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High-accuracy irradiance calibration of space UV remote sensing instrument (SURSI) from 160 to 250 nm in vacuum using a liquid nitrogen cooled device

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Abstract
A signal degradation feature in pre-launch irradiance calibration of space UV remote sensing instrument (SURSI) in vacuum has been identified. We discuss the possible degradation factors, degradation mechanisms and degradation rules, and then demonstrate that the irradiance degradation of the deuterium lamp as the calibration source is the significant cause of the signal degradation. A liquid nitrogen cooled device (LNCD) has been developed and the irradiance degradation is reduced to 1% during the radiometric calibration. On the basis of this LNCD, a high-accuracy irradiance calibration of the SURSI in vacuum from 160 to 250 nm has been performed and the calibration uncertainty is ±4.5%. Finally, the extraterrestrial solar spectrum from 170 to 250 nm measured by the SURSI is compared with the one derived from the NOAA-11 SBUV/2, showing an agreement of better than ±3.2%.

Keywords: vacuum calibration, deuterium lamp, signal degradation, diffuser

(Some figures may appear in colour only in the online journal)

1. Introduction

Space UV remote sensing instrument (SURSI) is an optical payload on the second generation of polar-orbit meteorological satellite in China. The principal purpose of SURSI is to measure total column ozone and its altitude profile. This is done by measuring the radiance of backscattered ultraviolet at selected wavelengths between 252 and 340 nm, and measuring the incident solar irradiance at the same wavelengths, thereby obtaining a measure of the UV scattering by the stratospheric ozone. Beyond this, the instrument can perform a continuous scan of wavelength from 160 to 400 nm providing frequent measurements of solar spectral irradiance. Although not its primary product, these solar spectral irradiance data are used by some researchers for comparison with similar measurements by other instruments to obtain instrumental trends and diagnostics [1–3]. The pre-launch irradiance calibration of the SURSI is separated into two sections according to different wavelength regions. From 250 to 400 nm, the calibration is performed in air using a NIST-calibrated 1000 W tungsten–quartz–halogen lamp as the standard of spectral irradiance [4, 5]. From 160 to 250 nm, the calibration is performed in vacuum using a PTB-calibrated deuterium lamp with MgF_2 window [6, 7]. The calibration in vacuum is not as easy as in air. The SURSI output signal gradually decreased during about 60 min of calibration measurement (the first 30 min for preheating the deuterium lamp and instrument, and the second 30 min for measurement). We obtained the signal degradation by normalizing the output signal to the first measurement when the deuterium lamp and

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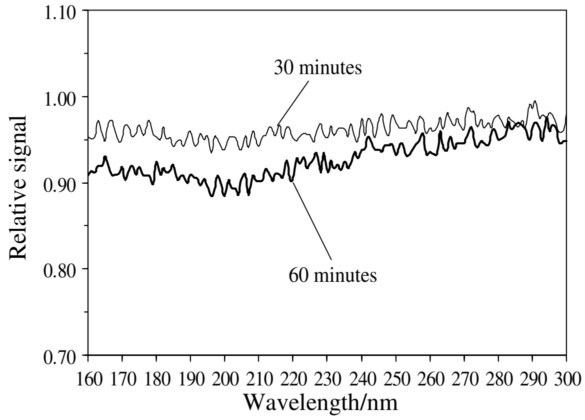

Figure 1. Changes in relative SURSI output signal with increasing calibration time.

