CCD FINE SUN SENSOR FOR SCIENTIFIC SATELLITES

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ABSTRACT

A two-dimensional fine sun sensor using linear charge coupled devices (CCDs) is described. The sensor has a wide rectangular field of view of (±50°) x (±50°) around its normal, with the angular resolution of 0.025 degrees. The sensor has been developed as one of applications of CCDs to spacecraft and is to fly for the first time on ASTRO-C, an X-ray astronomy research satellite which also incorporates onboard a set of star trackers using area CCDs. Through the performance and environmental tests on the sensor unit, it has been qualified to meet all the requirements. The current development at ISAS of a CCD sun sensor with higher accuracy is also briefly mentioned.

Keywords; Attitude sensor for spacecraft, Sun sensor, Charge coupled device, Angular resolution, Performance and environmental tests.

1. INTRODUCTION

ASTRO-C, an X-ray astronomy satellite, is a 3-axis controlled one with bias-momentum stabilization. Its mission is to investigate the nature of extra galactic X-ray sources through the observation by large-area proportional counters. For this purpose, more accurate attitude sensors are required for attitude control and determination as compared with the former scientific satellites of ISAS. With this in mind, ISAS has been developing star trackers (see ref. (1)) and sun sensors using charge coupled devices (CCDs) as the image detectors.

The CCD sun sensor developed for ASTRO-C and later uses is a two-axis sensor that is tentatively called non-spin type solar aspect sensor (NSAS). In contrast to other sun sensors developed recently by using CCD as the detector, (see ref. (2) ∿ (4)) the feature of NSAS is employing linear CCDs as a means of obtaining high angular resolution for wide range of FOV. As a target specification, we set that the angular resolution be 0.05° and the field of view (±50°) x (±50°).

2. PRINCIPLE OF MEASUREMENT

The sensor head of NSAS consists of two optical units. The optical components of each unit are an ND filter and a prism with a slit aperture, a band-pass filter, and a linear CCD as a detector. The slit is arranged perpendicular to the CCD line sensor.

After passing through the slit, the sunlight is refracted by the prism and reaches CCD pixels behind it. The intensity distribution of the sunlight over the CCD by the diffraction at the slit can be evaluated by a simulation. Features of the simulation software we have developed are described below.

- o The calculation of the diffraction image by the slit is made by Fresnel integration. The calculation involves the range of the transmission wavelength of the band-pass filter, CCD spectral sensitivity, and the size of the sun (0.53°).
- o The optical parameters (slit width, refractive index and thickness of the optical components) and the sunlight incident angle can be arbitrarily set.

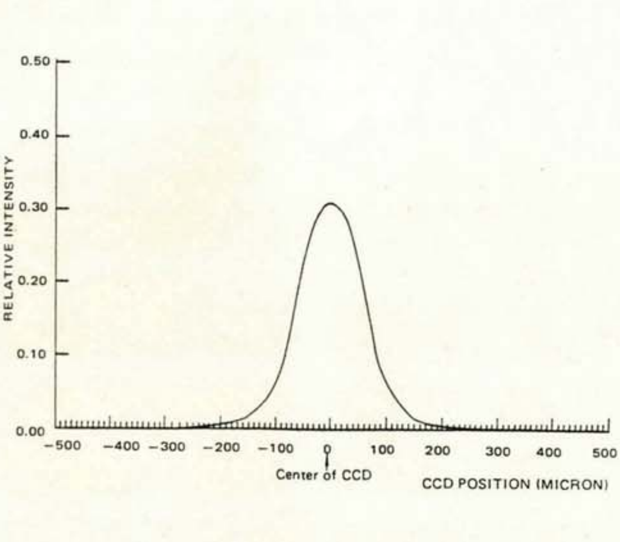

Figure 1 Intensity Distribution on the CCD

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o The output signals from the CCD can be synthesized based on the calcurated diffraction image.

The optical parameters such as the slit width have been designed to be the optimum values by means of this simulation. Fig. 1 shows the intensity distribution over the CCD when the slit width is 150 μm. According to this simulation, the diffraction image is independent of the solar incident angle and its intensity distribution is symmetrical within the NSAS field of view. So the solar incident angle can be derived from the calculation of the center position of the distribution measured by the CCD.

