Chapter 5 Nadir looking UV measurement. Part-II: UV polychromator instrumentation and measurements

- A high SNR and robust polychromator using a 1D array detector -

UV spectrometers onboard satellites have provided trend data of total O_3 for more than two decades. These data have shown the validity of satellite measurements. However, for next-generation observation and to monitor the recent O_3 depletion accurately, a high-fidelity spectrometer with high signal-to-noise ratio (SNR) is essential. In addition, in recent years, troposphere measurements from satellites have become more importation to monitor pollution caused by human activities. For these purposes, the UV polychromator has been designed to have higher spectral and spatial resolutions and wide spectral range. To remove the cloud contamination, filter radiometers for cloud top height detection are installed. The polychromator covers back-scattered light from 300 to 452 nm with 0.5 nm spectral and 20 km spatial resolutions using a Fastie-Ebert type polychromator and a one-dimensional UV Si-CMOS array detector. The array detector is designed and manufactured specially for this instrument. It has different size pixels and 234 on-chip CMOS amplifiers, which are tuned for each spectral radiance level. It is a nadir-look mapping spectrometer with a mechanical scanner, which can acquire global data in one day. It is expected to provide information about total O_3, SO_2, NO_2, BrO, OClO, H_2CO, surface albedo, and aerosol. In addition, the narrow band filter radiometer with 2 dimensional array detectors is installed beside the entrance optics.[1]

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[1] This chapter has been published in "Specifications of GCOM-A1/ODUS," SPIE 4150, 373-382 (2001) and was co-authored by Makoto Suzuki *et al.*. This is updated and revised.

5.1. Objectives

The UV polychromator discussed in this chapter is planned to be borne on the satellite of which specifications are summarized in Table 5-1. The altitude and the inclination are selected to provide global cover in one day. The satellite is a non-sun-synchronous orbit satellite for a solar occultation FTS to cover from low altitude to high altitude. Figure 5-1 shows an example of the coverage of one day.

For two decades, the total ozone mapping spectrometer (TOMS) carried on NIMBUS 7 (1978-1993), METEOR 3 (1991-1994), ADEOS (1996-1997), and Earth Probe (1996-) has provided UV backscattered data. The spectrometer has 6 UV spectral channels with 1 nm spectral and 44 km spatial resolutions [*Heath et al.*, 1975]. The global O_3 monitoring experiment (GOME) onboard the ESA ERS2 has been measuring continuous spectra since 1995 [*Burrows et al.*, 1995]. It has a 0.2 nm spectral resolution with a 40 by 320 km instantaneous field of view (IFOV). It is reported that in TOMS retrievals, the inappropriate O_3 profile model and estimation error of aerosol and surface albedo are the main error sources [*Wellemeyer et al.*, 2000]. In order to solve these issues, the instrument discussed in Chapter 4 has higher spatial and spectral resolutions and wider continuous spectral coverage than TOMS. For the next decade, in addition to this instrument, several instruments such as the Ozone Monitoring Instrument (OMI), GOME2, and the Ozone Mapping and Profiling Suite (OMPS) are being developed [*Laan et al.*, 2000, *Callies et al.*, 2000, and *Planet et al.*, 2000].

Recent Si detector and CMOS technologies have been used to develop a custom UV array detector, which has a large area array, and optimized pixel size and gain level. Using these techniques, the instrument can provide 306–452 nm continuous spectral data with 0.5 nm step and high SNR. In addition, it offers an onboard spectral and radiometric calibration capability.

Table 5-1. Assumed satellite orbit parameters.