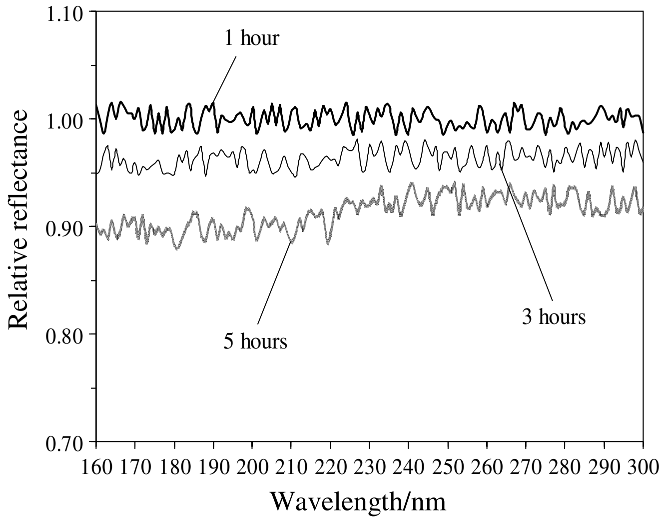

Figure 2. Changes in relative reflectance of the SURSI diffuser with increasing radiation time.

the SURSI started to work (figure 1). From figure 1, we can see that the degradation rates varied with wavelength and there was maximum degradation measured about 12% at 200 nm after 60 min. This is a far more serious discovery, because the effect is not localized but extends over the whole calibrated wavelengths in vacuum, which would bring a large uncertainty to the calibration results.

In this paper, we have discussed the possible degradation factors. In order to perform the high-accuracy irradiance calibration of the SURSI in vacuum, a liquid nitrogen cooled device (LNCD) has been developed to effectively overcome the signal degradation problem. Finally to verify the calibration accuracy, the extraterrestrial solar spectrum from 170 to 250 nm measured by SURSI was compared with the one derived from the Solar Backscatter Ultraviolet Radiometer (SBUV/2) on the NOAA-11 operational satellite.

2. Degradation study

2.1. Diffuser degradation

From the reflectance observation of long-term solar diffusers with Al substrate and MgF_2 coating of ten Backscatter Ultraviolet instruments [8], their reflectances all have appeared to degrade at different rates. The researchers find that photodeposition of spacecraft contaminants is a likely explanation for diffuser degradation [9, 10]. In this process contaminants adhering to the diffuser surface are fixed there via the interaction with solar radiation, usually wavelengths shorter than 200 nm.

The SURSI diffuser is fabricated with Al substrate and MgF_2 coating and the deuterium lamp has relative strong radiation at wavelengths shorter than 200 nm. In addition, there is more or less contamination in the vacuum chamber. Thus we considered that the signal degradation during the vacuum calibration might be associated with the reflectance degradation of the SURSI diffuser.

Change in diffuser reflectance by vacuum (10^{-5} Pa) ultraviolet radiation has been studied by using a double diffuser (test and reference) mechanism of the SURSI. Two diffusers could alternately move into the optical path at the same angle to reflect the deuterium lamp irradiance into the SURSI. During the measurement, the test diffuser was irradiated by the deuterium lamp for 5 h continuously, except when the reference diffuser was being measured. Every 1 h, we obtained the changes in the test diffuser reflectance and the deuterium lamp irradiance by normalizing the SURSI output signal to the first measurement when the lamp and the SURSI started to work. It was assumed that the signal change caused by instability of the lamp and instrument was less than that caused by degradation. After the measurement with the test diffuser every 1 h, the reference diffuser was immediately moved into the optical path to study on the change in the deuterium lamp irradiance by the same normalized method. In the whole process, the cumulative radiation time of the reference diffuser was less than 10 min, so we approximately considered that its reflectance did not change. Finally the normalized results of the reference diffuser were used to correct that of the test diffuser, and then we could obtain the changes in relative reflectance of the test diffuser with the radiation time (figure 2). From figure 2, we can see that: (i) the degradation extended over the whole wavelength range from 160 to 300 nm; (ii) the degradation value increased with increasing radiation time; (iii) the degradation rates at short wavelengths were slightly higher than those of long wavelengths for 5 h radiation. However, there was little signal degradation after 1 h radiation. Because the radiation time of the diffuser in formal calibration measurement lasts only for 30 min (diffusers are not moved into the optical path during the preheating time), the signal degradation caused by the diffuser can be neglected.

