solar spectrometer is listed in Table 1 and the curve for the spectral irradiance responsiveness of UV-VUV solar spectrometer is shown in Fig. 3.

The calibration uncertainty of the spectral irradiance responsiveness of UV-VUV solar spectrometer includes the calibration uncertainty of the transfer standard deuterium lamp and the measurement uncertainty of UV-VUV solar spectrometer [12,13].

The uncertainty of the spectral irradiance of the transfer standard deuterium lamp, described as follows:

1) The uncertainty of the spectral irradiance of the deuterium V0195 by PTB is 5% in 165 nm–400 nm.
2) The deuterium lamp is supplied by a DC stabilized current power supply. The lamp current of the transfer standard deuterium lamp is 300 mA, measured by a standard resistor and a digital voltmeter, and the current stability is 0.01 %/h. The instability and the inaccuracy of the lamp current leads an uncertainty of the deuterium lamp radiation, estimated about 0.04 %.
3) The deuterium lamp works in the vacuum chamber. The vacuum chamber is vacuumized by the condensation pump. The contamination deposition of the remanent oil vapour on the lamp widow is ultimately polymerized by the EUV radiation of the lamp generating a thin carbon layer and the thickness of the thin carbon layer increases with time. It reveals a drift of the output signal of UV-VUV solar spectrometer, about 0.1 %/each spectrum scan. It leads an uncertainty, estimated about 0.1 %.
4) The distance between the lamp and the pre-diffuser is measured by an inside micrometer and is 256 mm ± 1 mm. It leads an uncertainty, estimated about 0.2 %.

The deuterium lamp irradiates the pre-diffuser directly. The radiation transmits to the detector through the optical components of

Table 1
The calibration data for the spectral irradiance responsiveness of UV-VUV solar spectrometer.

Wavelength(nm)	I(uW/(sr nm))	E(uW/(cm^2 nm))	S(Counts/s)	R((Countscm^{2}nm)/(s uW))
170	77.7290	0.1186	131.9443	1112.4678
200	63.0546	0.0962	558.3227	5802.9482
230	40.4337	0.0617	740.9640	12009.7533
260	21.9864	0.0335	463.2609	13808.6822
290	13.3395	0.0203	170.6957	8386.1763
320	8.3900	0.0128	37.0003	2890.1688

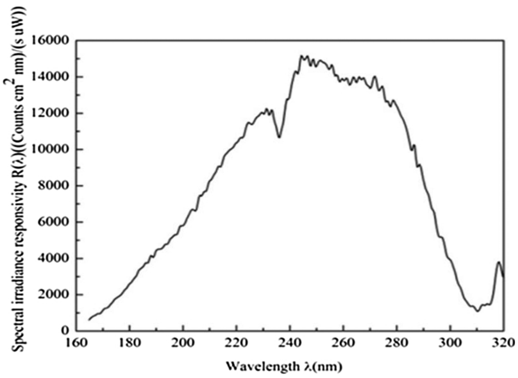

Fig. 3. The curve for the spectral irradiance responsiveness of UV-VUV solar spectrometer.

the UV-VUV solar spectrometer such as the slits, the concave gratings, the turning plane mirrors and the filters. Finally the output signals of the photomultiplier detector system form a solar spectrum. The variation of each intermediate link leads to an uncertainty, described as follows:

1) The wavelength accuracy and the wavelength reproducibility for UV-VUV solar spectrometer were tested by means of the spectral lines of Hg lamp (The wavelengths respectively are 184.8912 nm, 253.6506 nm and 296.7283 nm). The peaks of spectral lines are obtained by Gauss fitting. Shows a linear relationship between the step number of the stepping motor of UV-VUV solar spectrometer and the wavelength of UV-VUV solar spectrometer. The measurement results reveal that the difference between the real wavelength and the fitting straight line is less than 0.01 nm. The measurement results for the spectral lines of Hg lamp also reveal that the wavelength reproducibility is less than ± 0.007 nm. The reproducibility and the accuracy of the wavelength of UV-VUV solar spectrometer lead to an uncertainty, 0.02 %
2) The movement and reproducibility of the mechanical components such as the filter wheel and the quartz plate wheel leads to an uncertainty, estimated about 0.05 %.
3) The drift, the fatigue and the degradation of spectral responsiveness of the photomultiplier leads an uncertainty, estimated about 0.3 %.
4) The electronic drift and degradation of the photon counter lead to an uncertainty, estimated about 0.2 %.
5) The drift and the degradation of the transmission performance of UV-VUV solar spectrometer leads to an uncertainty, estimated about 0.1 %.
6) The detector system of UV-VUV solar spectrometer consists of photomultiplier R2078 (Hamamatsu, Japan) and photon counter. It was measured that the nonlinearity of R2078 photomultiplier is 1.5 % and the nonlinearity of the photon counter is 15 % with a maximum counting rate 107 counts/s under the maximum spectral irradiance of UV-VUV solar spectrometer. The nonlinearity of the detecting system of UV-VUV solar spectrometer and its modifying operation lead to an uncertainty about 0.5 %.
7) Based on the measured signal-noise ratio, the noise leads to an estimated uncertainty less than 0.8 % [13].

The uncertainty sources and the uncertainties are listed in Table 2. An analysis shows the synthesized uncertainty of the spectral irradiance responsiveness of UV-VUV solar spectrometer is 5.1 %.

Table 2
The synthesized uncertainty of the spectral irradiance responsiveness calibration of UV-VUV solar spectrometer [10].

Uncertainty sources	Uncertainty
PTB deuterium lamp calibration	5.0 %
The deuterium lamp current	0.04 %
The contamination of the lamp window	0.1 %
The distance between the lamp and the pre-diffuser	0.2 %
The reproducibility and the accuracy of the wavelength of UV-VUV solar spectrometer	0.02 %
The stability and the reproducibility of the moving parts of UV-VUV solar spectrometer	0.05 %
The drift, the fatigue and the degradation of the photomultiplier	0.3 %
The electronic drift and the degradation of photon counter	0.2 %
The drift and the degradation of the transmission performance of UV-VUV solar spectrometer	0.1 %
The nonlinearity of the photomultiplier and the photon counter	0.5 %
The noise of UV-VUV solar spectrometer detecting system	0.8 %
The synthesized uncertainty	5.1 %

5. Conclusion

In order to meet the requirement of the investigation on solar physics, atmospheric physics, meteorology, climatology and environment science, a set of solar spectral irradiance spectrometer as satellite payload is developing by Changchun Institute of Optics, Fine Mechanics and Physics CAS. At present the development of the engineering proto of UV-VUV solar spectrometer has been completed. This paper mainly reports the calibration equipment of the spectral irradiance responsiveness of UV-VUV solar spectrometer, the calibration method, the calibration of the engineering proto. The calibration results and the calibration uncertainty are given. The analysis reveals the calibration synthesized uncertainty is 5.1 %. This work laid the foundation for the high accuracy calibration of UV-VUV solar spectrometer, the enhancement of the quality of the on-orbit measurement data and the improvement of the data production accuracy.

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