Visible Auroral Television Camera for the Sounding Rockets of S-310JA-8, -9, and -10

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In order to study the detailed structure of auroral light emissions and related precipitating auroral particles, a new type of a low-light-level visible auroral television (VAT) camera was developed and installed on board three sounding rockets, S-310JA-8, -9 and -10. They were launched in 1984 from Syowa Station, Antarctica, into the three different types of aurora. The VAT had a capability of taking one synthesized still picture (100 (H)×101 (V) array) every 4.2 sec from the spinning rocket in downward looking. This camera was rotated in an opposite direction to the rocket spin by using an auto-feedback loop circuit with an angular rate sensor, a kind of a rate-gyroscope. Clear auroral images were obtained; the rotational drift rate of the picture was from about 1.1 to 0.1 degree/sec in each flight.

1. Introduction

The morphological study of visible auroras associated with the magnetospheric substorms has made great strides since the global auroral images were photographed from space. Especially the ISIS 2 (e.g., ANGER *et al.*, 1973; LUI *et al.*, 1977) and the Defense Meteorological Satellite Program (DMSP) spacecrafts (e.g., ROGERS *et al.*, 1974; EATHER, 1979; MENG *et al.*, 1979; MENG and LUNDIN, 1986) have been widely utilized. In recent UV imageries by KYOKKO (KANEDA, 1979), the Dynamic Explorer 1 (FRANK *et al.*, 1981) and the VIKING satellite (ANGER *et al.*, 1987), they provide plenty of data together with simultaneous auroral particle data for correlative investigations. Ground-based auroral imaging techniques such as an all-sky camera (e.g., WINNINGHAM *et al.*, 1973) and a TV camera (e.g., ONO *et al.*, 1987b) also make it possible to study a relation between a visible auroral development and auroral particles observed by the satellite. Changes in auroral particle energy spectrum and auroral display associated with substorm developments, however, have not been satisfactorily clarified yet, since an active aurora at the substorm expansion phase moves and changes its light emission intensity so rapidly that high spatial and temporal resolutions are required. For quantitative discussions with time variations of precipitating particle energy spectrum and auroral emissions, it is essential to

measure these quantities along the geomagnetic field line.

Three sounding rockets, S-310JA-8, -9 and -10 were launched from Syowa Station, Antarctica, in order to investigate the causality between auroral particle energy spectra and the corresponding auroral light emissions at various stages of polar substorm activities (EJIRI *et al.*, 1988a). A new low-light-level visible auroral television (VAT) camera was developed and installed to take an auroral picture downwards from the spinning rockets. This VAT camera adopted a CCD (charge coupled device) area-sensor with an image intensifier as an image detector for snap shot imaging, and data were transmitted by PCM telemetry system through digital signal processing circuits. The solid state device CCD is now widely adapted in space use (e.g., TORR and DEVLIN, 1982). To take a still picture, an auto-feedback loop circuit was designed to cancel the rocket spinning motion. This paper describes the principles of VAT system and the observed examples of auroral images as well. The relations with other physical parameters such as electron density, electron temperature and detailed particle energy spectrum observed simultaneously on board the same rocket are presented by EJIRI *et al.* (1988b).

2. Visible Auroral Television (VAT) Camera System

Three sounding rockets, S-310JA-8, -9 and -10, were equipped with identical instrumentation. It consisted of ESP (a quadrispherical electrostatic spectrometer and a magnetic spectrometer) for particle energy spectrum measurements, NEL (an impedance probe) for electron number density, LP (a Langmuir probe) for DC and AC currents, TEL (an electron temperature probe), and VAT camera with PHO (a photometer). An exterior view of the payload sensors with their construction is illustrated in Fig. 1. After the nose-cone jettison at around 70 km in altitude, they were exposed into space, and the probe deployments (NEL, LP, TEL) and a camera extension (VAT, PHO) were initiated by an electrical programable timer (EPT).

2.1 Optical and electrical systems

The auroral images were taken in a visible range from about 400 to 800 nm. A charge coupled device (CCD: TCD 203C) with an image intensifier (II; ITT F4767) was used as an image detector. The size of CCD sensitive area is 8.36 mm (H: Horizontal) $\times$ 6.37 mm (V: Vertical), and total pixels are 400 (H) $\times$ 500 (V), effective pixels being 380 (H) $\times$ 490 (V). An FOV (field of view) of this imager was 53.4° (H) $\times$ 33.9° (V).