The NSAS coordinate system is shown in Fig. 2. The two optical units constitute an X-axis sensor and a Y-axis sensor. The position data, x and y, measured by each CCD and the angular components, X and Y, projections of the solar incident angle onto the X and Y axes, have the following relationships.

$$x = (1/L)\sum_i \frac{Hi \cdot \tan X}{\{Ni^2+(Ni^2-1)(\tan^2 X+\tan^2 Y)\}^{1/2}} + x_c \quad (1)$$

$$y = (1/L)\sum_i \frac{Hi \cdot \tan Y}{\{Ni^2+(Ni^2-1)(\tan^2 X+\tan^2 Y)\}^{1/2}} + y_c \quad (2)$$

where Ni = refractive index (i = 1 to 4)
Hi = thickness of the optical component (i = 1 to 4)
L = length of CCD pixel (0.014 mm)
xc, yc = address of the pixel at the CCD center

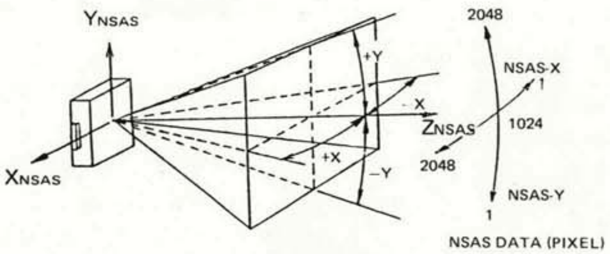

Figure 2 NSAS Coordinate System

The number of the pixels of the CCD is 2048. The angular resolution of one pixel with ±50° FOV is shown in Fig. 3. The angular resolution is about 0.05° per pixel and nearly constant over the entire FOV range because of the prism inserted between the slit and CCD. The band-pass filter is used for the purpose of minimizing the effect of the dispersion by the prism.

3. PERFORMANCE

NSAS consists of a sensor head and an electronics. The external view of a flight model of NSAS is shown in Fig. 4. The performance of NSAS are presented in Table 1.

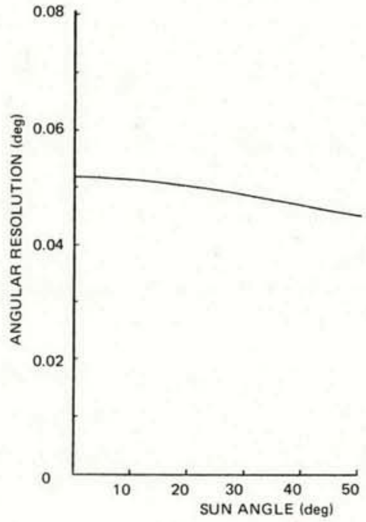

Figure 3 Angular Resolution per Pixel

Table 1 Performance of the NSAS

FOV	±50° x ±50°
Resolution	0.025°
Data	16 bits/axis o 12 bits: data o 4 bits : flags (status)
	Sun presence signal
Data rate	0.5 sec
Operating mode	(1) measure mode (2) caliblation mode (4096 CCD data)
Size	Sensor head: 116 x 76 x 40 Electronics: 180 x 130 x 90 (unit:mm)
Weight	Sensor head: 0.42 kg Electronics: 1.6 kg
Power consumption	2.5W

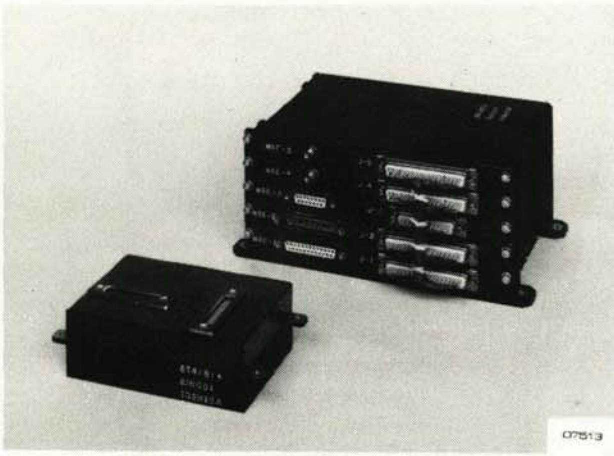

Figure 4 NSAS Flight Model

3.1 Sensor head

The sensor head consists of two optical units, namely, an X-axis sensor and a Y-axis sensor whose slit arranged perpendicular to the other, CCD drive circuits, and preamplifier circuits that amplify the sunlight signal from the CCD to the appropriate level. Structure of the sensor head is shown in Fig. 5.