Orbit	Non-sun synchronous (Yaw maneuver)
Altitude	650 km
Inclination	68 deg
Period	98 min

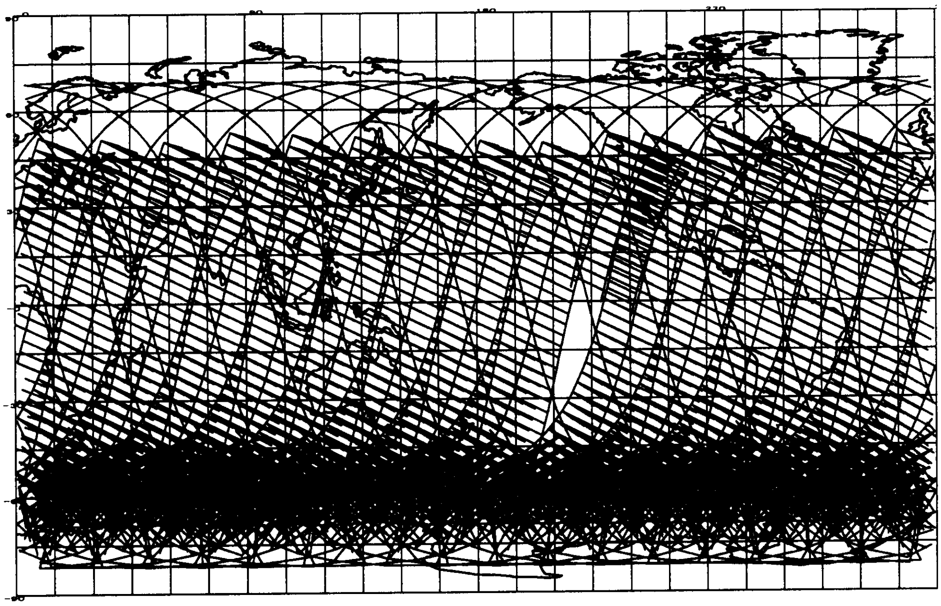

Figure 5-1. Example of one-day coverage for the inclination of 69 deg.

5.2. TOMS Measurement and Data retrieval

NASDA Earth Observation Research Center (EORC) has developed its own algorithm to retrieve total O_3 and albedo of TOMS. All ADEOS TOMS data are processed at EORC [*Kuze et al.*, 1998]. TOMS can retrieve the earth surface albedo and aerosol data from 6 channels of data. Both back-scattered spectral radiance and solar radiance are measured. O_3 can be retrieved in such a way as to minimize the deviation between the measured and model calculated values. To reduce the instrument degradation effect, the pair method is applied and O_3 sensitive and insensitive channels are paired. ADEOS TOMS has 4 pairs, A (312.59 and 331.31 nm), B (317.61 and 331.31 nm), C (322.40 and 331.31 nm), and D (308.68 and 312.59 nm).

As the instrument channel has a finite spectral width, the measured data will be the convolution of the solar Fraunhofer spectra, the slit function, and the O_3 absorption cross section. As shown in Figure 5-2 and Figure 5-3, the absorption cross section has a spectral structure and the Fraunhofer line has a random-like structure. The error due to simplifying the spectral response by calculating at one wavelength, which is the center wavelength of the channel, is one of the major error sources in the total O_3 retrieval. Therefore, when the optical thickness, which is the product of air mass factor, O_3 absorption cross section, and O_3 amount, is large, the spectra of each channel have to be calculated with fine step convolution to minimize the non-linearity effect. When the bandwidth of the channel is small enough and the O_3 absorption cross section has little spectral dependency, the error due to simplifying the spectral response without convoluting the slit function, the O_3 absorption cross section and the solar spectra over the bandwidth, is small. As the absorption cross section at the 317.61 nm channel has little spectral dependency, the retrieval accuracy using B-pair is the best among the 4 pairs.

