Signal Level Analysis of a Camera System for Satellite Application

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Abstract: A camera system for the satellite application performs the mission of observation by measuring radiated light energy from the target on the earth. As a development stage of the system, the signal level analysis by estimating the number of electron collected in a pixel of an applied CCD is a basic tool for the performance analysis like SNR as well as the data path design of focal plane electronic. In this paper, two methods are presented for the calculation of the number of electrons for signal level analysis. One method is a quantitative assessment based on the CCD characteristics and design parameters of optical module of the system itself in which optical module works for concentrating the light energy onto the focal plane where CCD is located to convert light energy into electrical signal. The other method compares the design parameters of the system such as quantum efficiency, focal length and the aperture size of the optics in comparison with existing camera system in orbit. By this way, relative count of electrons to the existing camera system is estimated. The number of electrons, as signal level of the camera system, calculated by described methods is used to design input circuits of AD converter for interfacing the image signal coming from the CCD module in the focal plane electronics.

Keywords: CCD, Satellite, Focal plane Electronics, Camera system, quantum efficiency

1. Introduction

Remote sensing using a satellite implies that the instrument used to gather information from a target on the ground is located on a platform of the satellite and it scans ground to collect the light energy reflected from the target as the satellite moves around.[4] The light energy illuminated on the CCD which is built into the camera subsystem as a part of a payload in a satellite is then converted into electron and electrical signal to be transmitted to ground station where image information is processed. Therefore, at the beginning of the developing program of a satellite with optical payload, the analysis of the number of electrons collected on the CCD through the optics is required for the SNR(Signal to Noise Ratio) calculation as one of the most important figure-of-merit. This number is also used for the analysis of the signal level of the CCD output which is critical parameter to design data path between CCD and A/D converter. The FPE(Focal Plane Electronics) designer should decide whether the dividing-circuit is necessary or not between them from the analysis. If it is necessary, the optimized dividing factor of the level should be implemented. This paper describes the analysis of the electron count of a camera system for a satellite application and then of the signal level for the interface design between CCD and A/D converter using two methods. One is a quantitative assessment based on the design parameters of the camera system, the other method compares the design parameters in comparison with those of the existing camera system in orbit for relative counting of the electrons and the signal level estimation. Chapter 2 describes the radiometry of the camera system of a satellite application to show equations for electron counting, Chapter 3 describes a camera system briefly to explain the data flow of imagery information from CCD and Chapter 4 explains the two methods for the analysis of the number of electrons and the signal level. Then conclusion is made in chapter 5.

2. Radiometry of Camera System

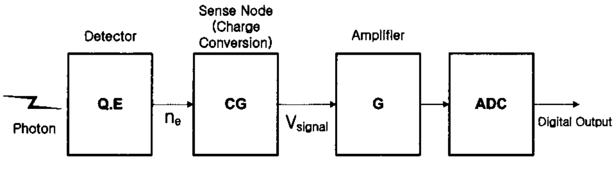

Figure 1. Signal Transfer diagram

Figure 1 illustrates a signal transfer diagram of a camera system. The detector converts the incident photons into electrons at a rate determined by the quantum efficiency. It includes both photoelectrons and dark current electrons. A voltage is then created when the electrons are transferred to the sense node capacitance of the CCD. The signal level after the source follower amplifier becomes;[1,2,3]

$$V_{signal} = n_e \frac{Gq}{C} \qquad (1)$$

where

-n_e = the total number of electrons in the charge packet of CCD.

-G = Amplifier Gain of the CCD Module

-C = Sensing node Capacitance of the CCD Module

-q = electron charge, 1.6×10^{-19} coulomb

The output conversion gain Gq/C, is typically 4 ~ 6 uV/e-. The source follower amplifier gain, G, is near unity and, therefore, it is sometimes omitted from radiometric equation. [1]

The formula for the number of electron is derived from the following steps with the consideration of the satellite application where M_{OPTICS} approaches zero because the source is assumed to be at long distance($R_1 >> R_2$). [1,2,3]

$$\Phi_{lens} = L_e A_S \frac{A_0}{R_1{}^2} T_{ATM}, \qquad (2)$$

$$\Phi_{image} = L_e A_S \frac{A_0}{R_1{}^2} T_{ATM} \tau_{optics} = L_e A_S \frac{A_I}{R_2{}^2} T_{ATM} \tau_{optics} \qquad (3)$$

$$\begin{aligned} \Phi_{\det ector} &= \Phi_{image} \frac{A_D}{A_I} = L_e A_S \frac{A_I}{R_2{}^2} \tau_{ATM} \tau_{optics} \frac{A_D}{A_I} \\ &= L_e (\frac{\pi}{4}) \frac{1}{F^2 (1 + M_{OPTICS})^2} A_D \tau_{OPTICS} \tau_{ATM} \qquad (4) \\ &\cong L_e (\frac{\pi}{4}) \frac{1}{F^2} A_D \tau_{OPTICS} \tau_{ATM} \end{aligned}$$