2.2. Deuterium lamp degradation

In the process of studying diffuser reflectance degradation, we also obtained the irradiance degradation of the deuterium lamp using the measured signals with the reference diffuser (figure 3). From figure 3, we found that the degradation characteristics of the deuterium lamp were similar to those of the diffuser. In addition, the degradation rates of the deuterium lamp had a more sensible dependence on wavelength. There

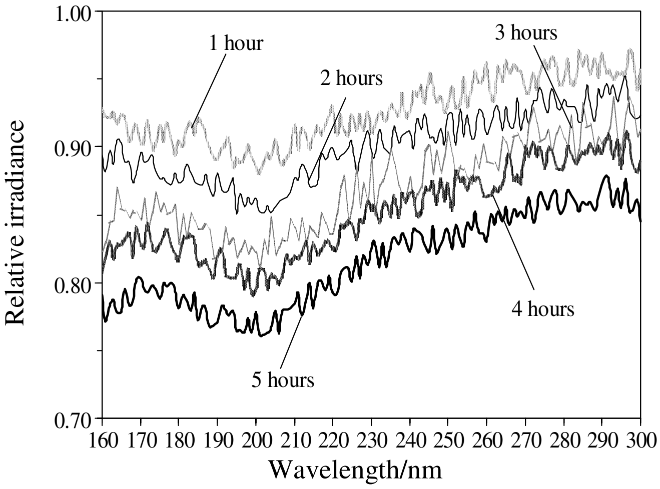

Figure 3. Changes in relative irradiance of deuterium lamp with increasing operating time.

was maximum signal degradation measured about 28% at 200 nm and minimum about 10% at 300 nm after 5 h operating time. We also found that the degradation value and rule of deuterium lamp irradiance were almost the same as those of the SURSI output signal in vacuum calibration after 1 h (see figures 1 and 3). We therefore concluded that the deuterium lamp degradation is a significant cause of the signal degradation.

Key *et al* (1985) has reported that a significant cause of deuterium lamp irradiance degradation is contaminant deposition on its window [11]. When short UV wavelength radiation falls onto the magnesium fluoride window, an electrostatic charge builds up on the crystal. This charge would then establish an electric field in front of the window. If the residual vacuum molecules become ionized by the ultraviolet radiation they would then be attracted toward or repelled from the window, depending on the polarity of the field. No other forces of significant strength are applied to the ionized molecules, which would be accelerated in an electric field once close to the window. Having impinged on the window, the molecules must be stabilized and form a thin deposited film with increasing radiation time. The effect on the window irradiated in this way is to reduce its transmission, which causes the output irradiance degradation of the deuterium lamp.

A LNCD is developed to overcome the degradation problem (figure 4). The LNCD is connected with a vacuum chamber by two interface flanges. The liquid nitrogen inlet tube, outlet tube and the cooled tube are connected together. The liquid nitrogen cooled screen consists of an internal screen which is surrounded by the cooled tube and an external screen with the inlet tube welded on one side and the outlet tube on the other side. The deuterium lamp room is connected with the LNCD by a fixation flange. The LNCD is put in front of the deuterium lamp and has three functions to reduce its irradiance degradation: (i) cooling function. The LNCD could locally reduce the pressure around the deuterium lamp window and hence decrease the number of molecules striking the window; (ii) obstructing function. Molecules rarely collide with themselves and mainly travel in straight lines from one surface to another in the vacuum chamber. The LNCD could effectively obstruct the hydrocarbons from being close to the window in all directions except for the direction of deuterium lamp radiation transmission; (iii) restricting radiation function. On the premise of illuminating the instrument field of view, by decreasing the clear aperture size of the cooled screen as small as possible, the LNCD can restrict the radiation solid angle of