To improve the O_3 retrieval accuracy when using other than B-pair, both fine step spectral calculation and accurate slit function modeling (the instrument function) are required. However, the radiative transfer calculation in the UV region has to consider the multiple scattering and the polarization effect. These calculations are time consuming. Furthermore, when the optical thickness is larger, the signal is weaker and the SNR will become low. In addition, as the O_3 absorption cross section changes at the rate of about 30 %/nm, spectral calibration of the order of 0.01 nm and stability during the calibration intervals are required. As the full width half maximum (FWHM) of the TOMS slit function is 1 nm, the resolution is not high enough to detect the 0.01 nm wavelength shift and calculate the convoluted radiance accurately. An instrument with a higher spectral resolution than TOMS will improve the accuracy of the convolution calculation and the wavelength calibration on board. Also, continuous spectral acquisition will provide spectral channels of the appropriate optical thickness for a wide range of air mass factor and total O_3 amount.

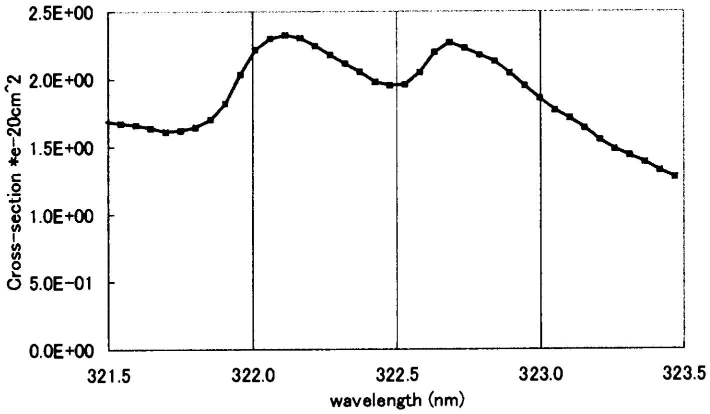

Figure 5-2. O_3 absorption cross-section around 322.5 nm.

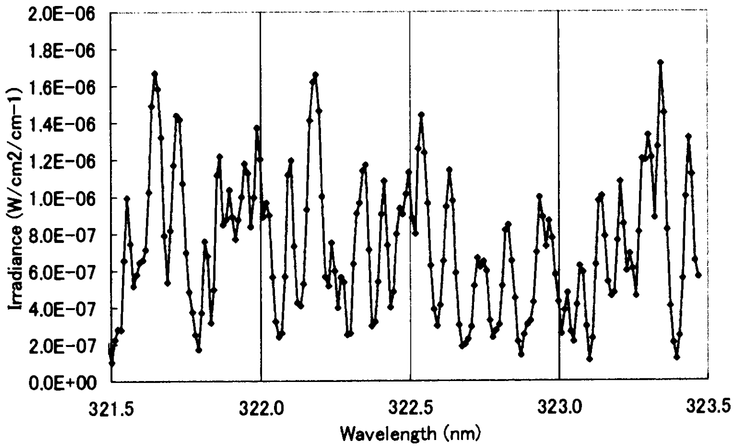

Figure 5-3. Solar Fraunhofer spectra around 322.5 nm.

5.3. Requirements

To continue and improve the O_3 measurements of existing instruments, the instrument has to be designed. The scientific objectives will be to obtain information about:

(1) Global total and tropospheric O_3 distribution,

(2) Dynamics in the stratosphere using O_3 distribution data,

(3) Pollution source monitoring (oxidization process) (acid deposition: NO_2 and SO_2),

(4) UV region radiation budget including surface albedo mapping,

(5) Aerosol optical thickness in UV and visible, and,

(6) Cloud height.

To achieve the above scientific requirements, the specifications for the instrument are as follows.

Field of view (FOV). To monitor the total O_3 globally in one day, the instrument must have a wide cross-track field of view (+/- 60 deg).

IFOV. Fine spatial information on the cloud top height, aerosol and surface albedo are required. In addition, high spatial resolution data of the O_3 distribution will improve detection of the pollution source measurement of the dynamics of the stratosphere.

Spectral coverage. Continuous spectral data of the O_3 sensitive region (306-335 nm) are used for both total O_3 and tropospheric O_3 retrievals. In addition, O_3 insensitive spectral data (335-400 nm) are used for the retrieval of additional data such as aerosols. Furthermore, the band 2 (432-452 nm) should be added for NO_2 detection.