Where

- R_1 =Distance between a source and imaging system
- R_2 =Distance from imaging system to a focal plane
- $\Phi_{lens}, \Phi_{image}, \Phi_{\det ector}$ = Radiant flux of Optical system, Image plane, detector
- L_e = Input Radiance
- A_S, A_0, A_I, A_D = the Area of source, optical system, Image plane, Detector
- $\tau_{optics}, \tau_{ATM}$ = Transmittance of Optics, atmosphere
- D, fl = diameter and focal length of imaging system
- $M_{OPTICS} = R_2 / R_1$ Optical Magnification
- $F = fl / D$ f-number

If an imaging system is at a distance R_1 from a source, the radiant flux incident onto the optical system of area A0 becomes Φ_{lens} in equation (2). Then, it converts into on-axis radiant fluxes($\Phi_{image}, \Phi_{\det etor}$) reaching the image plane and effective sensitive detector respectively by equations (3), (4). The number of photons generated by the CCD is then calculated by;

$$n_{ph} = \frac{\Phi_{\det ector} T_{\text{int}}}{E_g} = \frac{\Phi_{\det ector} T_{\text{int}}}{hc / \lambda} \qquad (5)$$

Where

- n_{ph} =the number of photons incident onto CCD
- T_{int} =Integration Time of CCD
- E_g =Energy band gap of CCD material
- h = Planks's constant
- c, λ = the speed and wavelength of the light

The number of photoelectrons collected by the CCD is calculated by multiplying quantum efficiency $\eta(\lambda)$ to n_{ph} as shown in equation (6) for all wavelength of concern. In a discrete form of calculation of the electron by applying approximation of equation (4), equation (7) is presented. [1,2,3]

$$n_e = \int_{d\lambda} \eta(\lambda) \times n_{ph} d\lambda = \int_{d\lambda} \eta(\lambda) \times \frac{\Phi_{\det ector} T_{\text{int}}}{hc / \lambda} d\lambda \qquad (6)$$

$$n_e \cong \eta(\lambda) L_e (\frac{\pi}{4}) \frac{1}{F^2} A_D \tau_{OPTICS} \tau_{ATM} T_{\text{int}} \frac{\lambda}{hc} \Delta\lambda \qquad (7)$$

Form this, the number of electrons is estimated using detector area, transmittance of optics, integration time being decided from the linerate and GSD(Ground Sampling Distance) and wavelength over the small range of wavelength $\Delta\lambda$. Integration time is associated not only with linerate but also with the TDI(Time Delayed Integration) operation which is the special for the scanning camera system employing linear CCD module like a satellite application to have the effect of increasing the illumination time. When a moving satellite scans the target on the ground to create 2D image using linear CCD arrays, the camera system gets to accumulate more light energy as TDI level increases. The count of electrons is summed up over the all wavelength as a final value.

3. Satellite Camera System

A payload consists of a EOS(Electro-Optical System) and PDTS(Payload Data Transmit System). The PDTS stores and transmits these digital image data which were generated in the EOS to the ground station through X band antenna. The EOS in a satellite system, as an imaging instrument, has the general configuration of OM(Optical Module) and a camera subsystem. A camera subsystem basically consists of several FPMs(Focal Plane Module) to configure panchromatic and multispectral image bands. Each FPM comprise a CCD module and FPE(Focal Plane Electronics). As an example, a FPM block diagram is shown in Figure 2 in which a 4-output CCD module converts the light energy into electrical charge according to the equation (6) or (7) and then into analog signal by multiplying conversion gain (Gq / C) in equation (1), and the FPE changes the analog signal to digital data using CSP(CCD Signal Processor) which includes AD converter as shown in Figure 3.[5] Then, 4-output digital data are sent, after being multiplexed and parallel-serial conversion, to the PDTS for the compression, encryption and transmission, etc. The designer of the FPE should consider whether the overflow of AD converters shall happen by pre-estimation of signal level on it from equation (6) or (7) and (1). As a result of this analysis, the serial and parallel resistance (Rs and Rp in Figure 3) are decided together with the operational decision on the TDI level.