As is shown in Fig. 2, 4×4 pixels of original image were added to make one element of a sub-picture which consists of 100 (H) $\times$ 101 (V) array. The resultant signals are fed to a dual sample and hold amplifiers, whose output signal is proportional to the input and free from the drift due to the device temperature variation (ONO *et al.*, 1987a). After 8-bit A/D conversion, 16 sub-pictures (one picture per 262.5 ms) are successively superposed to make one picture per 4.2 sec, whose one pixel signal has expanded to 12 bits. It is again compressed to 8 bits through the ROM compression circuit. The words for synchronization (FAF3208F)_H and 12 dummy

Payload of S-310JA-8, 9, 10

Fig. 1. An exterior view of the payload sensors.

Fig. 2. Signal flow diagram of VAT system (see text).

words are added to the top of the picture data, and all of them are converted from 8-bit parallel format to 16-bit serial. Due to the limitation of bit rate (14.4 kbps) of the PCM telemetry, one picture is transmitted every 5.62 sec though the total exposure time of 16 sub-pictures is 4.2 sec.

The lens used in this camera had a F-number f (inverse of an aperture ratio) of 2.8. The illuminance E of an object through a lens is given on the optical axis by

$$E = \frac{\tau \pi L}{4f^2} \text{ (lx) ,}$$

where τ is transmissivity (transmission factor) of a lens, and L ($\text{lm}/\text{m}^2/\text{sr}$) luminance of the object. The photometric calibration of VAT was carried out with same intensification by II as in flight condition, putting an interference filter of 557.7 nm. This CCD was a sensitivity of 135 mV/lx for the exposure time of 16 ms and a dark current of 1.5 mV at 25°C (one half every -7°C). The 8-bit full scale (255) of the output corresponded to the input brightness of a screen of 0.0213 lx, 0.0551 lx, and 0.0213 lx for S-310JA-8, -9 and -10, respectively. Since this flight experiment was the first attempt for VAT to image an aurora, it was operated in total light imaging mode for simplicity. Because the high-voltage to the image intensifier which determines the amplification factor was not monitored by the telemetry, it is now difficult to discuss the exact absolute value of the image intensity. Instead of II amplification monitoring, photometer (PHO) was installed to obtain an absolute intensity of auroral brightness at the center of the TV view field in one of principal auroral emissions, $N_2^+ 1 \text{ NG (1, 0) band (427.8 nm)}$.

The PHO output current I is expressed as

$$I = (J/4\pi) \cdot \alpha \cdot S \cdot \Omega \cdot \eta \cdot \eta' \cdot q ,$$

where J is an apparent emission rate of aurora ($\text{photons}/\text{cm}^2 \cdot \text{sec}$), α an anode current amplification factor of a photomultiplier, S an aperture area, Ω a solid angle of FOV, η quantum efficiency, η' filter transmissivity and q a charge of electron (1.6×10^{-19} coulomb). Applied design parameters to the above equation, i.e., $\alpha = 10^6$ (photomultiplier; R647), $S = 7 \text{ cm}^2$ (an aperture of the lens being 32 mm ϕ), $\Omega = 0.03$, $\eta = 0.25$ and $\eta' = 0.6$, then we have $I = 4 \times 10^{-9} \text{ A}$ for $J = 10 \text{ R (Rayleigh)}$. Since the dark current of this photomultiplier was $5 \times 10^{-9} \text{ A}$, this means a sensitivity of 10 R is obtained for $S/N \sim 1$. Therefore, the dynamic range was set to be from 10 R to 100 kR, using two channels, PHOH (high gain) and PHOL (low gain), separated by 20 dB. A frequency response of the amplifier was about 110 Hz (-3 dB). Interference filters with following spectral characteristics were used; maximum transmission wave length $\lambda_{\text{max}} = 429.5 \text{ nm}$, maximum transmissivity $\eta' = 0.64$, transmission full width at half maximum $\Delta\lambda(1/2) = 5 \text{ nm}$ for S-310JA-8, $\lambda_{\text{max}} = 428.5 \text{ nm}$, $\eta' = 0.60$, $\Delta\lambda(1/2) = 5 \text{ nm}$ for S-310JA-9, and $\lambda_{\text{max}} = 428.0 \text{ nm}$, $\eta' = 0.64$, $\Delta\lambda(1/2) = 5 \text{ nm}$ for S-310JA-10. The photometric calibration of the total system of PHO was carried out with the spectral-calibrated incandescent light bulb and the combination of several ND filters. The

maximums (8-bit full scale) of the output of PHOH channel were 10.75 kR, 13.60 kR and 10.28 kR for S-310JA-8, -9 and -10, respectively. The dynamic range more than 60 dB was confirmed for the dark current (no light input). The FOV was also measured to be about 10.8° in full angle.

