ERROR PROPAGATION ANALYSIS FOR IN-ORBIT GOCI RADIOMETRIC CALIBRATION

Gmsil Kang, Heong-Sik Youn

Korea Aerospace Research Institute (KARI), 45 Eoeun-Dong, Yuseong-Gu, Daejeon, 305-333, Korea
kgs@kari.re.kr, youn@kari.re.kr

ABSTRACT
The Geostationary Ocean Color Imager (GOCI) is under development to provide a monitoring of ocean-color around the Korean Peninsula from geostationary platforms. It is planned to be loaded on Communication, Ocean, and Meteorological Satellite (COMS) of Korea. The GOCI has been designed to provide multi-spectral data to detect, monitor, quantify, and predict short term changes of coastal ocean environment for marine science research and application purpose. The target area of GOCI observation covers sea area around the Korean Peninsula. Based on the nonlinear radiometric model, the GOCI calibration method has been derived. The radiometric model of GOCI has been validated through radiometric ground test. From this ground test result, GOCI radiometric model has been changed from second order to third order. In this paper, the radiometric test performed to evaluate the radiometric nonlinearity is described and the GOCI radiometric error propagation is analyzed. The GOCI radiometric calibration is based on on-board calibration devices; solar diffuser, DAMD (Diffuser Aging Monitoring Device). The radiometric model error due to the dark current nonlinearity is considered as a systematic error. Also the offset correction error due to gain/offset instability is considered. The radiometric accuracy depends mainly on the ground characterization accuracies of solar diffuser and DAMD.

KEY WORDS: COMS, GOCI, Calibration, Error propagation

1. INTRODUCTION

Space based observations of ocean color began with CZCS (Coastal Zone Color Scanner) which was launched in 1978. Since then many missions have been launched by various countries with increasing sophistication for ocean color monitoring: SeaWiFS (Sea Viewing Wide Field Sensor), OCTS (Ocean Color and Thermal Scanner), OCM (Ocean Color Monitor), MODIS (Moderate Resolution Imaging Spectro-Radiometer), MERIS (Medium Resolution Imaging Spectro-Radiometer). These ocean color sensors on low Earth orbiting satellites are capable of supplying highly accurate water-leaving spectral radiance with high spectral and spatial resolution at a global revisit period of approximately two to three days [1]. The relatively low frequency coverage of these sensors, further reduced in the presence of clouds, is inadequate to resolve processes operating at a shorter time scales. In addition, the current sun-synchronous polar orbiter observations along coasts are aliased with the tidal frequency. High frequency observations have been required in order to remove the effects of tidal aliasing and to validate tidal mixing terms in coastal ecosystem models. Ocean color observation from geostationary platform is required to remedy the coverage constraints imposed by polar orbiting platforms. Unfortunately, no current geostationary platform possesses the ability to measure ocean color.

Korea Aerospace Research Institute (KARI) has a plan to launch COMS for consistent monitoring of the Korean Peninsula and studying processes which can vary rapidly in time on land, oceans, and atmospheres. Geostationary Ocean Color Imager (GOCI) is one of the main payloads of COMS which will provide a monitoring of ocean-colour around the Korean Peninsula from geostationary platforms. The COMS contract to develop the COMS satellite and to provide support for system activities has been award by KARI to ASTRIUM France.

The GOCI radiometric calibration is based on in-orbit solar calibration using on-board calibration devices; solar diffuser, DAMD (Diffuser Aging Monitoring Device). The GOCI is modelled as the nonlinear system due to the nonlinear characteristic of CMOS detector array. The GOCI radiometric model will be validated during ground test. In this paper, the GOCI radiometric error propagation is examined. The radiometric model error due to the dark current nonlinearity is analyzed as a systematic error. Also the offset correction error due to gain/offset instability is considered. The radiometric accuracy depends mainly on the ground characterization accuracies of solar diffuser and DAMD.

