SNR Analysis for Practical Electro-Optical Camera System

Youngsun Kim*, Jong-Pil Kong, Haeng-Pal Heo, Jong-Euk Park
and Young-Jun Chang
Korea Aerospace Research Institute, Eun-Dong 45, Yusung-Gu, Daejon, Korea
*yskim1203@kari.re.kr
kjp123@kari.re.kr
hpyoung@kari.re.kr
pje@kari.re.kr
yjchang@kari.re.kr

ABSTRACT:

An electro-optical camera system consists of many subsystems such as the optics, the detector, and the electronics and so on. They may create variations in the processed image that were not present original scene. The performance analysis of the electro-optical camera system is a mathematical construct that provides an optimum design through appropriate trade off analysis. The SNR(Signal to Noise Ratio) is one of the most important performance for the electro-optical camera system. The SNR analysis shown in this paper is performed based on the practical high resolution satellite camera design. For the purpose of the practical camera design, the analysis assumes that the defined radiance, which is calculated for the Korean peninsula, reached directly to the telescope entrance. In addition, the actual operation concept such as integration time and the normal operation altitude is assumed. This paper compares the SNR analysis results according to the various camera characteristics such as the optics, the detector, and the camera electronics. In detail, the optical characteristics can be split into the focal length, F#, transmittance, and so on. And the system responsivity, the quantum efficiency, the TDI stages, the quantization noise and the analogue noise can be used for the detector and the camera electronics characteristics. Finally this paper suggests the optimum design to apply the practical electro-optical system.

KEY WORDS: SNR, Electro-optical System, Satellite Camera, Detector

1. Electro-Optical System Performance Analyses

Electro-optical imaging system analysis is a mathematical construct that provides an optimum design through appropriate tradeoff analyses. A comprehensive model includes the target, background, the properties of the intervening atmosphere, the optical system, the detector, the electronics, the display, and the human interpretation of the displayed information. Finding the optimum design is an iterative decision process. Every step in the design process that has conflicting needs requires a tradeoff analysis. Many performance parameters can only be increased at the expense of another[1].

The performance of the electro-optical system such as a dark noise, a residual photo response non-uniformity, a non-linearity, a MTF(Modulation Transfer Function) and a SNR(Signal to Noise Ratio) affects direclty to camera system. Among these performance, the SNR, which is defined simply as signal level comparing to noise level, is one of the most important performance.

The SNR analysis shown in this paper is performed based on the design of the practical LEO high-resolution camera. For the practical camera design, the analysis assumes that the radiance calculated for the Korean peninsula reached directly to the camera entrance. And the actual operation concept such as the integration time and the nominal operation altitude are assumed. This paper compares the respective SNR analyses results according to the optics, the detector and the electronics based on the practical LEO electro-optical system. In detail, the electro-optical characteristics is split into the focal length, the F#, the transmittance, the responsivity, the quantum efficiency, the TDI(Time Delay and Integration) stages, the quantization noise and the analog noise, and so on. In addition, this paper separates a panchromatic system and a multi-spectral system for the analysis of the band characteristics.

2. SNR Analysis Method and Basic Assumption

The SNR depends on the various characteristics of the system and the environmental condition such as the F# the optical transmittance, the characteristics of the detector, the quantization noise of electronics and the radiance from ground, and so on. In these characteristics, some characteristics cannot be increased by the design, some can be. For example, the radiance from ground and the integration time cannot be increased by the design, but the characteristics of the optics and the electronics can be increased by design. Especially, the design or the selection of the detector is the main key to increase the SNR.

2.1 SNR Analysis Method

The SNR in the electro-optical camera is defined as following;

$$SNR = \frac{Radiance(\lambda) \cdot SR(\lambda) \cdot OT(\lambda) \cdot TI}{\sqrt{SN^2 + EN^2}} \quad (1)$$

Where *SR* is system the responsivity, *OT* is the optics transmittance, *TI* is the time integration, *SN* is the shot noise and *EN* is the electronics noise.

In the Eq. (1), the system responsivity relies on the detector pixel size, the focal length, the mirror diameter, the detector quantum efficiency and so on. The optical transmittance is determined by the optics design, and the time integration is decided by the operation line-rate and the TDI stages. In the noise part, the electronics noise is derived by the detector noise, the ADC quantization noise and the analog noise, and the shot noise is determined directly by input radiance.

Eq. (2) explains Eq. (1) in detail.

$$SN(\lambda) = \sqrt{Radiance(\lambda) \cdot SR(\lambda) \cdot OT(\lambda) \cdot TI}$$

$$R = \frac{Quantum\ Efficiency(\lambda) \cdot C \cdot Band\ Width}{Photon\ Energy(\lambda)}$$

$$C = \frac{\pi \cdot Pixel\ Area}{4 \cdot F\#^2}[cm^2]$$

$$EN = \sqrt{DN^2 + RN^2 + AN^2 + QN^2}$$

$$Quant\ Noise = \frac{lsb}{\sqrt{12}} \tag{2}$$

As shown in Eq. (1), the optics design is charge of making the signal higher and the electronics design is charge of decreasing the noise. That is to say in detail, when the optics system transmits much quantity of light to the detector and the electronics decreases noise together, the SNR results can be higher.