2.2 Servomechanism of the system

A camera deployment from the rocket body is shown in Fig. 3. The television picture was taken downwards from the spinning rocket. In order to obtain a still picture, the camera was rotated to compensate for the rocket spin motion by using an angular rate sensor (ARS). By this despinning the camera view remain unchanged in the earth fixed frame of reference. The shadows of the rocket motor and rear fins can be eliminated by integrating sixteen images over 4.2 sec to make one picture, since in the picture the shadows rotate with the rocket spin rate of 0.5 ± 0.1 Hz.

Figure 4 shows a servomechanism diagram used in this system. Just prior to the rocket firing, "CAL" signal was sent to detect and to hold (in the A/D and D/A circuits) the level of the ARS for compensating the level drift.

The ARS was the "tuning fork" ARS-C131-1A (Watson Corp.), and the DC servo-motor with a tacho-generator was the 28 GL18-219 (Portescap Corp.).

The required specification is as follows.

Controllable range of despin	0.2 Hz $\sim$ 2.0 Hz
Setting time	0.5 s $\sim$ 1.05 s
Accuracy of rate setting	$\pm 0.35^\circ$ / revolution at 0.5 Hz
Despin direction	CCW (rocket spin CW)
Motor load weight	1.5 kg
Operating temperature	$-20 \sim +50^\circ \text{C}$

Figure 5 shows a signal flow diagram equivalent to Fig. 4. The difference between the rocket spin rate " ω_r " and the camera despin rate " ω_c " is detected by the ARS, and the output " e " is integrated by the phase compensation circuit (PHASE COMP). The

Fig. 3. A photograph of the camera. A counter-balance weight is in the right portion of the picture, which keeps the mass center of the camera system on the rocket spin axis.

Fig. 4. Servomechanism diagram of the system.

Fig. 5. Functional signal flow diagram of the servomechanism.

output signal from the tacho-generator is also fed to the motor main amplifier (AMP). This loop forms a negative feed-back circuit itself. The transient response of this system to a step input, $\mathcal{L}(1)=1/s$, where $\mathcal{L}$ is a Laplace transformation and s a parameter, is examined by a model simulation and by applying an external input to the actual system. Both results are fairly well agreed. (See Appendix). The camera rotation phase relative to the rocket body was monitored on board by using an LED positioning sensor, a signal of which was transmitted to the ground.

3. Results of Three Sounding Rockets

Three sounding rockets, S-310JA-8, -9 and -10, were launched from Syowa Station, Antarctica, at 19:27:01 (UT) on April 4, 1984, into active auroral arcs at a substorm expansion phase, and at 22:14:10 (UT) on May 3, into quiet stable arcs at a pre-breakup phase, and at 23:17:13 (UT) on May 28, into a diffuse aurora at a post-breakup phase, respectively. These three observations were designated as to AURORA I, II and III. The three rockets were flown northward along the geomagnetic meridian (launching angles; 313° in azimuth and 80° in elevation) in order to let the rocket spin axis be aligned nearly along the geomagnetic field line. The detailed flight conditions and the geophysical ground-based observation data together with the rocket trajectories are given by EJIRI *et al.* (1988a). With the aid of a Yo-Yo despinner the spin rates for three rockets were reduced from the initial rate of about 3 Hz to 0.43 Hz, 0.54 Hz and 0.54 Hz with precession half angles of 11° (a period of 450 sec), 22° (310 sec) and 17° (350 sec), respectively. Note that the blurring of the VAT image due to the motions of these precessions is negligible, i.e., within one pixel.

3.1 Instrument performance

The VAT systems with PHOs for three sounding rockets were perfectly operated. Sequential still pictures taken by the VAT showed specific auroral emission changes for distinctly different types of auroras.

“CAL” signal was sent to set a level of the ARS at 50 s prior to the rocket firing, and the angular rate sensor (ARS) was started by the electrical programable timer (EPT) to follow the rocket spin motion at $X+47$ s where X indicates a rocket firing time. The relative position of the VAT picture every one rocket spin, $\theta(t)$, with respect to the rocket fixed frame was monitored and delineated in Fig. 6. The error of the servomechanism system is expressed by the difference between the actuating signal ω_T and the output ω_C ;

$$(\pi/180) \cdot d\theta(t)/dt = \omega_T(t) - \omega_C(t) .$$

From the observed curve, the time derivatives of $\theta(t)$ are deduced to be nearly equal to $+0.52^\circ/\text{s}$, $+0.13^\circ/\text{s}$, and $-1.06^\circ/\text{s}$ for S-310JA-8, -9 and -10, respectively. A value of $0.5^\circ/\text{s}$ corresponds approximately to the blurring of two pixels at the edge of the picture.