Features of the sensor head are shown in Table 2.

The linear CCD detector used is TCD102C-1, with 2048 pixels, manufactured by TOSHIBA. The size of a pixel is 14 μm x 14 μm. The integration time is 8 msec.

The support of each optical component is made of titanium to minimize the effect of temperature variation on the accuracy of NSAS, so that the coefficient of the dilatability of titanium is nearly equal to that of the CCD ceramic package.

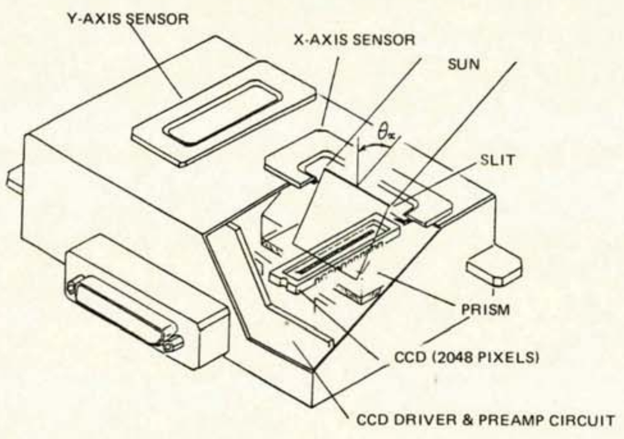

Figure 5 Structure of the Sensor Head

Table 2 Features of the Sensor Head

Sensor head	2 optical units
Optical components	
(1) ND filter	Transmittance : 1/100%
(2) Prism	Quartz glass Slit width: 150 μm
(3) Band pass filter	Center wave length and band width: 530 nm ±60 nm
Detector	TCD102C-1 2048 pixels Pixel size: 14 μm x 14 μm Integration time: 8 ms

3.2 Electronics

The block diagram of the electronics is shown in Fig. 6. The electronics unit is constructed with the following units.

3.2.1 Signal processing unit. The sunlight signal from the CCD, amplified by the preamplifier, is further amplified by the main amplifier after the dark voltage of the CCD is eliminated. The gain is selectable among 16 levels, and can be finely adjusted by the ground command in Manual mode so that the peak voltage of the signal after amplification is constant indepedent of the sun angle. The gain setting can be performed in either AUTO or MANUAL mode. In AUTO mode, the optimum gain can be always selected automatically according to the signal level from the CCD (AGC).

The amplified signal is compared with the preset discri-level by the discriminater. As shown in Fig. 6, the address x1, x2 of the pixels whose signals exceed the discri-level is derived, and the address x of the pixel corresponding to the center of the sunlight distribution is calculated as $x = (x1 + x2)/2$ by using the counters. Thus the data resolution is determined by 1/2 pixel (0.025°).

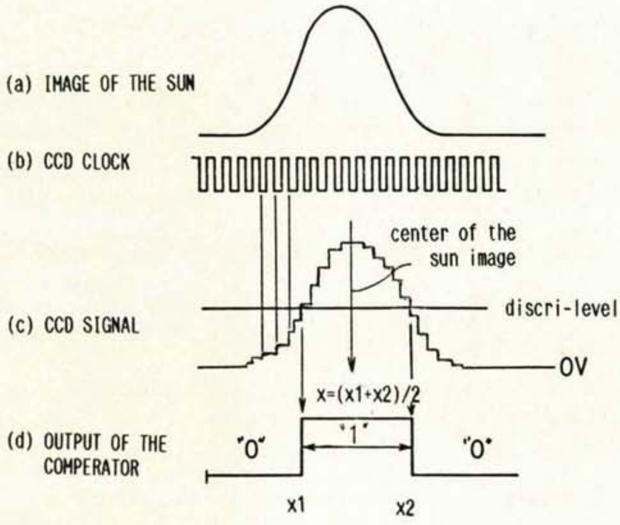

Figure 7 Calculation of the Sun Angle

The discri-level is selectable among 4 levels by the ground command in Manual mode. The level setting can be also performed in either AUTO or MANUAL mode. In AUTO mode, the level can be automatically changed in successive order within one subframe (4 sec) in step with the updating of the NSAS data. By averaging these data, the center of the sunlight distribution can be determined more accurately.