2. OVERVIEW OF GOCI SPECIFICATION

The GOCI has been designed to provide multi-spectral data to detect, monitor, quantify, and predict short term changes of coastal ocean environment for marine science research and application purpose. The target area for GOCI observation covers sea area around the Korean Peninsula. Table 1 shows the summary of the major requirement specification of the GOCI. The spatial resolution (GSD) shall be less than 500m in both E/W and S/N directions at the center of the target area defined. The GSD is varied over the target area because of the imaging geometry including the projection on Earth and the orbital position of the satellite.

Table 1 GOCI requirement specifications

Items	Technical requirements
Ground Sample Distance (GSD)	≤ 500m × 500m at the center of the target area
Target area	≥ 2500km × 2500km centered on 36N° latitude and 130 E°
Spectral coverage	412 nm ~ 865 nm (8 channels)
Bandwidth	10 nm ~ 40 nm
SNR	750 ~ 1200
Dynamic range	NEdR ~ Maximum cloud radiance
Radiometric calibration accuracy	4 %
Digitization	12 bit

The detector array for GOCI is a custom designed CMOS image sensor featuring rectangular pixel size to compensate for the Earth projection over Korea, and electron-optical characteristics matched to the specified instrument operations. The step and staring method using CMOS detector array and pointing mirror supported by a 2-axis scan mechanism is adapted in order to capture the target area. The eight spectral channels are obtained by means of a filter wheel which includes dark plate in order to measure the system offset as well as 8 spectral filters. The single spectral channels will be acquired for two gain levels (integration time) corresponding to sea and cloud radiance revels. The shutter wheel carrying two on-board calibration devices is placed in front of optic entrance. One of the on-board calibration devices is the solar diffuser of transmission type which is used on short time period to perform solar calibration. The Diffuser Aging Monitoring Device (DAMD) is the other calibration device which is used on long time period in order to correct the degradation factor of solar diffuser.

3. GOCI RADIOMETRIC CALIBRATION

The GOCI radiometric calibration is based on in-orbit solar calibration using the on-board calibration devices. Thanks to the geostationary platform, the Sun can be used as a constant calibration reference covering the full GOCI detection chain (same optic for the Earth view) which provides the uniform radiance distribution.

The GOCI radiometric calibration consists of three parts in Figure 1; on-ground characterization, in-orbit calibration, and ground processing. The nonlinear radiometric model of the GOCI has been validated through on-ground radiometric test. Also characterization of on-board calibration devices has been performed during on-ground calibration activity. The absolute gain (radiometric parameters of GOCI model) will be estimated periodically through the in-orbit solar calibration. The apparent radiance in front of the GOCI will be calculated using the Sun angle and the diffusion factor of solar diffuser characterized through on-ground test. The change of radiometric response between pixels will be corrected through this in-orbit calibration. In-orbit calibration will be performed when the Sun is available in calibration field of view using solar diffuser. The DAMD will be used in order to measure the degradation factor of the solar diffuser.

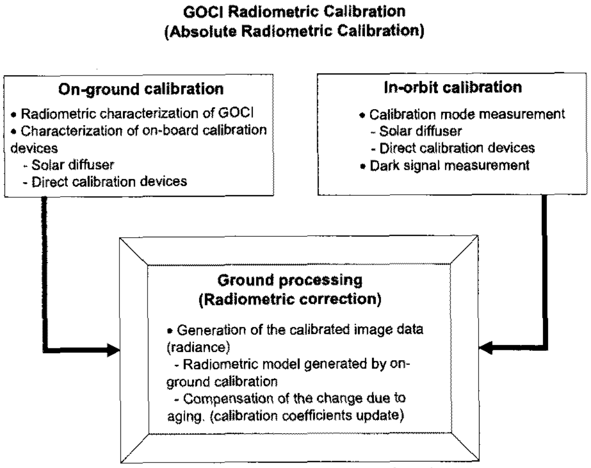

Figure 1. GOCI radiometric calibration concept

3.1 Radiometric Model Verified During On-ground Test

The radiometric model of the GOCI was constructed as (1) according to the functional model [2]. The calibration algorithm was derived from the radiometric model given by (1) and the error analysis was also done for this model. But through on-ground test, the radiometric model has been modified, like as (2). Accordingly the calibration algorithm has been changed. The error propagation characteristic of new GOCI radiometric model is examined in this paper.