Signal to noise ratio (SNR). The total O_3 measurement needs a high detectivity of weak solar UV scattered light of the shorter wavelength. A study on the sensitivity and retrieval algorithm on the tropospheric O_3 showed that continuous spectral measurement with high SNR is required [*Kuze et al.*, 2000]. In addition, the O_3 insensitive spectral data will be used to retrieve the surface albedo and aerosol. These parameters behave similar in radiative transfer, so the discrimination needs high SNR ratio. The required SNR is better than 40 at 306 nm and better than 400 for wavelengths longer than 310 nm.

Polarization scramble. The instrument measures the back-scattered solar light, which is highly polarized. On the other hand, the light diffracted with a grating is also polarized. Because both the scene flux and the light inside the spectrometer are polarized, the input flux must be scrambled before entering the spectrometer.

Spectral resolution. The O_3 absorption cross-section has strong spectral dependency. As the tropospheric O_3 retrieval algorithm uses its peak and bottom structure, the spectral resolution must be smaller than the spectral structure of the O_3 absorption cross section. Furthermore, the fine step spectral sampling makes adequate optical thickness pairs. The spectral resolution of 0.6 nm (FWHM) is required, and spectral intervals of better than 0.5 nm are essential for wavelength calibration of +/- 0.01 nm accuracy onboard.

Cloud height detection. Cloud height should be detected with 1 km accuracy for the tropospheric O_3 retrieval.

Onboard spectral calibration. The spectral position information of each channel is needed for accurate data retrieval. The accuracy of +/- 0.01 nm is required for the entire mission.

Onboard radiometric calibration. For the O_3 retrieval itself, the pair method is applied, therefore the degradation onboard will be cancelled. However, for retrieval of other geophysical parameters such as the surface albedo and aerosol optical thickness, the absolute radiance information is needed. As the instrument will follow a non-sun synchronous orbit and the sun angle will change, special care is needed for the radiometric calibration using solar irradiance. The above requirements are summarized in Table 5-2.

5.4. Instrumentation

(1) System Design

Figure 5-4 shows the instrument, which consists of fore-optics, spectrometer optics, a detector and its related electronics and structure. The spectrometer is a Fastie-Ebert polychromator, which has the good optical performance in the dispersion direction in the entire spectral range. Therefore, it can provide the high fidelity slit function. Compared with TOMS, it has both higher spatial and spectral resolutions by replacing the single photo multiplier tube with a linear array solid-state detector. It also has a mechanical scanner to acquire cross-track mapping data. In comparison with an imaging spectrometer, it provides a uniform slit function independent of viewing angle.

(2) Fore-optics Design

The fore-optics assembly is attached to the optical bench, which is the interface of the spectrometer and the structure. The assembly consists of a scanning mirror, a depolarizer, relay optics, entrance optics, a Hg calibration lamp, and rotating diffuser plates.

Scanning mirror. This is driven by a compact stepper motor without a harmonic drive. It also has an Eddy current damper, which minimizes the stepper motor jitter caused by fast scanning.

Depolarizer. The instrument has a Lyot type calcite depolarizer, which scrambles the input flux polarization over 0.6 nm spectral width, which is the coverage of one spectral channel. With 18 mm thickness, the depolarizer rotates polarized spectra by 360 degrees in every 0.03 nm. The designed polarization sensitivity is less than 5%.

Entrance optics. These consist of two cylindrical lenses. The square IFOV of 1.8 by 1.8 degrees is converted to the rectangular slit of 0.26 by 1.04 mm. To illuminate the parallel flux on the grating, the aperture stop is placed at the entrance optics.

Table 5-2. Specifications of the polychromator.