In addition, a different discri-level for the sun presence signal to the attitude control electronics (ACE) is set to check for the presence of the sun within the field of view.

Data acquisition is performed every 8 msec, which corresponds to the CCD integration time.

3.2.2 Control unit. This unit contains a command circuit, two CCD drive/timing circuit, the AGC circuit mentioned in 3.2.1, and a calibration mode circuit.

The parameters for the signal processing circuits of each sensor can be independently set by the block command.

The CCD drive/timing circuits are provided for each CCD of the X-axis and Y-axis sensor.

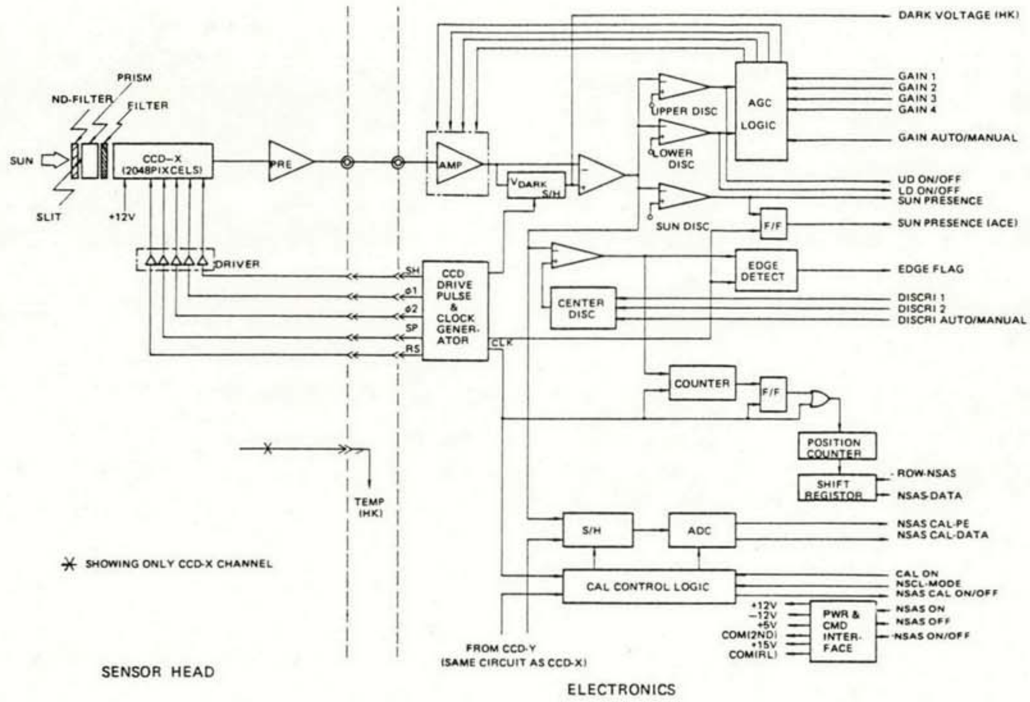

Figure 6 Block Diagram of NSAS

3.2.3 Data output unit. The NSAS data is a combination of status flags and the sun angle data that indicates the address of the pixel corresponding to the center position of the sun image distributing over each CCD of the X-axis and Y-axis sensor. These data are 16-bits and output to the data processor (DP). The sun angle data are 12-bits and the LSB is 1/2 pixel. The flags comprise 4 bits; 1 bit of sun presence, 1 bit of edge flag that indicates whether the sun is at the edge of the FOV and the image is located at the edge of the CCD, 2 bits of upper and lower discrimination that indicate whether the peak level of the signal after amplification is within the discri range, that is, between the preset upper and lower limits.

The data is transmitted every 8 frames (0.5 sec) alternately for X-axis and Y-axis.