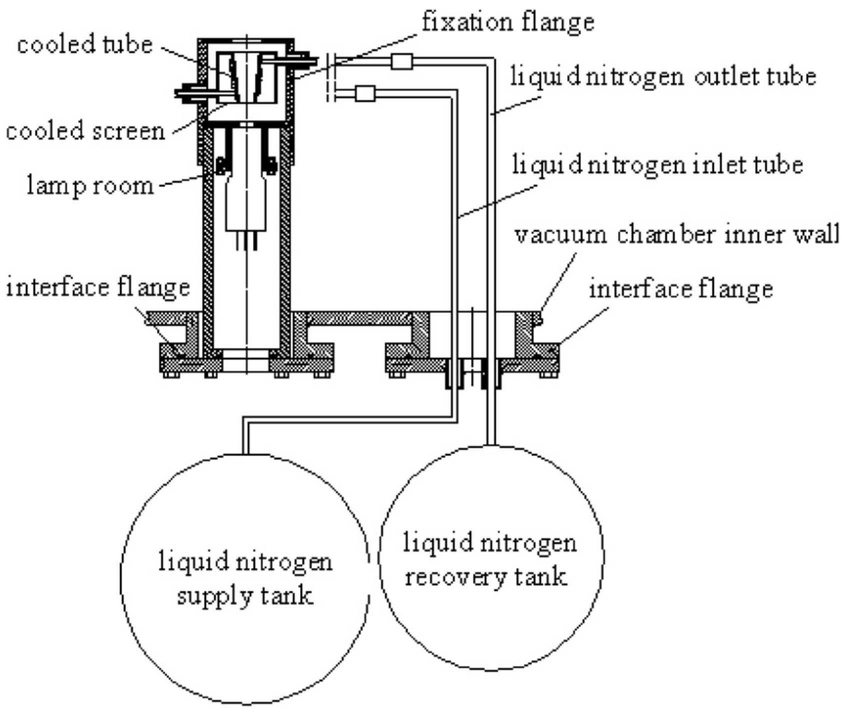

Figure 4. Liquid nitrogen cooled device.

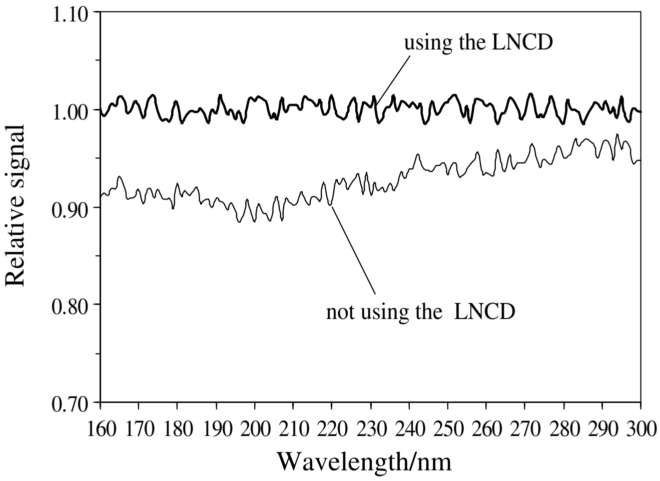

Figure 5. Degradation result with LNCD after 1 h.

the deuterium lamp, and then decrease the number of ionized molecules incident on the cooled screen.

With the LNCD, we have successfully overcome a deuterium lamp degradation problem and improved its irradiance stability. The average degradation from 160 to 250 nm is only 1% after 1 h and the degradation is nominally independent of wavelength (figure 5).

3. Calibration and results

On the basis of the LNCD, we have performed a high-accuracy irradiance calibration of SURSI in vacuum. The calibration equipment except for the LNCD is described by Wang *et al* (2007, 2010).

In order to remove the contaminant deposition on the deuterium lamp window and make the source intensity return to the original value, we polished the window with high-purity alumina before the calibration measurement. Liquid nitrogen was filled into the LNCD when vacuum level reached 10^{-5} Pa. The local temperature around the deuterium lamp window reached −80°C within 30 min. Then, the deuterium lamp and the SURSI were preheated and the irradiance calibration measurement was made.