$$S = G \times T_{\text{int}} \times L + b \times T_{\text{int}}^2 \times L^2 + T_{\text{int}} \times O + F \qquad (1)$$

$$S = G \times T_{\text{int}} \times L + b \times T_{\text{int}}^3 \times L^3 + T_{\text{int}} \times O + F \qquad (2)$$

where S: Output digital number of detector pixel

L: Spectral average radiance in the front of the GOCI

G, b: Linear gain and Nonlinear gain, respectively

T_{int}: Integration time (adjusted during the mission life)

O, F: Offset parameters

The radiometric model of the GOCI given by (2) defines the relationship between the output digital count and the input radiance for a pixel. The radiometric model given by (2) includes the linear gain, the third order non-linear gain, and the offset parameters. The integration time is considered as one of coefficients to take into account the adjustment of integration time during mission life. The integration time for each spectral channel will be commanded by ground operation center in order to achieve the proper radiometric performance. During mission life, it will be increased to compensate the degradation of the radiometric performance which is caused by the radiation environment. The temperature variation effect has been examined for the radiometric model. For temperature variation of the detector, the dark current and the detector fixed offset will be changed resulting in the offset signal change. Although this variation on offset signal may cause the offset correction error corresponding temperature variation range between offset measurement and channel measurement, the temperature variation effect is not reflected in the GOCI radiometric model because it is expected that constant detector temperature will be kept during imaging period. The detector will be controlled to keep stable temperature by fine temperature control during mission life. The gain change and offset change due to the temperature variation has been checked through the ground test.

4. RADIANCE ESTIMATION AND ERROR PROPAGATION

The incident radiance at the GOCI will be calculated for each pixel (i,j) from the radiometric model using the estimated radiometric parameters, as follows;

$$\tilde{L} = \frac{1}{T_{\text{int}}}\frac{\bar{S}}{\tilde{G}}\left[1 - K - 3K^2\right],\quad \mathrm{K} = \frac{\tilde{b}\bar{S}^2}{\tilde{G}^3 + 3\tilde{b}\bar{S}^2} \qquad (3)$$

where $\bar{S}$ means the output DN number after offset correction. The estimated gain parameters $\tilde{G}$ and $\tilde{b}$ means in-orbit gain parameters, which will be estimated through in-orbit solar calibration.

The first step to analyze the radiance estimation error propagation is to figure out all error contributors. Table 2 shows the identified contributors which are propagated to gain estimation and/or radiance estimation. The uncertainty due to the solar spectrum model and the Sun activity variation has not been considered for this analysis. For the radiance estimation errors, error contributors are divided into a systematic error and a random error; the offset correction errors due to radiometric model error and offset and gain stability are considered as systematic error. The radiometric parameter estimation errors due to ground characterization uncertainty are considered as random error. The radiometric model error is induced by the linear approximation of detector dark current offset for the simplicity of GOCI radiometric model.

Table 2 Error contributors

Error contributors	Type
Radiometric model error	Systematic error
Characterization accuracy of solar diffuser	Random error
Characterization accuracy of DAMD	Random error
Degradation of DAMD over mission life	Random error
Reflectivity variation of pointing mirror	Systematic error
Integration time accuracy	Random error
Sun angle estimation	Random error
Short term offset variation(2 min)	Systematic error
Short term gain variation (2 min)	Systematic error
Long term gain variation (a day)	Systematic error
Noise (SNR)	Random error

Even though the GOCI solar calibration using the solar diffuser covers the full optical and detection chain, any potential differences between the solar calibration and the Earth observation should be examined. There are two potential error contributors due to different operational condition; the system gain change between the Sun view and the Earth view due to the pointing mirror angle variation. The system gain variation (during a day) due to the temperature variation. These dependencies have not been reflected to GOCI radiometric model. Instead these potential errors have been estimated through the ground test. Then, these have been included in GOCI radiometric error budget as a systematic error.