A calibration mode setting by the ground command is provided as an additional function. In this mode, all data from the CCD pixels is converted into digital form, and a total of 4096 data, 8 bit per pixel, is output to the data processor. This function enables not only checking of CCD operation, but observation of detailed sunlight distribution, so more accurate angle detection based on centroid calculation.

4. TESTS

4.1 Performance tests

In the performance tests, verifications of NSAS angular resolution and accuracy have been performed by using a solar simulator and a 2-axis gimbals. In addition, a field test has been performed for the purpose of the gain check by the sunlight.

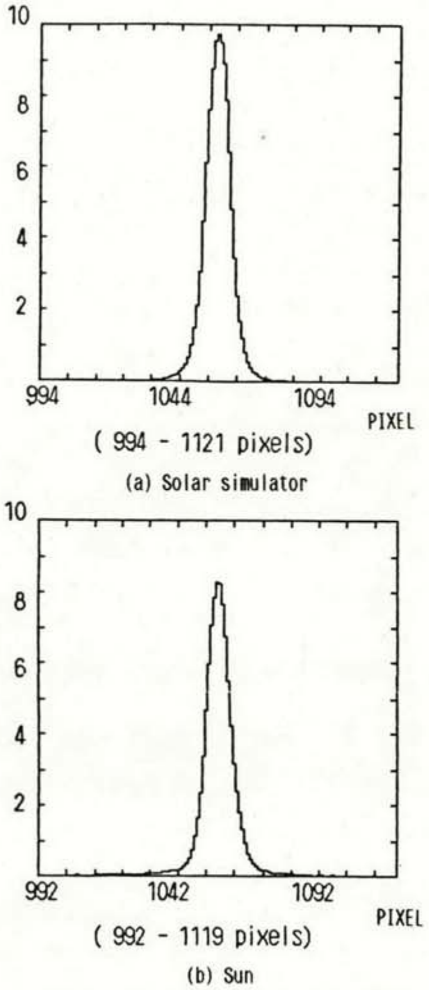

Figure 8 NSAS Calibration Data

The solar simulator was developed for the test, which has a 30 cm of aperture, 0.53° of parallelism, 0.017 solar of intensity. A light sources is a xenon lamp. The diffraction image by the simulator is shown in Fig. 8(a) obtained in NSAS calibration mode and the diffraction image of the sunlight measured in the field test is shown in Fig. 8(b). These intensity distributions are in good agreement with each other, which shows the excellence of the simulator characteristics. In addition, the test results are also in good agreement with the estimation based on the simulation shown in Fig. 1.

The verifications of the output transfer characteristics and angular resolution were performed with the sensor head mounted on the 2-axis gimbals. The solar simulator was used as the light source. The test results show that 1/2 pixel, that is, 0.025° of angular resolution is realized. An example of the test results is shown in Fig. 9.

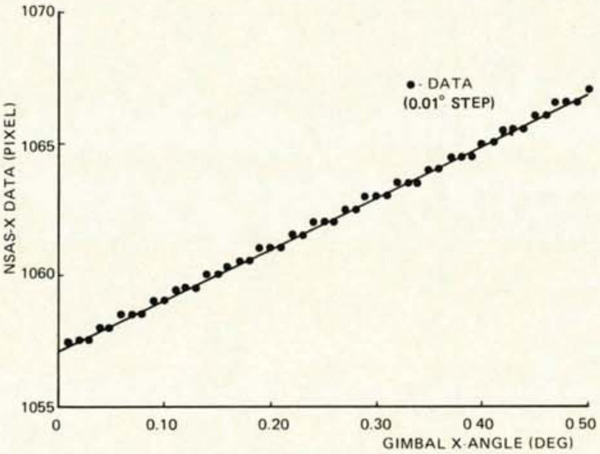

Figure 9 Transfer Characteristics of NSAS

Further, we performed centroid calculations using the data obtained in calibration mode (Fig. 8). It was confirmed from this calculation that the angle detection can be made with a high accuracy - the accuracy of the position detection by the centroid calculation is 6/100 pixel (3σ), that is, 0.003° (3σ) in terms of angle.

In normal satellite operation, however, this mode is not used because a vast amount of data must be handled and data transfer takes much time.

