FULL-FIELD-OF-VIEW STRAY LIGHT ESTIMATION FOR FY-2 METEOROLOGICAL SATELLITE BASED ON THE HIGH-ORDER STATISTICAL EIGENVALUES

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ABSTRACT

Based on the analysis for the principle of the stray light of the FY-2 meteorological satellite, the main component of the stray light, generated from the folding mirror direct reflections, is physically modeled. By learning the pre-known knowledge of the stray light outside of the earth region as well as extracting the high-order statistical eigenvalues of the designated objective areas, the stray light function matrix, **A**, can be calculated using the total least squares (TLS) method, which is applied to the inside of the earth region, and the full-field-of-view (FFOV) stray light estimation can be produced efficiently in the end. It is shown that the mean restoration errors of the stray light outside of the earth region of the IR and WV channels are less than 1 bit, while the daily trend of the restored stray light of the VIS channel is relative stabilization and the stray-light-free images of all channels are better in sight. The estimation method will be used in the operations of the FY-2 and its subsequences in the near future.

Key Words: FFOV Stray Light Estimation, High-Order Statistical Eigenvalues, VISSR, TLS

1. INTRODUCTION

FY-2 uses the spin-stabilized attitude control scheme, which is relatively simple, to alleviate the technological difficulties of the satellite system, however, it is the sacrifice of the reduced scanning ratio, which is about 5%, of the payloads. So, for the designers, increasing the optics efficiency of the payloads is one of their main goals. Currently, the scheme of the field-of-view separation between channels (FOVSBCH) is adopted extensively in the payloads on the same satellite platform of the world and the successful applications in FY-2A and FY-2B confirm its validity.

In fact, everything has the two aspects. When the FOVSBCH scheme is used, the optics system of the payloads will suffer from the larger instant-field-of-view (IFOV), which will introduce stray light easily. On the other hand, because of the use of the telescope tube swing scheme, it is difficult to set the appendages to reduce the incident stray light. Obviously, the best way to restrain the stray light is in the process of the payloads' designs. However, for the satellite ground users, it is necessary to make a reasonable and efficient estimation of the stray light of FY-2 VISSR since the stray light in the system is unavoidable, which offers the required numerical materials for improving the quantitative applications on ground.

Based on the analysis for the principle of the stray light of the FY-2 meteorological satellite, the main component of the stray light, generated from the folding mirror direct reflections, is physically modeled. By learning the pre-known knowledge of the stray light outside of the earth region as well as extracting the high-order statistical eigenvalues of the designated objective areas, the stray light function matrix, **A**, can be calculated using the TLS method, which is applied to the inside of the earth region, and the FFOV stray light estimation can be produced efficiently in the end. It is shown that the mean restoration errors of the stray light outside of the earth region of the IR and WV channels are less than 1 bit, while the daily trend of the restored stray light of the VIS channel is relative stabilization and the stray-light-free images of all channels are better in sight. With relative algorithm and software engineering optimizations, the estimation method will be used in the operations of the FY-2 and its subsequences in the near future.