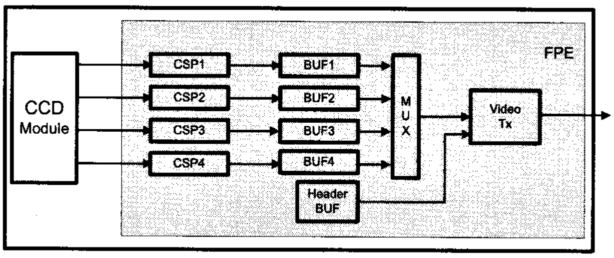

Figure 2. Focal Plane Module block diagram

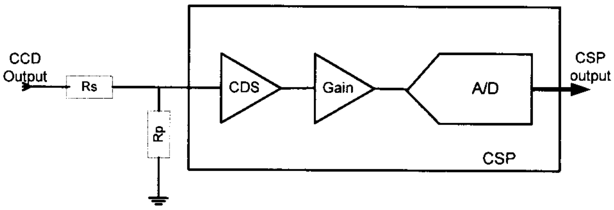

Figure 3. Interface between CCD Module and CSP

4. Signal Level Analysis

The analysis of the signal level is performed based on the design parameters of EOS into which the camera subsystem is built. The system on the development stage has one panchromatic and 4 multispectral image-bands, and is intended for earth observation as a main payload of a satellite. The analysis is done using two methods of direct calculation and comparison and the result is used in the interface design between CCD module and CSP.

4.1 Direct Calculation Method

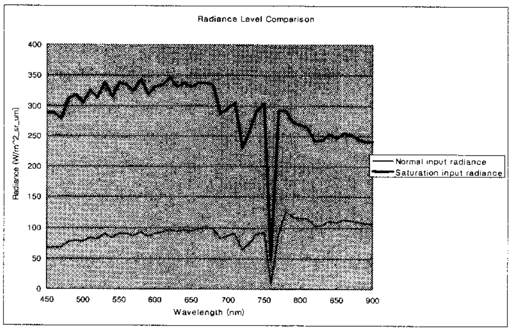

Figure 4. Input Radiance Level

This method calculates the number of electrons from the equation (6) and evaluates signal level of voltage using equation (1). The input radiance for each wavelength was taken as specified in the requirement specification of the system on the development. As shown in Figure 4, two kinds of radiance level is specified; one is "Normal input radiance" which is expected from the target like city, yard, etc., while "Saturation input radiance" simulates the very bright area like sands.

The calculation results in the Table 1 in which electron counts and its signal levels by applying conversion factor of 4 uV/e- for each image bands are shown depending on two kinds of input radiance and the used TDI level. In the Table, the voltage level above 0.5 V means saturation for the multispectral bands when considering the pixel binning after AD conversion while 1 V for the panchromatic band. Some multispectral image bands need, therefore, voltage dividing circuit between CCD module and CSP to avoid saturation of the relevant pixels for the higher level of TDI operation while panchromatic band performs the imaging mission without saturation whatever the input radiance level and TDI level is.

Table 1. Electron count and Signal Level

TDI Level	Blue		Green		Red		NIR		PANchromatic	
	Nominal	Saturation	Nominal	Saturation	Nominal	Saturation	Nominal	Saturation	Nominal	Saturation
TDI1 (e-No)	1,433	5,717	4,501	16,782	6,298	21,765	21,861	52,732	827	2,541
voltage	0.0029	0.011	0.009	0.034	0.013	0.044	0.044	0.105	0.003	0.010
TDI8 (e-No)	11,463	45,736	36,011	134,255	50,387	174,119	174,885	421,855	6,616	20,324
voltage	0.023	0.091	0.072	0.269	0.101	0.348	0.350	0.844	0.026	0.081
TDI32 (e-No)	45,851	182,943	144,044	537,019	201,549	696,475	699,539	1,687,421	26,466	81,297
voltage	0.092	0.366	0.288	1.074	0.403	1.393	1.399	3.375	0.106	0.325
TDI64 (e-No)	91,703	365,886	288,089	1,074,037	403,099	1,392,951	1,399,078	3,374,841	52,931	162,596
voltage	0.183	0.732	0.576	2.148	0.806	2.786	2.798	6.750	0.212	0.650

4.2 Comparison Method of Design Parameters

This method compares the design parameters which affect electron counts in equation (6) between two electro-optical systems. The system on development (sys1) is compared to the existing system in orbit (sys2). We compare the design parameters of the electro-optical system such as f-number, transmittance, area of the detector including fill factor, integration time, quantum efficiency, and conversion factor of the sensing node. From the comparison result, the decision whether voltage divider is necessary or not is confirmed.