The VAT cameras for three rockets were extended at $X+59$ sec, $X+54$ sec and $X+54$ sec, respectively, and they took about 5 sec for full extension. Therefore, observations were carried out from the altitudes of about 87 km, 80 km and 80 km, respectively; no clear auroral images were taken in initial few pictures, which might contain the scattered lights from the atmosphere and ground surface below the rocket.

Fig. 6. Observed angular drift motions of the VAT. X is a rocket firing time.

3.2 Auroral images taken by the VAT camera

For each flight, one typical example of auroral images is illustrated in Figs. 7(a)–(c), (a) active auroral arcs (the downward looking image from S-310JA-8; the rocket altitude of about 186 km at $X+163.0$ to 167.2 sec), (b) stable arcs (S-310JA-9; about 202 km at $X+205.0$ to 209.2 sec), and (c) diffuse auroras (S-310JA-10; about 207 km at $X+224.2$ to 248.4 sec). Note that the color scale of Fig. 7(b) is changed from (a) or (c) in order to enhance the arc. The intensity of red level in (b) corresponds to that of the green portion in (a) and (c). In order to interpret the shape of the image taken by VAT system, we have to determine the relative distance and view angle between the aurora and the camera. Since the measured emission intensity is an integrated one along the line of sight and the auroral emissions are distributed along the geomagnetic field line, it might be inappropriate to assume a fixed height for auroral emission. However, many observations and model calculations have revealed the predominant concentration of auroral luminosity just above the lower border with ordinary auroral forms, then it would be plausible as a first approximation to assume auroral emission at a fixed altitude. The coordination of image data is possible with fair ease, on the basis of this assumption by the aid of the angle $\theta(t)$, rocket trajectory and other on board attitude sensor data. Supposing the auroral

emission to be at 110 km in altitude, the widths of the center and the lower left arcs in (a) are calculated to be about 35 km and 9 km. As for the arc in (b), it is about 1.8 km in the narrow portion extending eastward and 6.5 km in wide center portion of the arc. The structured auroral emission can not be identified from the all-sky picture (EJIRI *et al.*, 1988a) in the case of (c), whereas the onboard auroral television camera revealed fine patchy structures of the diffuse aurora. There is one intense patch travelling at the edge of aurora from west to east. The data taken by the PHO and comparisons with VAT data are presented by EJIRI *et al.* (1988b).

Previously an auroral emission height is assumed to be at 110 km in altitude. To test this assumption, an all-sky picture taken at Syowa Station and auroral image by VAT are combined as the stereoscopic observation of aurora. Figure 8 shows in the left the former (19 h 29 m 40 s, April 4, 1984; 7 sec exposure) and in right the latter (the same as Fig. 7(a)) assuming auroral emission height at 110 km. Both are expressed in the identical polar coordinates (a center is the zenith of Syowa Station, and a radial distance from it denotes the zenith angle with a solid circle at every 30°). The basic arc structures in both are similar, but the details are fairly different mutually, in spite of almost simultaneous shots. Though taking into consideration that both are obtained by independent instruments different in sensitivity, spectral response and resolution, it seems recommended that the height distribution of auroral emission should be introduced in interpretation of the detailed comparisons of these data.

4. Conclusion

A new visible auroral television (VAT) camera was successfully developed and installed to three sounding rockets of 25th wintering party of Japanese Antarctic Research Expedition in 1984. They were launched from Syowa Station, Antarctica, into different types of aurora corresponding to pre-substorm, substorm expansion and post substorm phases. The VAT camera performance during the rocket flights was complete as designed, and successive fine auroral images every 5.62 sec were obtained.

Besides UV imaging with a revised model of KYOKKO VUV optics (KANEDA *et al.*, 1977), monochromatic visible (557.8 nm) imaging, a satellite version of VAT, is newly nominated to EXOS-D satellite which will be launched in 1989. Both UV and monochromatic images with high spatial resolution (376 (H)×244 (V) array) will be taken at the rate of a shot every 8 sec. This rate is determined by the spin motion of the satellite. Though the optical system is different, the image-pickup and its signal processing systems are basically the same as this VAT camera, i.e., II+CCD, and a dual sample and hold circuits free from the temperature drift. Using a despun mirror system to cancel the satellite spin motion, the snap-shot two-dimensional image with an exposure time less than 1 s is obtained within one spin motion. This rocket instrument gave a fundamental design base to the EXOS-D auroral television camera.