4.2 Environmental tests

The following tests were performed in accordance with ISAS requirements to verify the NSAS performance.

(1) Random vibration test
  - o Thrust axis 20 to 2000 Hz; 14.86 Grms (30 sec)
  - o Cross axis 20 to 2000 Hz; 19.78 Grms (30 sec)

(2) Shock test
  - o Thrust axis 25 G; 10 msec (2 trials)

(3) Thermal vacuum test
  - -30 to +60°C; < 10^{-5} torr

(4) EMC test

The result of misalignment before and after the test is 1 arc min or less.

5. APPLICATIONS AND FURTHER DEVELOPMENT

This type of sensor with the wide FOV will be used as the standardized sun sensor of ISAS' scientific satellites such as EXOS-D scheduled for launch in 1989. For missions having more stringent performance requirement for attitude determination and control (e.g. SOLAR-A, a high energy solar physics mission in 1991), another type of CCD sun sensor is also being investigated along with the application of the principle of operation thus far.

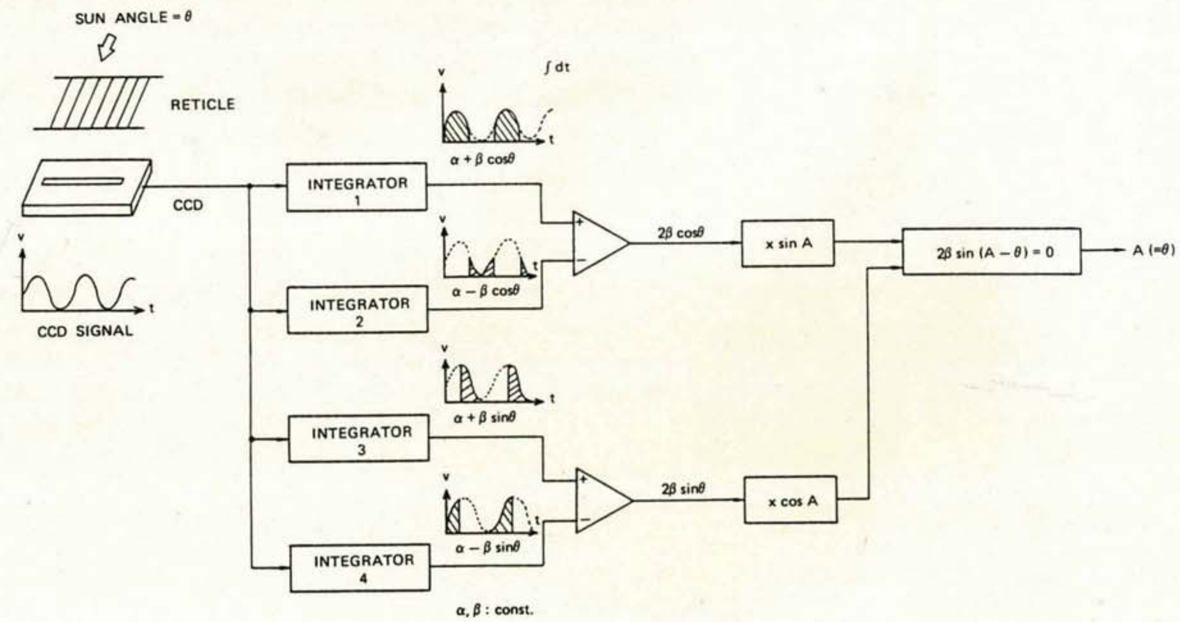

Figure 10 Basic Electronics Function

The scheme is based on the angle detection by the phase comparison of CCD output for the sensor head configuration such as shown in Fig. 10. Basic electronics function is also shown in Fig. 10. The result of the analysis and the preliminary experiments on laboratory setup is promising. The present goal on accuracy of this sensor is set to 18 arc sec (3σ) for the sensor FOV of $\pm 2°$.

6. CONCLUSION

The performance of NSAS has been verified by tests. As the result, the angular resolution of 0.025° for ($\pm 50°$) x ($\pm 50°$) FOV has been confirmed. Based on the experience gained by the development of NSAS, a higher accuracy CCD sun sensor is being developed.

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