The systematic radiance estimation error is computed, as follows;

$$\frac{e_L}{\tilde{L}} = C_{\rho_{SD(0)}L} \times \frac{e_{\rho_{SD}(0)}}{\rho_{SD}(0)} + C_{\bar{S}^A_{SD}L} \times \frac{e_{\bar{S}^A_{SD}}}{\bar{S}^A_{SD}} + C_{\bar{S}^B_{SD}L} \times \frac{e_{\bar{S}^B_{SD}}}{\bar{S}^B_{SD}} \qquad (4)$$

$$+ C_{\bar{S}L} \times \frac{e_{\bar{S}}}{\bar{S}} + C_{\rho_{SD(0)}L} \times \frac{e_{G_p}}{G} + C_{GL}\frac{e_{G_u}}{G} + C_{bL}\frac{e_{b_u}}{b}$$

where $e_{\rho_{SD(0)}}$ means systematic error caused by solar diffuser aging factor estimation. The systematic errors $e_{\bar{S}^A_{SD}}$ and $e_{\bar{S}^B_{SD}}$ are considered in order to reflect the error caused by in-orbit solar diffuser calibration. The systematic error $e_{\bar{S}}$ means the error contributor introduced during earth view. The mirror reflectivity variation over the incident angle range is also considered as a systematic error contributor, which is presented by e_{G_p}/G. Error propagation coefficient of this optical gain variation is exactly same to $C_{\rho_{SD(0)}L}$ because $e_{\rho_{SD(0)}}$ means optical gain variation. The system gain instabilities during one day are considered as systematic error contributors, which are presented by e_{G_u}/G and e_{b_u}/b.

With assumption of uncorrelation between the radiometric parameter estimation errors, the random error propagation of GOCI is presented by

$$\frac{\sigma_L}{\tilde{L}} = \sqrt{\begin{aligned} &\left(C_{\rho_{SD(0)}L} \times \frac{\sigma_{\rho_{SD(0)}}}{\rho_{SD(0)}}\right)^2 + \left(C_{R^A_{SD}L} \times \frac{\sigma_{R^A_{SD}}}{R^A_{SD}}\right)^2 + \left(C_{\theta^A_{SDl}L} \times \frac{\sigma_{\theta^A_{SD}}}{\theta^A_{SD}}\right)^2 \\ &+ \left(C_{T^A_{SD}L} \times \frac{\sigma_{T^A_{SD}}}{T^A_{SD}}\right)^2 + \left(C_{\bar{S}^A_{SD}L} \times \frac{\sigma_{\bar{S}^A_{SD}}}{\bar{S}^A_{SD}}\right)^2 + \left(C_{R^B_{SD}L} \times \frac{\sigma_{R^B_{SD}}}{R^B_{SD}}\right)^2 \\ &+ \left(C_{\theta^B_{SDl}L} \times \frac{\sigma_{\theta^B_{SD}}}{\theta^B_{SD}}\right)^2 + \left(C_{T^B_{SD}L} \times \frac{\sigma_{T^B_{SD}}}{T^B_{SD}}\right)^2 + \left(C_{\bar{S}^B_{SD}L} \times \frac{\sigma_{\bar{S}^B_{SD}}}{\bar{S}^B_{SD}}\right)^2 \\ &+ \left(C_{T_{\text{int}}L} \times \frac{\sigma_{T_{\text{int}}}}{T_{\text{int}}}\right)^2 + \left(C_{\bar{S}L} \times \frac{\sigma_{T_{\text{int}}}}{T_{\text{int}}}\right)^2 \end{aligned}} \qquad (5)$$