FOV	120 deg
IFOV	1.8 deg (20 km at nadir)
Cross-track scan	Stepper motor
Spectral coverage	
Band 1	306- 400 nm (grating spectrometer)
Band 2	432- 452 nm (grating spectrometer)
Band 3	760 nm (filter radiometer)(2 dimensional imager)
Spectral resolution	0.5 nm (sampling interval) 0.6 nm (FWHM)
Signal-to-noise ratio (SNR)	> 40 at 306 nm > 400 at longer than 310 nm
Polarization sensitivity	< 5 %
Depolarizer	Calcite (Lyot type)
Solar irradiance measurement	Sand blasted Al (3) Spectralon (1)
Wavelength calibration	Hg lamp

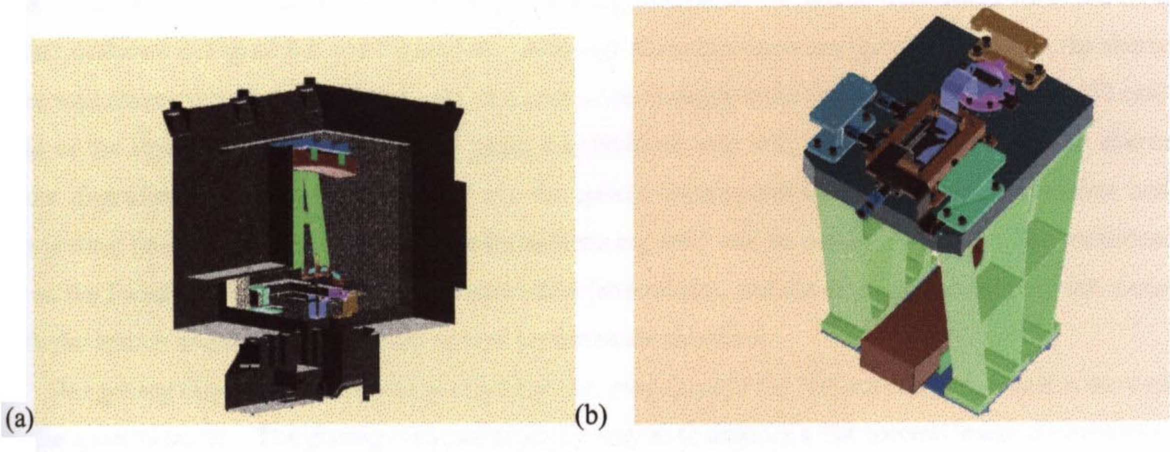

Figure 5-4 The instrument: (a) the outer structure and (b) spectrometer structure .

Cloud detection radiometer. The scene flux is introduced using a scanning mirror and is divided into two parts. The center of the flux is collected at the entrance optics, and the side flux is folded and collected with four small filter radiometers. These radiometers have the same IFOV as the main spectrometer; the IFOV is divided into 5-by-5 pixels using a two-dimensional array detector. The specifications are listed in Table 5-3. The instrument measures the integrated absorption over the $\mathrm{O}_2\,A$ band spectra with a high SNR using the filter radiometers. The signals are less sensitive to the temperature variation than grating spectrometers.

Table 5-3. Specifications of the cloud detection radiometer (band 3).

Type	Filter radiometer
Number of channel and spectral region	4 Ch 1 770.7 nm (weak absorption) Ch 2 764.8 nm (strong absorption) Ch 3 754.7 nm (no absorption) Ch 4 500.0 nm (aerosol detection)
Number of pixels per channel	1 or 5 by 5, 2 dimensional array
Spectral bandwidth	5 nm +/- 1 nm
IFOV	The same as the spectrometer
Detector	Si photo diodes