2. ANALYSIS FOR THE PRINCIPLE OF THE STRAY LIGHT OF FY-2 VISSR

2.1. The main types of the stray light of FY-2 VISSR

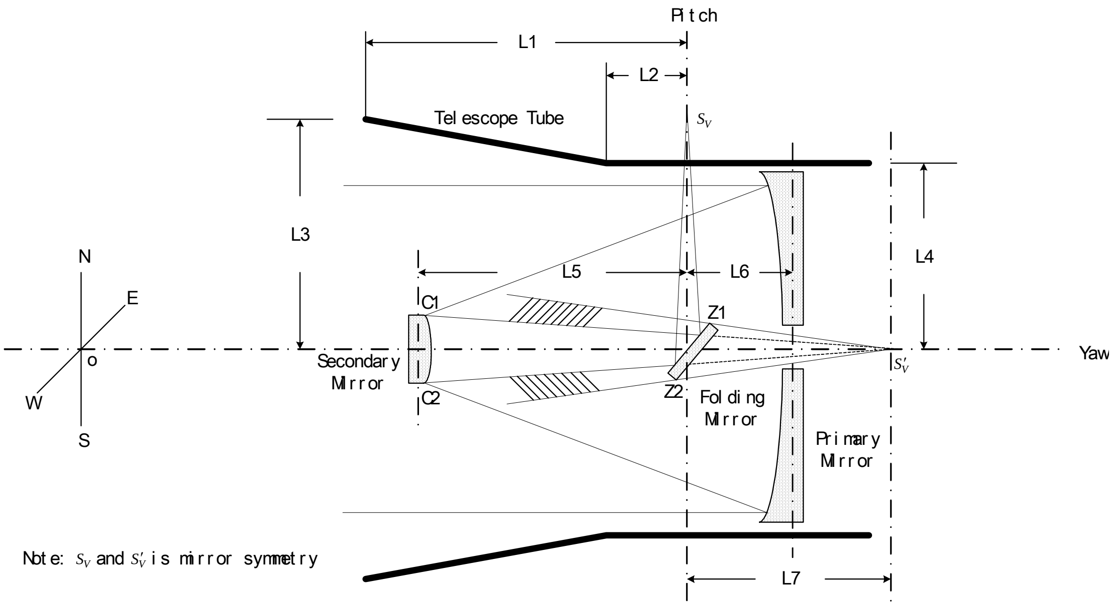


Figure 1. The main optics of FY-2 VISSR side elevation.

There are three different way in which the stray light will be introduced in FY-2 VISSR:

1. The stray light is introduced by the folding mirror direct reflections of the designated objects of the inside of the earth region, which extensively exists in all channels, and its generation principles are invariable daily except for varying with the objects' radiation/reflection characteristics. In fact, this type of stray light is the main component of FY-2 stray light and will be modeled in the paper.
2. At about middle night of the satellite local time, the stray light is introduced by solar direct incidence to the telescope tube in the VIS channel. At that time, since the illuminated earth region is a nearly crescent form and the images have little quantitative application value, this type of stray light is ignored in the following discussions.
3. The stray light is introduced by the radiation from the VISSR in the IR channel. It should be pointed out, when the daily variety of the temperature of the VISSR is apparent, for example exceeding 10K, the impact of this type of stray light will be obvious. Practically, because FY-2 is a spin-stabilized satellite, which suffers little from the solar direction illumination, the introduced stray light of this type will be also ignored in this paper.

It can be drawn that the main component of the stray light of FY-2 VISSR is the stray light introduced by folding mirror direct reflections of the designated objects of the inside of the earth region. The generation principles will be analyzed in details in the following section.

2.2. The model of the stray light introduced by the folding mirror direct reflections

At the beginning, for the convenience of the analysis, the FY-2 VISSR optics system side elevation is shown in Figure 1. In the figure, the shadow areas of ∠Z1Sv'C1 and ∠Z2Sv'C2 are the folding mirror direct reflection areas of the center position of the VIS sensors at the subsatellite point. According to the structures of the optics and mechanism of VISSR, Figure 2 shows the folding mirror direct reflection areas of the position designated in the Figure 1, which uses the polar coordinates. In the figure, the positions on the 0, 90, 180 and 270 degrees represent the East, the North, the West and the South respectively and the radial values equal to the numbers of the standard pixels. Meanwhile, the corresponding areas of the IR and WV sensors can also be calculated accurately.

Accurate analysis shows that the folding mirror direct reflection areas corresponding to different scan positions are slight different during the VISSR scanning, the effects of which on the high-order statistical eigenvalues of the designated areas can be omitted. However, the differences among the different sensors must be considered and the designated area templates should be offered respectively.

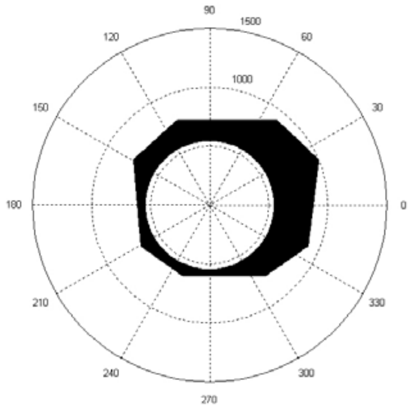


Figure 2. The area of the folding mirror direct reflection in the subsatellite point.

