Postprint: Measurement Methods for the Slit Function of Spaceborne Hyperspectral Imaging Spectrometers

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Abstract

To meet the requirements for high-precision measurement of atmospheric trace constituents, it is necessary to accurately characterize the instrument slit function of space-borne hyperspectral atmospheric trace constituent detectors. A slit function measurement instrument has been developed to address the characteristics of hyperspectral atmospheric trace constituent detectors, including large field of view, wide spectral band, high spatial resolution, and high spectral resolution. This paper first introduces the working principle of the slit function measurement instrument. Subsequently, leveraging its capability to simultaneously achieve high-resolution and wide-spectral-range measurements, full-field slit function testing is performed on the hyperspectral atmospheric trace constituent detector, the characteristic distribution of the instrument's slit function is presented, and the results are analyzed. The test results demonstrate that the slit function characteristic curve of the hyperspectral atmospheric trace constituent detector approximately follows a Gaussian distribution. Due to the spectral smile phenomenon inherent in space-borne wide-field imaging spectrometers, the resolution capability at the edge of the field of view is slightly lower than that at the center. The full-field spectral resolution of the hyperspectral atmospheric trace constituent detector is better than 0.6 nm.

Full Text

A Study on the Slit Function Test Method for Spaceborne Hyperspectral Imaging Spectrometers

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Abstract

To meet the requirements for high-precision measurement of atmospheric trace constituents, an accurate characterization of the instrument slit function for spaceborne hyperspectral atmospheric trace constituent detectors is essential. Considering the characteristics of large field-of-view, wide spectral range, and high spatial and spectral resolution, a dedicated slit function measurement instrument has been developed. This paper first introduces the working principle of the slit function measurement instrument. Leveraging its capability for simultaneous high-resolution, wide-spectral-range measurements, we conducted full-field-of-view slit function testing of the hyperspectral atmospheric trace constituent detector, presented the instrument' s slit function characteristic distribution, and analyzed the results. The test results demonstrate that the slit function characteristic curve of the hyperspectral atmospheric trace constituent detector approximately follows a Gaussian distribution. Due to the spectral smile phenomenon inherent in spaceborne wide-field imaging spectrometers, the resolving power at the edge of the field is slightly lower than that at the center. The spectral resolution across the full field of view is better than 0.6 nm.

Keywords: Slit function; Hyperspectral atmospheric trace constituent detector; Echelle diffraction grating

1. Introduction

In recent years, hyperspectral imaging technology [1-6] has become one of the primary methods for space environment detection, particularly gaining widespread application in meteorological observation and environmental monitoring. To address China' s urgent need for environmental pollution monitoring, a hyperspectral atmospheric trace constituent detector has been developed for the Fengyun satellite series. This detector is an imaging spectrometer based on the Differential Optical Absorption Spectroscopy (DOAS) principle, covering a spectral range of 375–500 nm with a total field of view of 112° and a spectral resolution of approximately 0.4–0.6 nm. By detecting atmospheric backscattered radiation from orbit and employing the DOAS algorithm to analyze trace gas distributions and variations, it enables global monitoring of atmospheric trace constituents.

The DOAS algorithm, founded on Beer-Lambert law, exploits differences in how molecular Rayleigh scattering and wavelength-dependent absorption vary with wavelength. Using spectral differential techniques, it decomposes extinction into slowly-varying and rapidly-varying components. The slowly-varying component is eliminated through low-order polynomial fitting, while target gas column information is extracted from the rapidly-varying component. Calibration of spaceborne atmospheric trace constituent detectors is a prerequisite for high-precision quantitative products, with slit function measurement being a critical calibration task [8-9]. The accuracy of differential absorption spectrometer data retrieval depends heavily on the precision of the instrument slit function characterization, making high-precision slit function measurement crucial for spaceborne atmospheric trace constituent detectors. In 2004, the Ozone Monitoring Instrument (OMI) aboard the Aura satellite employed a specialized diffraction device based on echelle grating principles for instrument slit function measurement [10-14]. Echelle gratings feature low groove density and large blaze angles, offering high resolution and dispersion characteristics suitable for slit function measurement.