(3) Optical Design

When designing a polychromator, (1) the flatness of the focus position, (2) the image quality in the dispersion direction over the spectral region, and (3) the image quality in the cross-dispersion direction must be considered. For the design, (1) and (2) have priority to achieve a uniform slit function over the wide spectral range. A Fastie-Ebert type polychromator, which has excellent optical performance in the dispersion direction, is used for wide-range (306-452 nm) continuous measurements. It consists of an entrance slit, a spherical mirror (functions of collimating and collecting), a grating, aberration-correction cylindrical lens, and an array detector as shown in Figure 5-5 and Figure 5-6. Although the optics has an astigmatic aberration, the aberration can be well characterized and modeled. As this aberration is fairly large for band 2 region (432-452 nm) and height of the image at the focus becomes large, a cylindrical lens will be inserted to collect the aberration without degrading the spectral resolution. As the optical components such as the spherical mirror and the plane grating have simple specifications, the manufacturing error can be negligibly small. The performances such as the focus position, the defocus characteristics (aberration), and the alignment sensitivity are measured before the launch and calculated with an optical performance simulator.

The grating dispersion is selected to minimize the image size of the 306 nm channel, which is the weakest over the spectral range. The grating is placed in such a way as to produce a flat spectral image on the focus. In this configuration, the height of the focus image (cross-dispersion direction) becomes larger than the width (dispersion direction). This changes gradually as the wavelength increases, but the distortion in the cross-dispersion direction is still very small. The ratio of the height to the width of the entrance slit can be expanded without changing the detector size. By selecting the aspect ratio of 4, the SNR can be optimized assuming that the detector noise is proportional to the square root of the detector area. The specifications of the optics are summarized in Table 5-4.

Table 5-4. Specifications of the optics.

Entrance optics	Two cylindrical lens
Entrance slit	0.26 by 1.04 mm
Aspect ratio of the slit	1:4
F number	5
Focal length	250 mm
Spectrometer	Fastie-Ebert polychromator
Astigmatic aberration correction	Cylindrical lens for band 2
Grating	2160 grooves/mm
Grating material	Zerodur
Mirror material	Zerodur
Structure	Super invar
Temperature control	23+/-1 degrees C

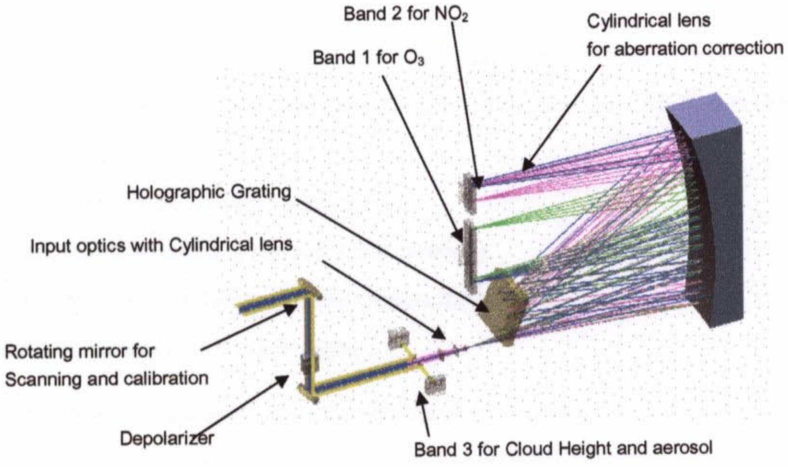

Figure 5-5. Optics layout of the optics.

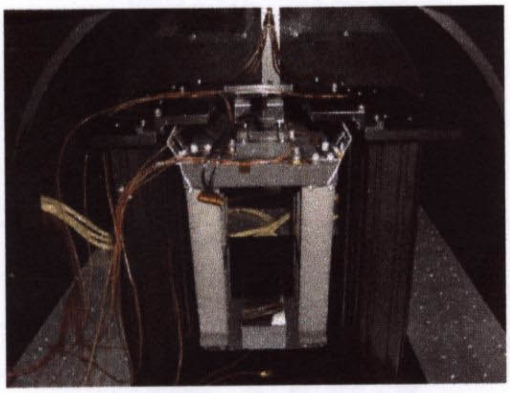

Figure 5-6. View of the engineering model optics during the thermal vacuum test.