3. THE BASIC MATHEMATIC MODEL AND ANALYSIS

It can be concluded that the main approach in which the stray light is introduced is the folding mirror direct reflections from the analysis of the generation principles of the stray light above. Unfortunately, the interaction and process of the energy transformation between the radiation/reflection of the objective areas which cause the stray light and VISSR are still unknown, which contains two aspects: one is that because the stray light is from the off-axis objects and free of the reflections of the primary mirror and the secondary mirror, the different principles in imaging between the stray light and the parallel light from the current scan object is apparent; the other is that when the stray light from different reflection ways are considered, the issue will be extremely complex and the direct modeling for the stray light is quite difficult. So, the mapping between the designated area (refers to the folding mirror direct reflection area) and the stray light quantitative values on the scan position is established, from which the issue will be solved further.

The basic approach of the FFOV stray light estimation is that, based on learning the pre-known knowledge of the stray light of all the channels outside of the earth region, the stray light function matrix, **A**, can be calculated, which is applied to the inside of the earth region, and the FFOV stray light estimation can be produced reasonably, and the flow chart of which is shown in Figure 3. In above process, there are two hypothesizes are made:

1. The stray light distribution outside of the earth region contains all the information of the total stray light, which means that the model function can be described fully with them.
2. During the 25 minutes of the imaging of the VISSR, the model's characteristics are linear and invariable.

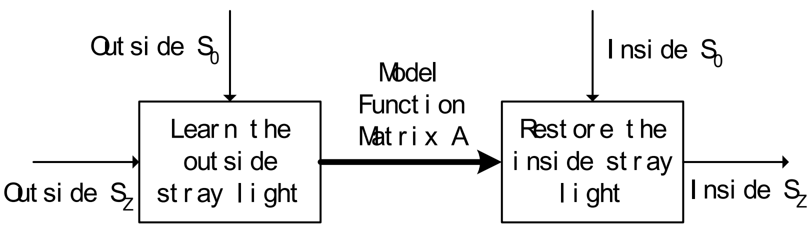


Figure 3. The flow chart of FFOV stray light estimation model.

Considering these factors, the basic mathematic model can be expressed by:

$$\mathbf{S}_Z = \mathbf{S}_0 \cdot \mathbf{A} + \mathbf{e} \tag{1}$$

Where $\mathbf{S}_Z$ is $m \times 1$ stray light matrix, $\mathbf{S}_0$ is $m \times n$ stray light information input matrix, $\mathbf{A}$ is $n \times 1$ stray light function matrix, and $\mathbf{e}$ is $m \times 1$ observation error matrix, which is assumed to be satisfied with the normal distribution.

For the reason of the obvious non-gauss distribution of the histogram of the stray light in the images, the high-order (1~4th order) central moments are selected as input eigenvalues of the designated area. When the random variable X is used to present the quantitative values of the radiation/reflection of the designated area, the corresponding i th order central moment is defined as follows:

$$\mu_i = E\left\{\left(X - E[x]\right)^i\right\} \qquad i = 1,2,3,4 \tag{2}$$

Here, the physical meaning of each order central moment is presented respectively. Specially, When $i = 3$, $s = \mu_3 / \sigma^3$ is defined as the skewness coefficient, which describes the asymmetry of the probability density and represents the scales of the deviation to the symmetry center in the image histograms, as shown in Figure 4-1. When $i = 4$, $K = \mu_4 / \sigma^4$ is defined as the kurtosis coefficient, which describes the acuity of the probability density and represents the scales of the collection to the mean in the image histograms, as shown in Figure 4-2. The kurtosis coefficient of the gauss distribution equals 3.