Table 2. Design Parameter Comparison

PAN Ch	F#	Transmittance	A_det	T_int (us)	QE_average	Fill Factor	uV/e	Total
SYS2	15	0.47	169	147	25.16	1	6	
SYS1	11.81	0.608	77	103	26.92	0.75	4	
Ratio	1.61	1.29	0.45	0.70	1.07	0.75	0.67	**0.35**

MS Ch	F#	Transmittance	A_det	T_int (us)	QE_average	Fill Factor	uV/e	Total
SYS2	3.75	0.14	169	588	25.16	1	6	
SYS1	11.81	0.608	1225	412	34.36	0.85	4	
Ratio	0.10	4.34	7.25	0.70	1.37	0.85	0.67	**1.72**

As shown Table 2, the signal level of the sys1 is lower than the sys2 by a factor of 0.35 for panchromatic image band under the condition of same light energy as input radiance while bigger by a factor of 1.72 for multispectral bands. In the Table, the quantum efficiency is compared with solar-weighted average value ($\eta(\lambda)_{avg}$) which follows equation (8) based on the quantum efficiency graph shown in Figure 5.[2]

$$\eta(\lambda)_{avg} = \sum_{\lambda_1}^{\lambda_2} \eta(\lambda) M_e(\lambda)\Delta\lambda / \sum_{\lambda_1}^{\lambda_2} M_e(\lambda)\Delta\lambda \qquad (8)$$

Where

- $M_e(\lambda)$ =Spectral Radiant Exitance

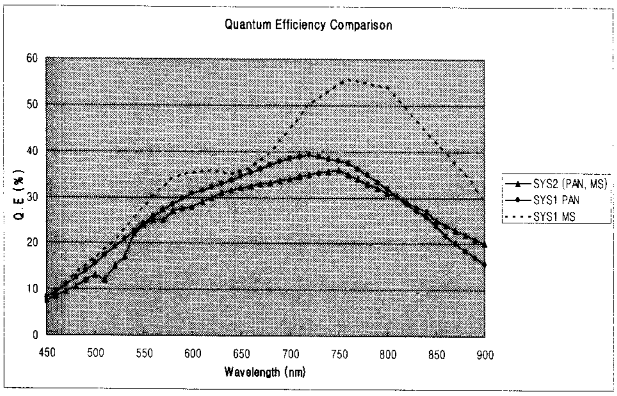

Figure 5. Quantum Efficiency graph of sys1 and sys2

4.3 Interface between CCD module and CSP

The analysis results of signal level from the two methods show whether dividing circuits between CCD module and CSP is necessary or not. In the case of panchromatic image-band, there is no need to install it because the signal level from the CCD module is far lower than the saturation level of the CSP input in any operational condition as shown in the Table 1, and sys1 compares favorably with sys2 in terms of installation of the dividing circuits. However, in the case of multispectral image, some bands exceed the saturation level depending on the used TDI level and sys1 compares unfavorably with sys2, which means that higher chance to exceed the saturation level is foreseen. Therefore, in order to avoid saturation in multispectral bands, TDI level during the imaging mission should be optimized by predicting the input radiance of the target area or optimized dividing circuits for each band should be considered. From the Table 1, It is shown that if we assume a target is ordinary area and camera operation is working with TDI32 for the Blue, Green, RED image-band and TDI8 for the NIR(Near Infra-Red) image-band, no saturation is expected even though dividing circuit is not implemented. However, NIR band is likely to be saturated even with the low TDI level of TDI8 if “Saturation input radiance” in Figure 4 is expected, which requires dividing circuit in order not to be saturated. At the same time, we still have an option to operate the system with TDI1 to avoid saturation even under “Saturation input radiance” for NIR image band.

5. Conclusion

We presented the calculation methods of the signal level by which the number of electrons was estimated quantitatively and comparatively under the some assumption on the design parameters of electro-optical system. From the calculation results, we showed that dividing circuit between CCD module and CSP for the voltage level is not required for the panchromatic band for any operational condition and might be required for the multispectral bands depending on the input radiance and operational condition of the camera system. And if we use the more realistic value as input radiance instead of analytically-gained value, it would result in more reliable result.

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