(4) Comparison with an imaging spectrometer

The optical throughput can be optimized with the combination of an aspherical cylindrical lenses and optimizing the aspect ratio of the slit. In Table 5-5, comparison of three types of grating polychromators is summarized.

Table 5-5. Comparison of three types of grating polychromators.

	Grating	Spectral resolution	Spectral coverage	Optical throughput	Scanning for imaging	Instrument function
Fastie-Ebert (Czerny-Turner)	Plane	High	Wide	Moderate-high	Mechanical	Simple (Uniform)
Echelle Littrow mount	Echelle	Very high	Limited	High	Mechanical	Must be modeled
Imaging spectrometer	Flat-field aberration corrected cone cave	Moderate	Moderate	Moderate	Electrical	Must be modeled

(5) Detector

A CMOS type Si array detector has been custom-designed for UV-spectrometer. Its specifications is shown in Table 5-6 and, respectively. In comparison with a CCD detector, a CMOS detector has the following advantages.

(1) Manufacturing capability of large area pixels,

(2) Very low dark current (cooling device is not needed),

(3) Flexible CMOS amplifier design (easily customized), and

(4) High quantum efficiency in the UV region.

Table 5-6. Specifications of the custom-designed detector.

Type	Si-CMOS
Number of pixels	Band 1 306 - 400 nm (188 ch) Band 2 432 – 452 nm (40 ch) 2 for dark current monitor
Operation	Instrument temperature
Detector size	Width (Pitch) 0.26 mm Height 1.42 – 3.42 mm
Integration	30 msec
Amplifier	CTIA (Capacitive Tran Impedance Amplifier)
Sampling	CDS (Correlated Double Sampling)
Gain	2 levels 0.1 pF and 1 pF
Offset	Stabilized circuit for each channel
Saturation	Extraction circuit for each channel

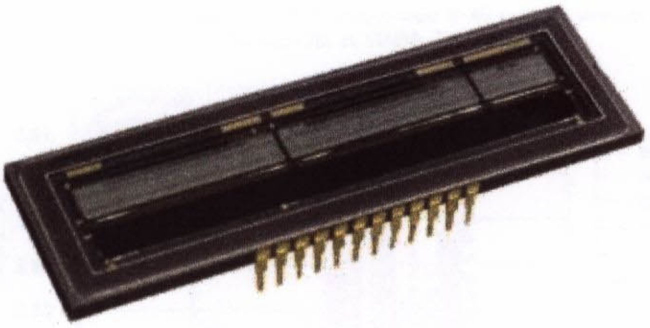

Figure 5-7. View of the detector with ceramic package.

The detector shown in Figure 5-7 has 232 Si-pixels and C-MOS amplifiers for continuous spectral coverage and 2 additional ones for dark level monitoring. Each pixel has a different height depending on image size in the cross-dispersion direction in order to collect as much input flux as possible. The height is 1.42 mm for the shortest wave channel and 3.42 mm for longest wave channel. The thin passivation is carefully designed to maximize the UV quantum efficiency, and is more than 60% between 300 and 350 nm.

Each pixel is directly connected to its own pre-amplifier, which is mounted on the same tip. Each channel has two gain levels, which can be selected depending on the input scattered light level. The amplified signals are multiplexed and transmitted to the data formatter. The gain levels of the CMOS pre-amplifiers are designed based on the simulated input spectral radiance. Thus, the array detector design is optimized to achieve high SNR.