Moreover, in order to describe the spatial distribution of the stray light, the unit coordinates of the current scan position on the project plane are included in the eigenvector of the model. So, the total number of the eigenvalues in the model is six and the model function matrix, A, can be expressed by:

$$\mathbf{A} = [a_0, a_1, a_2, a_3, a_x, a_y]^T \tag{3}$$

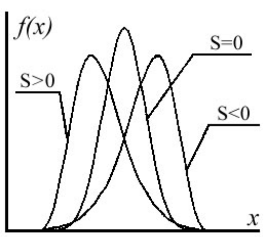


Fig. 4-1 The probability densities with different skewness coefficient

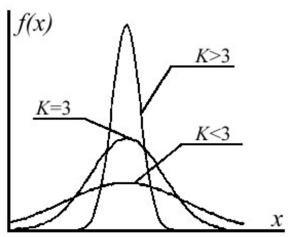


Fig. 4-2 The probability densities with different kurtosis coefficient

Figure 4. The probability densities with different high-order central moments.

To gather as more as possible information about the stray light model, normally, the number of the learning samples, m, is satisfied with $m >> n$, and the equation (1) is a classic overdetermined algebraic equation and its best compromise solution can be got by using the linear least squares method. The relative issues can be found in some literatures and not be discussed further here.

4. EXPERIMENT RESULTS

In order to confirm the validity of the FFOV stray light estimation model, nine FY-2B VIS images (marked with BJT) in Jan 4 2001 are selected in Figure 5. Using the model and the relative statistical methods, the dynamic range and the stray light mean of each image are calculated and plotted with the time in Figure 6. The results show, because the angle between the solar incident light and the earth project plane and the albedo both reach the minimums at about BJT06:00, the dynamic rang of the image is minim. At the same time, the calculated mean of the stray light almost reaches the nadir. Similarly, because the solar incident angle is maxim at about BJT12:00, the dynamic range and the stray light mean of the image nearly reach the peak points simultaneously. The above results approve the validity of the model in some content. On the other hand, to know more about the visual effects of the stray-light-free images of each channel, the IR, WV images at BJT13:00 Jan.1 2004 with semi-disc mode and VIS images at BJT13:00 Jan.4 2001 with full-disc mode are processed and the output images are shown in Figure 7.