where $\sigma_{\rho_{SD(0)}}$, $\sigma_{R^A_{SD}}$, $\sigma_{\theta^A_{SD}}$, $\sigma_{T^A_{SD}}$, $\sigma_{\bar{S}^A_{SD}}$, $\sigma_{R^B_{SD}}$, $\sigma_{\theta^B_{SD}}$, $\sigma_{T^B_{SD}}$, $\sigma_{\bar{S}^B_{SD}}$ and $C_{\rho_{SD(0)}L}$, $C_{R^A_{SD}L}$, $C_{\theta^A_{SD}L}$, $C_{T^A_{SD}L}$, $C_{\bar{S}^A_{SD}L}$, $C_{R^B_{SD}L}$, $C_{\theta^B_{SD}L}$, $C_{T^B_{SD}L}$, $C_{\bar{S}^B_{SD}L}$ mean the random error contributors introduced through in-orbit solar calibration and corresponding error propagation coefficients, respectively. The error contributors, such as $\sigma_{\rho_{SD(0)}}$, $\sigma_{R^A_{SD}}$, $\sigma_{R^B_{SD}}$ originated from solar diffuser characterization error. Other contributors $\sigma_{T_{\text{int}}}$, $\sigma_{\bar{S}}$ mean the random error contributors introduced during earth view and corresponding propagation coefficients, respectively.

For radiance estimation, major random error contributors are originated from the on-ground characterization error of solar diffuser, such as $\sigma_{\rho_{SD(0)}}$, $\sigma_{R^A_{SD}}$, and $\sigma_{R^B_{SD}}$. Error propagation coefficients for these error sources given by (6) ~ (8) are function of output DN number expect (6), which depends on input radiance level.

$$C_{\rho_{SD(0)}L} = \frac{\rho_{SD}(0)}{\tilde{L}} \frac{\partial \tilde{L}}{\partial \rho_{SD}(0)} = -1 \tag{6}$$

$$\begin{aligned} C_{R^A_{SD}L} &= \frac{R^A_{SD}}{\tilde{L}} \frac{\partial \tilde{L}}{\partial R^A_{SD}} \\ &= -C_{R^A_{SD}G} + \frac{-K-9K^3}{1-K-3K^3}\left\{C_{R^A_{SD}b} - \frac{K}{\tilde{b}\bar{S}^2}\left[3\tilde{G}^3 C_{R^A_{SD}G} + 3\tilde{b}\bar{S}^2 C_{R^A_{SD}b}\right]\right\} \end{aligned} \tag{7}$$

$$\begin{aligned} C_{R^B_{SD}L} &= \frac{R^B_{SD}}{\tilde{L}} \frac{\partial \tilde{L}}{\partial R^B_{SD}} \\ &= -C_{R^B_{SD}G} + \frac{-K-9K^3}{1-K-3K^3}\left\{C_{R^B_{SD}b} - \frac{K}{\tilde{b}\bar{S}^2}\left[3\tilde{G}^3 C_{R^B_{SD}G} + 3\tilde{b}\bar{S}^2 C_{R^B_{SD}b}\right]\right\} \end{aligned} \tag{8}$$

where $K = \frac{\tilde{b}\bar{S}^2}{\tilde{G}^3 + 3\tilde{b}\bar{S}^2}$ and $C_{R^A_{SD}G}$, $C_{R^A_{SD}b}$, $C_{R^B_{SD}G}$, $C_{R^B_{SD}b}$ means the error propagation coefficient of solar diffuser error source for gain parameter estimation.

In order to examine the propagation characteristic of these major error sources according to input radiance level, those error propagation coefficients are calculated. Figure 2 shows variation of error propagation coefficients according to level of output DN number.