To satisfy the high-precision measurement requirements for atmospheric trace constituents and accurately characterize the slit function of spaceborne hyperspectral atmospheric trace constituent detectors, a slit function measurement instrument has been developed specifically for this payload' s characteristics of large field-of-view, wide spectral band, and high spatial and spectral resolution. This paper primarily introduces the working principle of the developed slit function measurement instrument and presents full-field-of-view slit function characteristic measurements of the hyperspectral atmospheric trace constituent detector.

1.1 Working Principle of the Slit Function Measurement Instrument

The optical schematic of the slit function measurement instrument is shown in [Figure 1: see original paper]. Here, the front optical system is replaced by a single lens with effective area A .

[Figure 1: see original paper]

The grating diffraction equation is given by:

$$sin\alpha + sin\beta = \frac{m\lambda}{d}$$

where α is the incident angle, β is the diffraction angle, m is the diffraction order, λ is the central wavelength, and d is the grating constant.

From this equation, the spectral broadening corresponding to the slit width is:

$$d\lambda = \frac{cos\beta}{m \cdot n \cdot f} \cdot l$$

where n is the groove density, l is the exit slit width, and f is the exit focal length. With a groove density of 79.01 grooves/mm and a diffraction angle of 71.5°, the instrument achieves a spectral resolution of 0.0394–0.0578 nm across the 370–505 nm range when the collimating mirror focal length $f = 615.894$ mm, meeting the test requirements. The spectral resolution capability is summarized in .

From the schematic, the radiant power entering the spectrometer slit is:

$$P = \frac{E_{50} \cdot \eta \cdot A_g \cdot A_i}{A_0 \cdot L^2}$$

where E_{50} is the irradiance at 50 cm from the source, η is the efficiency of the front optical system, A_i is the entrance slit area, and A_g is the area of the source image on the slit, given by:

$$A_g = \left(\frac{A_i}{A_0}\right) \cdot L^2$$

Substituting this into the previous equation yields:

$$P = \frac{E_{50} \cdot \eta \cdot A_i}{50 \cdot F^2}$$

where F is the spectrometer' s f-number and A_0 is the source area. This expression shows that when the source image dimensions exceed those of the spectrometer entrance slit, the entering energy depends only on the source irradiance at 50 cm, front optical system efficiency, entrance slit area, source area, and the spectrometer f-number.

The hyperspectral atmospheric trace constituent detector has a spectral resolution better than 0.6 nm. To accurately characterize its slit function, the measurement instrument must achieve a spectral resolution of 0.06 nm. The calculations confirm that the developed instrument meets this requirement.

1.2 Basic Structure of the Slit Function Measurement Instrument

The slit function measurement instrument consists of three independent modules: a stable light source system, a high-spectral-resolution echelle grating spectrometer, and a rear optical system. This modular design facilitates heat dissipation from the light source and enables adjustable output beams. The structural configuration is illustrated in [Figure 2: see original paper].

[Figure 2: see original paper]

2. Slit Function Measurement

2.1 Selection of the Test Light Source

The light source for the slit function measurement instrument must be selected based on the detection signal and sensitivity of the hyperspectral atmospheric trace constituent detector. The detector achieves a signal-to-noise ratio (SNR) of 1000 under standard signal detection conditions. Therefore, we selected the

L2479 ultra-quiet xenon lamp from Hamamatsu, Japan, which features high output power and stable energy distribution. The primary radiation characteristics are listed in .

In the slit function measurement instrument, the single mirror reflectance is 0.87, grating efficiency is 0.5, source size is 3×1 mm^2, and slit size is 5.2×0.5 mm^2. Using the aforementioned equations, the system output irradiance for a Φ20 mm output beam is calculated as shown in .

The data indicate that using a 300 W L2479 xenon lamp with a Φ20 mm output beam yields an SNR comparable to that of standard signal measurements.

2.2 Instrument Slit Function Measurement

Due to the large detection field of view of the spaceborne atmospheric trace constituent detector, spectral smile (spectral line curvature) inevitably occurs and cannot be completely corrected to perfect symmetry. To accurately characterize the instrument' s slit function, measurements must be performed across the entire field of view.

The experimental setup, shown in [Figure 3: see original paper], comprises a light source, slit function measurement instrument, high-precision rotation stage, detector under test, and computer.

[Figure 3: see original paper]

After activating the light source, the instrument integration time and gain are adjusted to ensure high SNR. Following a 10-minute stabilization period, measurements commence. Spectral data from the CCD photosensitive region, denoted as $S_{im,jn}$, are recorded, where i, j represent spatial dimension row indices and m, n represent spectral dimension column indices. The high-precision rotation stage is turned at 10° intervals, recording spectral data $S'_{im,jn}$ at each position. This process is repeated to capture spectral data across the full field of view.