This CMOS detector has passed the radiation tests; the single event latch-up by charged particles and the total-dose by gamma rays. The test data are presented in Figure 5-8 and Figure 5-9. The strong output appeared at the pixels where charged particles were hit during the radiation, however, the pixels recovered fully after the test as indicated in Figure 5-8. Gamma rays are radiated on the detector for total-dose test. The offset level had increased and some parts were saturated due to large dark current after the radiation test. However, the offset level has decreased gradually due to annealing effect. The radiation level is accelerated to simulate the accumulated radiation during the 3 years mission and save the radiation duration. The radiation level is sufficiently small to recover by annealing effect for real operation in orbit. The detector for the flight use will be integrated in a large ceramic package, which is the hybrid of the detector arrays (band 1 and 2) and their CMOS readouts. It is installed with the housing of super Invar, which is expected to decrease the radiation level.

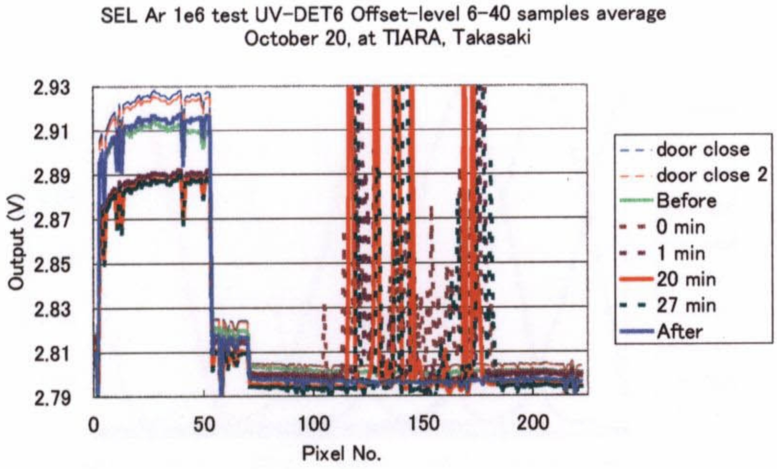

Figure 5-8. Detector output during the radiation hardness test of high energy charged particles (Ar) (single-event latch-up test) at the Takasaki Radiation Chemistry Research Establishment of the Japan Atomic Energy Research Institute (JAERI) on 20 October 1998.

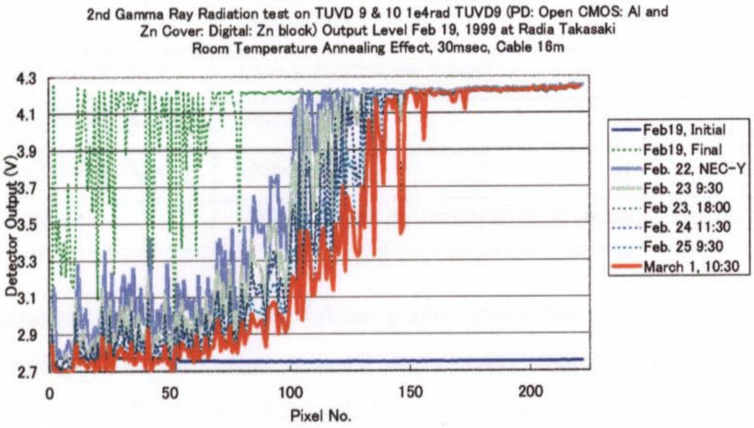

Figure 5-9. Dark level annealing effect after the total-dose test of gamma ray radiation (Co) at Radia Industry Co., Ltd. on 19 February 1999.

5.5. Pre-launch and Onboard Calibration

Pre-launch spectral calibration. The slit function represents the spectral response of the instrument. The shape of the slit function is assumed to be neither changed nor degraded after the launch, so the shape of the function has to be carefully measured and modeled before the launch. Figure 5-10 shows the slit function of the laboratory model measured with a 1 m monochromator and a Xe lamp light source. The slit function is also modeled with the optical performance simulator CodeV. As the result shows, the instrument has a uniform slit function. This characteristic is especially important for the pair method. The absolute level of the slit function will be calibrated with a well-calibrated light source. The pre-launch cross-calibration of other space-borne instruments using the transfer light source will be also considered.