2.2 Basic Assumption for Analyses

As shown in Eq (1), the SNR depends on the radiance from the earth and the integration time. It means that the SNR can be higher when the camera is imaging the bright area comparing to the dark area. In other words, if the camera covers wider spectral bands even if the camera looks at the same area, the SNR can be higher. Table 1 shows the spectral bands for the panchromatic camera and the multi-spectral camera assumed in these SNR analyses. As shown in Table 1, the panchromatic camera has wider spectral bandwidth than that of each multi-spectral camera. Therefore, we can guess that the SNR of the panchromatic system will be higher than that of the multi-spectral system in the point of spectral bands.

Table 1. Panchromatic and multi-spectral bands

Camera	Spectral Range[nm]	Center[nm]
Panchromatic Camera	500-900	700
Multi-Spectral Camera	450-520	485
	520-600	560
	630-690	660
	760-900	830

When it come to the integration time, it is assumed that the line-rate for the panchromatic camera and the multi-spectral camera are 10000 lines/sec and 2000 lines/sec respectively. It means that the integration time for the multi-spectral camera is four times bigger than the panchromatic camera. Thus, the SNR for the multi-spectral camera has a benefit in the point of integration time. Table 2 summarized the basic assumption for the GSD and the line-rate used in following analyses.

Table 2. GSD and Line-rate

Camera	GSD	Line-rate
Panchromatic Camera	0.7m	10000 lines/sec
Multi-Spectral Camera	2.8m	2500 lines/sec

Even if the radiance and the integration time are the dominant factors in the SNR calculation as explained in Eq (1), these do not have the big meaning in the system design. This is why these two items are fixed automatically when the system requirement is determined. In the point of the system design, it is important rather to design the optics to increase the system response and the transmittance and to design the electronics to decrease the electronics noise.

For the purpose of the practical camera system analyses, the analyses assume that the defined radiance shown in Table 3 shall be directly arrived to the camera telescope.

Table 3. Nominal radiance of Korean peninsula

Wavelength(nm)	Radiance[W/(m²·μm·sr)]
500	77.54
550	90.26
600	90.93
650	95.10
700	86.88
750	93.16
800	115.49
850	108.56
900	107.14

3. SNR Analysis for Practical Satellite Camera

For the analysis of the practical electro-optical system, it is a key-point the assumption of the realistic optics, the electronics and the detector. The design parameter applicable to the high-resolution satellite camera and the detector characteristics purchasable for space program are assumed for the analyses in this paper.

3.1 SNR Analyses of Panchromatic Camera

For the panchromatic system analyses, four detector samples, which are applicable to the LEO satellite camera design, are chosen. Furthermore, the practical optics and the electronics characteristics are applied for the high resolution satellite camera. Specially, the 10 bits or the 12 bits AD resolutions are used separately to analyze quantization error effect in detail.

Table 4. Characteristics of panchromatic camera

	SYS A	SYS B	SYS C	SYS D
Detector Pitch Size	8.75μm	4.375μm	13μm	13μm
Detector TDI	128 lines	128 lines	96 lines	96 lines
Detector Read Noise	50e	50e	70e	165e
Detector Dark Noise	45e	45e	88e	177e
Quantum Efficiency	0.28(Avg) 0.36(at 700nm)	0.28(Avg) 0.36(at 700nm)	0.25(Avg) 0.34(at 700nm)	0.42(Avg) 0.53(at 700nm)
Detector Saturation	450k	450k	400k	460k
Analog Electronics Noise	100e	100e	100e	100e
Focal Length	8.56m	4.28m	12.83m	12.83m
Aperture of Optical System	0.7m	0.7m	0.7m	0.7m
Optical Transmittance	0.7	0.7	0.7	0.7
AD Resolution	10bits/ 12bits	10bits/ 12bits	10bits/ 12bits	10bits/ 12bits

In Table 4, the focal length can be calculated by the pitch size of the selected detector, the GSD and the altitude as shown in Eq. (3).

$$Focal\ Length = Pixel pitch \cdot Range / GSD \quad (3)$$

As shown in Table 4, the same detector characteristics are used in the SYS A and the SYS B, except the difference of the detector pitch size. The pitch size of the SYS B is a half of SYS A's. When we compare the SYS C and the SYC D, the detector pitch size and the TDI stage are same, but the noise characteristics and the quantum efficiency are different.