Since the main purpose of the vacuum calibration is to extend the sweep mode irradiance calibration into the vacuum ultraviolet range from about 250 nm down to 160 nm, we have heretofore treated the vacuum calibration as accurate only on a relative scale, and have normalized it to the in-air calibration where the wavelength ranges overlap, to put it on an absolute scale. The irradiance responsivity can be determined from the following equation:

$$R(\lambda) = \frac{V_D(\lambda)}{V_D(300\,\text{nm})} \cdot \frac{V_W(300\,\text{nm})}{E_W(300\,\text{nm})} \cdot \frac{1}{D(\lambda)}, \qquad (1)$$

where $V_D(\lambda)$ is the measured irradiance signal from the deuterium lamp at wavelength λ with the SURSI; $V_D(300\,\text{nm})$ is the measured irradiance signal from the deuterium lamp at 300 nm with the SURSI; $E_W(300\,\text{nm})$ is the absolute irradiance of the NIST-calibrated 1000 W tungsten–quartz–halogen lamp at 300 nm; $V_W(300\,\text{nm})$ is the measured irradiance signal from the NIST lamp at 300 nm with the SURSI; $D(\lambda)$ is the relative spectral distribution of the deuterium lamp (normalized at 300 nm). The calibration uncertainty equation derived from equation (1) is described as follows:

$$\frac{\Delta R(\lambda)}{R(\lambda)} = \left[\left|\frac{\Delta V_D(\lambda)}{V_D(\lambda)}\right|^2 + \left|\frac{\Delta V_D(300\,\text{nm})}{V_D(300\,\text{nm})}\right|^2 + \left|\frac{\Delta V_W(300\,\text{nm})}{V_W(300\,\text{nm})}\right|^2 + \left|\frac{\Delta E_W(\lambda)}{E_W(\lambda)}\right|^2 + \left|\frac{\Delta D(\lambda)}{D(\lambda)}\right|^2\right]^{1/2}. \qquad (2)$$

Table 1. Uncertainty budget of the SURSI measurement repeatability from 160 to 250 nm in vacuum ($k = 1$).

Source of uncertainty	Uncertainty (%)
Drift of detector responsivity	1.3
Wavelength reproducibility	0.3
Drift of amplifier responsivity	0.4
Drift of high-voltage supply	0.2
Linearity error of detector and amplifier responsivity	0.3
Overall uncertainty	1.4

Table 2. Uncertainty budget of the SURSI irradiance calibration from 160 to 250 nm in vacuum ($k = 1$).

Source of uncertainty	Uncertainty (%)
Measured signal $V_D(\lambda)$	1.4
Measured signal $V_D(300\,\text{nm})$	1.4
Measured signal $V_W(300\,\text{nm})$	0.5
Calibration of quartz–halogen standard lamp	2.0
Calibration of deuterium lamp	3.5
Overall uncertainty	4.5

The calibration uncertainty is the combined uncertainty of the instrument measurement repeatability and two standard calibration lamps. The measurement repeatability uncertainty budget is presented in table 1. A summary of uncertainty budget for the SURSI irradiance calibration from 160 to 250 nm is presented in table 2. The deuterium lamp degradation is independent of wavelength with the LNCD and we treat the vacuum calibration only on a relative scale, so the degradation has no effect on the calibration results.

Figure 6 shows the extraterrestrial solar irradiance spectrum from 170 to 250 nm measured by the SURSI on Chinese meteorological satellite. The other spectrum from the Solar Backscatter Ultraviolet Radiometer (SBUV/2) on the NOAA-11 operational satellite has the same solar activity level as that of the SURSI spectrum ($F_{10.7} = 681$). The absolute calibrations of SURSI and SBUV/2 have been established with the same NIST standard of spectral irradiance. Due to differences in the slit functions of the two instruments, two measured spectra were convolved by the same triangular slit function (spectral resolution of 5 nm FWHM and wavelength step of 1 nm) to homogenize for local spectral inconsistency before comparison. On average the ratio between the SURSI and the SBUV/2 solar spectra is close to unity (figure 7), and the observed disagreement of ∼3.2% in the wavelength range