[Figure 4: see original paper] shows a single measurement output from the hyperspectral atmospheric trace constituent detector at the central field of view. The instrument simultaneously outputs multiple uniformly distributed spectral lines, which are imaged onto the detector' s focal plane array.

[Figure 4: see original paper]

Based on the detector' s spectral response range, fourteen strong spectral lines can be extracted and individually fitted to obtain the instrument slit function.

2.3 Test Results and Analysis

For an ideal spectrometer, the slit function would be trapezoidal or triangular. However, in practice, due to diffraction effects, scattering effects, and non-rectangular pixel response functions, the slit function curves of hyperspectral remote sensing instruments approximately follow a Gaussian distribution. The spectral resolution at the central wavelength is typically represented by the full width at half maximum (FWHM) of the slit function.

[Figure 5: see original paper] shows the slit function curves at 481.4 nm and 462.7 nm for the central field of view (a and b) and edge field of view (c and d). [Figure 6: see original paper] presents similar curves at 453.8 nm and 445.3 nm.

[Figure 5: see original paper]

[Figure 6: see original paper]

The hyperspectral atmospheric trace constituent detector' s visible channel output data were processed by dark current subtraction and Savitzky-Golay smoothing for noise reduction. After normalization and fitting, the instrument slit function curves were obtained. The fitting function is given by:

$$S(\lambda) = A\left[e^{-\frac{(\lambda-\lambda_s)^2}{2\sigma^2}} + e^{-\frac{(\lambda-\lambda_s)^2}{2\sigma_1^2}}\right] + \cdots$$

where λ_s is the central wavelength at peak intensity, σ characterizes the FWHM of the instrument slit function, and A, σ_1, λ_1 are correction parameters for the instrument slit function.

As shown in [Figure 5: see original paper] and [Figure 6: see original paper], the fitted curves agree well with the functional form. The central wavelength at the edge field of view exhibits a slight shift compared to the central field of view due to the smile effect in large-field imaging spectrometers. [Figure 7: see original paper] illustrates the spectral line curvature across the full field of view, showing a maximum curvature span of 4 pixels.

[Figure 7: see original paper]

Therefore, full-field-of-view slit function measurement is necessary to accurately characterize large-field imaging spectrometers. The spectral resolution of the hyperspectral atmospheric trace constituent detector ranges from 0.423 nm to 0.597 nm, meeting technical specifications. Due to spectral smile, the resolving power at the edge field of view is slightly lower than at nadir.

Furthermore, because the slit function measurement instrument can simultaneously output multiple discrete spectral lines with uniform distribution—unlike traditional spectral lamps [15] that have limited and non-uniform characteristic wavelengths, or conventional monochromators that output only one wavelength at a time—it enables efficient wavelength calibration for wide-spectral-range, high-resolution imaging spectrometers, improving spectral line position calculation accuracy and achieving high-precision spectral calibration.

The spectral resolution at wavelength λ can be derived from the fitting function as:

$$R = \frac{\lambda}{FWHM} = \frac{\lambda}{2\sqrt{2\ln 2}\,\sigma}$$

The measurement results for the hyperspectral atmospheric trace constituent detector slit function are summarized in , with parameters at 95% confidence level.

3. Conclusion

To meet the retrieval accuracy requirements of the Fengyun satellite hyperspectral atmospheric trace constituent detector, a slit function measurement instrument has been developed based on its characteristics of large field-of-view, wide spectral band, and high spatial and spectral resolution. By establishing a calibration setup, full-field-of-view slit function curves were measured, and the mathematical expression of the instrument slit function was derived. The results demonstrate that the spectral resolution ranges from 0.423 nm to 0.597 nm, the slit function curves follow Gaussian distribution well, and due to spectral smile, the edge field resolving power is slightly lower than that at nadir. Based on echelle diffraction grating design, the slit function measurement instrument can simultaneously output multiple uniformly distributed high-resolution spectral lines, making it suitable not only for measuring instrument slit functions of hyperspectral imaging spectrometers but also for spectral calibration of spaceborne hyperspectral instruments.

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Note: Figure translations are in progress. See original paper for figures.