Fig. 7. Pseudo-color display of auroral images. A number at the top left is a sequence number of the picture, followed by the exposure time interval in second after the launch and the rocket altitude. N indicates the geomagnetic north direction from the center of the picture, E east, S south and W west. (a) AURORA I (S-310JA-8), (b) AURORA II (S-310JA-9), and (c) AURORA III (S-310JA-10).

(c)

Fig. 7. (continued).

22. TIME= X+ 163.-167.
186.KM

Fig. 8. Pseudo-color auroral images observed by all-sky camera and by VAT on board the rocket at the almost same time.

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Appendix. Analysis of the Servomechanism

Linear servomechanisms are analyzed in terms of their transfer function, which is obtained by taking the Laplace transform of the differential equations of the open loop system with zero initial energy storage. The Laplace transform is defined as,

$$\int_0^{\infty} e^{-st} F(t) dt = f(s) \quad \text{or} \quad \mathcal{L}(F(t)) = f(s) .$$

The transfer function $G_{OL}(s)$ is the ratio of the Laplace transform of the output $\omega_C(s)$ to the Laplace transform of the actuating signal $\omega_T(s)$. Total transfer function $G(s)$ is given by the ratio of $\omega_C(s)$ to $\omega_T(s)$, that is,

$$G(s) \equiv \frac{\omega_C(s)}{\omega_T(s)} = \frac{G_{OL}(s)}{1 + G_{OL}(s)} .$$

The servomechanism shown in Fig. 5 is transformed to equivalent block diagram of a servomechanism with unity feedback as illustrated in Fig. 9. $G(s)$ can be approximated as a rational algebraic function, provided that the time constants of the amplifier and of motor armature are negligible small compared with that of the motor.

Fig. 9. Block diagram of a servomechanism with unity feedback.

$$G(s) = \frac{\frac{bd}{na}}{s^2 + \frac{n+bd}{na}s + \frac{bc}{na}} \cdot \left(s + \frac{c}{d}\right),$$

where

$$\begin{aligned} a &= R_a f T / (R_a f + K_b K_m + A K_m K_t), \\ b &= A K_m / (R_a f + K_b K_m + A K_m K_t), \\ c &= K_G K_2, \\ d &= K_G K_1, \end{aligned}$$

and a resistance of the motor armature $R_a = 6$ ohm, an inverse e.m.f. constant of the motor $K_b = 0.022$ V/rad/s, a tacho-generator constant $K_t = 0.019$ V/rad/s, a phase shift constant $K_1 = 0.05$, an integral phase lag constant $K_2 = 4.0$, a friction constant of the load $f = 24.9 \times 10^{-7}$ kg·m/rad/s, a motor torque constant $K_m = 0.0022$ kg·m/A, an output rate of the ARS $K_G = 5.72$ V/rad/s, a mechanical reduction gear ratio $n = 24$, a motor time constant $T = 2.0$ s, and an amplification factor of the AMP $A = 20$.

To test a response of this system, a step function F , i.e., $\mathcal{L}(1) = 1/s$ for $t > 0$ is applied to the point of the ARS output and its response x_2 is monitored. The simultaneous first order linear ordinary differential equations are obtained from Fig. 9, as follows.

$$\begin{aligned} x_0 &= (1/n)x_6, \\ x_2 &= -K_G x_0, \\ x_3 &= K_1(x_2 + F), \\ x_4 &= (K_2/s)(x_2 + F), \\ x_5 &= A(x_3 + x_4 - x_8), \\ x_6 &= K_m(x_5 - x_7) / R_a f (1 + Ts), \\ x_7 &= K_b x_6, \end{aligned}$$

and

$$x_8 = K_t x_6.$$

Then, the following differential equation for independent variables x_4 and x_6 is obtained.

$$\frac{d}{dt} \begin{Bmatrix} x_4 \\ x_6 \end{Bmatrix} = \begin{Bmatrix} 0 & -K_2 K_G / n \\ K_m A / R_a f T & (K_m A / R_a f T)(-K_1 K_G / n - K_t - K_b / A) - 1/T \end{Bmatrix} \begin{Bmatrix} x_4 \\ x_6 \end{Bmatrix} + \begin{Bmatrix} K_2 F \\ K_m A K_1 F / R_a f T \end{Bmatrix}.$$

Fig. 10. Simulation results of a response for a step function; (a) by calculation based on design parameters and (b) by test of the actual payload. A vertical scale is arbitrary and a horizontal scale 0.5 s/div.

Therefore the output x_2 from the ARS is expressed as,

$$x_2 = -(K_G/n)x_6.$$

The result of the above calculation is illustrated in Fig. 10(a) for the step function input ($t > 0$). On the other hand the payload of this system is tested by applying a step voltage and the result is also shown in Fig. 10(b).

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