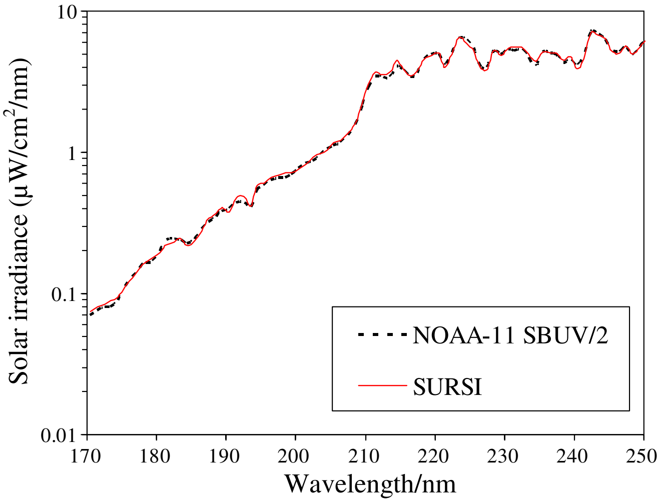

Figure 6. Extraterrestrial solar spectrum measured by SURSI and SBUV/2 from 170 to 250 nm.

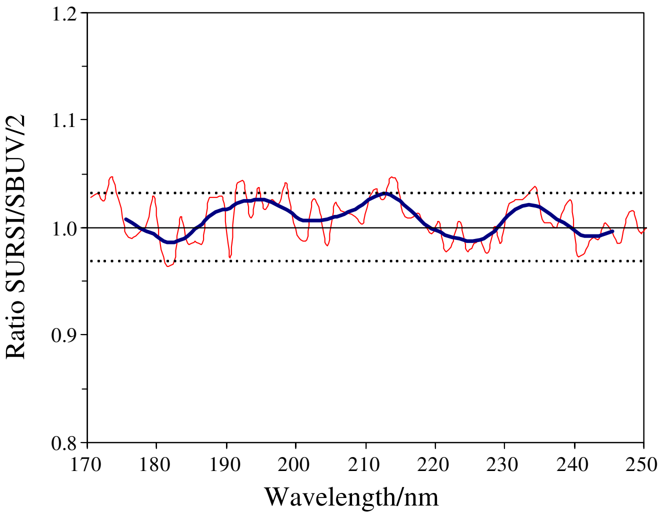

Figure 7. Ratio of the extraterrestrial solar spectrum measured by SURSI to that by SBUV/2. The thick line represents the ratio of two measured spectra that are convolved by the same triangular slit function with spectral resolution of 5 nm FWHM and wavelength step of 1 nm. The two dashed lines separately represent the 3.2% and −3.2% relative deviations.

(from 170 to 250 nm) is within the uncertainty limit usually present in solar UV spectral measurements [12–16].

4. Conclusion

A signal degradation feature in pre-launch irradiance calibration of SURSI from 160 to 300 nm in vacuum has been identified. We found that the signal degradation was associated with the deuterium lamp irradiance degradation caused by the contaminant deposition on its window. In order to overcome the problem, a LNCD was developed at State Key Laboratory of Applied Optics, Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences and the deuterium lamp irradiance degradation was reduced to only 1% during the calibration time. On the basis of this LNCD, we performed a high-accuracy irradiance calibration of SURSI from 160 to 250 nm in vacuum and the calibration uncertainty is $\pm 4.5\%$ relative to the NIST calibrated 1000 W tungsten–quartz–halogen lamp. Finally, the extraterrestrial solar spectrum measured by SURSI is compared with the one derived from the NOAA-11 SBUV/2 and agreement is better than $\pm 3.2\%$, which is consistent with the error budget. The irradiance calibration accuracy of SURSI could be further improved by improving the SURSI performance or using the irradiance calibration lamps with the same transfer standard, which is planned for the near future.

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