Table 5 shows the SNR analyses results of panchromatic camera. In most of systems, the SNR results are more than 300 which looks quite good. The main reasons the SNR is lowest in the SYS C are the low quantum efficiency and the lower TDI stages. When we compare the SYS A and the SYS B, we can know that the pitch size is independent of SNR results. That is why the focal length also decreases in the condition of the fixed GSD and the altitude the as the pitch size becomes smaller. If the AD resolution is increased the 10 bits to the 12 bits, the SNR is increased, but it looks small.

As the resolution of satellite camera is increased and the integration time decreased, it is expected to the system SNR shall be decreased. But, in step with the camera performance increment, the adjustable detector TDI level also is increased by the advanced detector manufacturing techniques. So, if the detector is designed or selected prudently considering the SNR performance, we can design the system, as shown in Table 5, without any SNR loss even if the integration time is decreased.

Table 5. SNR analyses results of panchromatic camera

		SYS A	SYS B	SYS C	SYS D
Signal		156ke	156ke	98ke	160ke
AD 10bits	Noise	432e	432e	364e	495e
	SNR	361	361	270	322
AD 12bits	Noise	414e	414e	347e	479e
	SNR	376	376	284	333

3.2 SNR Analyses of Multi-spectral Camera

Only one detector sample, which is same to the panchromatic camera SYS A, is used for the multi-spectral camera system analysis. For the analysis, the bi-focal optics is considered and the focal length is a quarter of that of the panchromatic camera because the GSD is four times of the panchromatic system as shown in Table 2. And the low optical transmittance is assumed comparing to the panchromatic system because the multi-spectral camera needs the additional optical structure such as the beam splitter. For the multi-spectral analyses, the AD resolution is fixed as the 10 bits in order to focus on the analysis for the band characteristics. Table 6 shows the characteristics of the multi-spectral camera assumed for the SNR analysis.

Table 6. Characteristics of multi-spectral camera

	SYS E
Detector Pitch Size	8.75μm
Detector TDI	Maximum 128 lines
Detector Read Noise	50e
Detector Dark Noise	45e
Detector saturation	450k
Quantum Efficiency	0.28(average) 40.36(at 700nm)

Analog Electronics Noise	100 e
Focal Length	(8.56/4)m
Aperture of Optical System	0.7m
Optical Transmittance	0.4
AD Resolution	10bits
Spectral Band	According to Table 1

Table 7 shows the SNR analyses results of the multi-spectral camera. The SNRs, except MS1, are more than 500 which looks quite better than that of the panchromatic camera.

As shown in Table 7, the detector TDI level should be adjusted in order to prevent the detector saturation. Especially, in the case of MS4, we can select only 16 TDI lines in the normal radiance condition shown in Table 3. Generally speaking, even if the multi-spectral camera has the narrow bandwidth, the multi-spectral camera can have higher SNR results because the multi-spectral camera has big benefits in the time integration and in the focal length. The primary reasons that MS1 has much lower SNR result comparing to other bands are the small band width in shown as Table 1 and the small radiance coming to the detector as shown in Table 3.

Table 7. SNR analysis result of multi-spectral camera

Band	TDI	Signal	Noise	SNR
MS1	128	53k	289	183
MS2	128	475k(satu)	711	668
	96	357k	622	573
MS3	128	771k(satu)	895	861
	64	385k	645	598
MS4	128	2381k(satu)	1692	1674
	16	620k	620	571

3. Conclusion

The SNR depends on the various system characteristics and the environmental condition such as the F# and the optical transmittance, the detector, the ADC quantization noise and the radiance from ground, and so on. In this paper, the SNR analyses were performed based on the practical satellite camera design for the panchromatic camera and the multi-spectral camera assuming that the defined radiance reached directly to the camera entrance. The design parameters applicable to the LEO high-resolution camera were assumed for the analyses.

The analyses of the panchromatic camera show that the SNRs of most cameras are more than 300 which looks quite good. The analyses also show that the pitch size is independent of the SNR result and the SNR is increased a little if the AD resolution is increased the 10 bits to the 12 bits. We can design the system without any SNR loss if the detector is designed or selected prudently considering the SNR performance in spite of the integration time decrement resulted from the ground resolution increment. The SNRs of the multi-spectral camera, except MS1, are more than 500 which looks quite better than that of the panchromatic camera. From the multi-spectral camera analysis, we can know that the detector TDI level, under the nominal radiance condition, should be adjusted in order to prevent the detector saturation. The analysis result shows that the multi-spectral camera can have higher SNR results even if the multi-spectral camera has the narrow bandwidth. That is why the multi-spectral camera has big benefits in the time integration and in the focal length. The primary reasons that MS1 has much lower SNR result are the relative small band width and the small radiance coming to the detector.

As the further work, the SNR analyses shall be performed with the more accurate model as the system design stage.

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