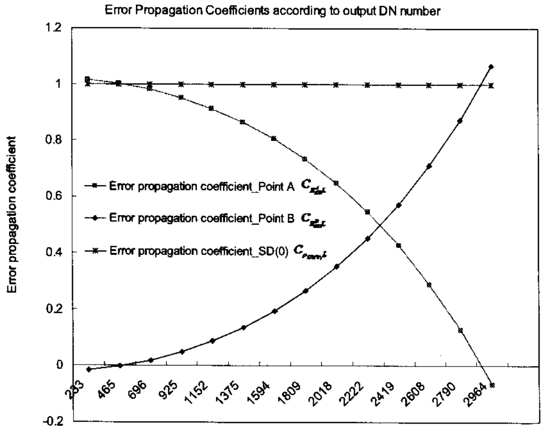

Figure 2. Error propagation coefficients variation

In Figure 2, Point A and Point B, which mean two sun measurement points required for in-orbit solar calibration, are assumed as 500LSB and 2900LSB, respectively. The coefficient $C_{R^A_{SD}L}$, $C_{R^B_{SD}L}$ mean propagation ratios of the on-ground characterization errors of relative diffusion factor R^A_{SD}, R^B_{SD} corresponding to measurement point A and point B, respectively. In Figure 8.1.1, the trend of $C_{R^A_{SD}L}$, $C_{R^B_{SD}L}$ means that the error $\sigma_{R^A_{SD}}$ will be major contributor in case of low output level and the error $\sigma_{R^B_{SD}}$ will be major in case of high output level. Also it is expected that the synthesized error propagation from $\sigma_{R^A_{SD}}$ $\sigma_{R^B_{SD}}$ will be lowest around 2200 DN number. The $C_{\rho_{SD(0)}L}$ is constant over the output range.

The propagation coefficients for each spectral filter at different input radiance level are given in Table 3 and Table 4. It is expected that the estimation errors of linear gain, output signal, and integration time are almost directly propagated to the retrieved radiance.

Table 3. Propagation coefficients for ocean radiance level

	T_{int} (sec)	$C_{R^A_{SD}L}$	$C_{R^B_{SD}L}$	$C_{\bar{S}L}$	C_{TL}
B1	1,18E-01	9.14E-01	8.62E-02	1.02E+00	-1
B2	6,92E-02	9.20E-01	7.97E-02	1.02E+00	-1
B3	7,38E-02	9.11E-01	8.92E-02	1.02E+00	-1
B4	6,61E-02	9.28E-01	7.23E-02	1.02E+00	-1
B5	8,15E-02	9.50E-01	4.95E-02	1.02E+00	-1
B6	1,95E-01	9.54E-01	4.59E-02	1.01E+00	-1
B7	1,65E-01	9.53E-01	4.69E-02	1.02E+00	-1
B8	2,08E-01	9.61E-01	3.94E-02	1.01E+00	-1

Table 4. Propagation coefficients for saturation radiance

	T_{int} (sec)	$C_{R^A_{SD}L}$	$C_{R^B_{SD}L}$	$C_{\bar{S}L}$	C_{TL}
B1	1,18E-01	7.64E-01	2.36E-01	1.06E+00	-1
B2	6,92E-02	7.61E-01	2.39E-01	1.06E+00	-1
B3	7,38E-02	7.25E-01	2.75E-01	1.07E+00	-1
B4	6,61E-02	7.92E-01	2.08E-01	1.05E+00	-1
B5	8,15E-02	7.79E-01	2.21E-01	1.06E+00	-1
B6	1,95E-01	8.22E-01	1.78E-01	1.05E+00	-1
B7	1,65E-01	7.76E-01	2.24E-01	1.06E+00	-1
B8	2,08E-01	7.71E-01	2.29E-01	1.06E+00	-1

5. CONCLUSION

The GOCI which will be first instrument providing the ocean observation from geostationary platform. For the radiometric calibration, the nonlinear radiometric model has been evaluated through the ground radiometric test. Based on this nonlinear model, the radiance calculation formula has been derived. In this paper, the error propagation of estimated parameters is analyzed. The error contributors for radiance estimation have been identified. The radiometric model error, offset variation and reflectivity variation of pointing mirror are considered as error contributor. The errors of ground characterization accuracy of the solar diffuser will be major error contributor and directly propagated to estimated radiance.

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