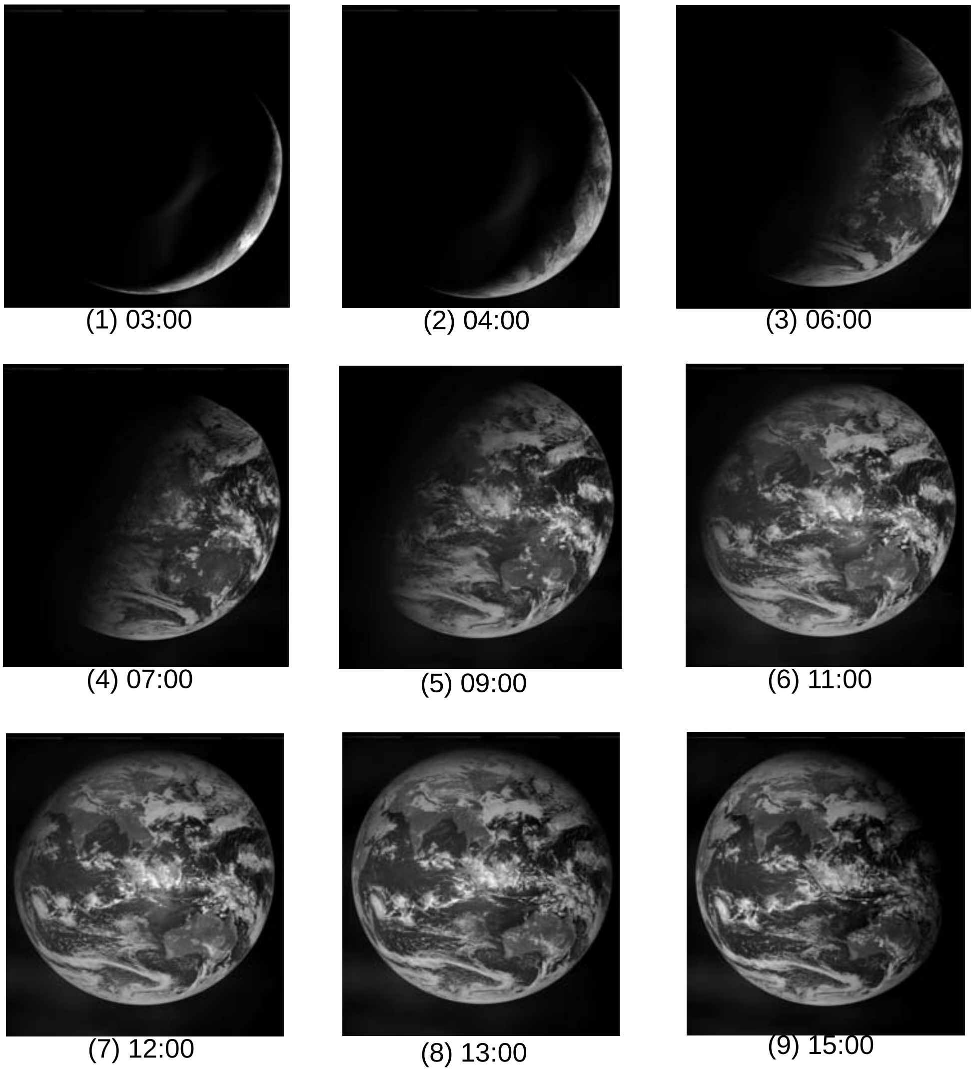


Figure 5. Nine FY-2B VIS images in different acquisition time in Jan 4 2001.

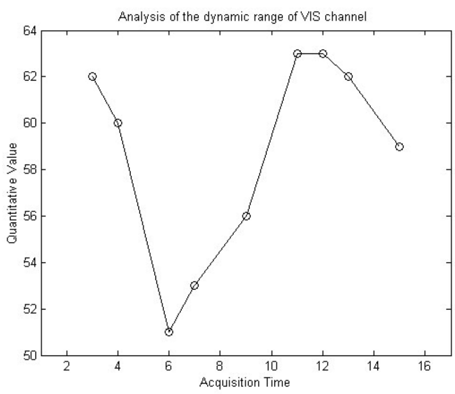


Fig. 6-1 The dynamic range of VIS channel

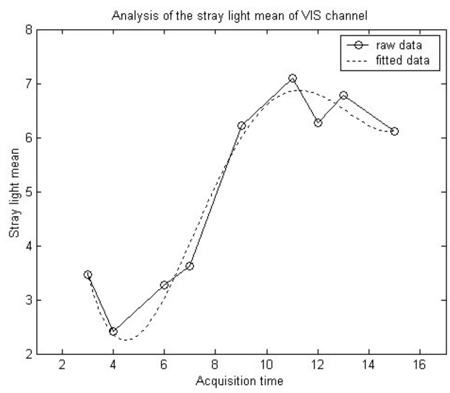
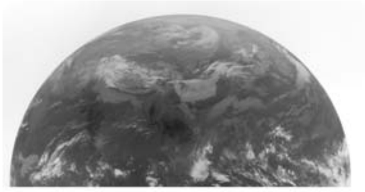
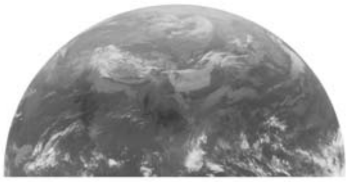


Fig. 6-2 The stray light mean of VIS channel

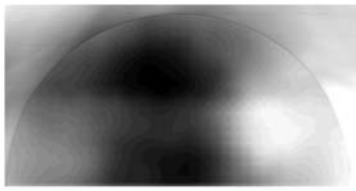
Fig. 6 The estimation of VIS channel stray light



(1) IR semi-disc raw

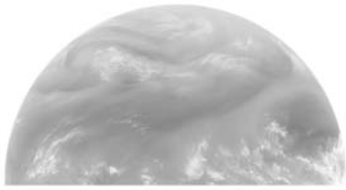


(2) IR semi-disc stray-light-free image

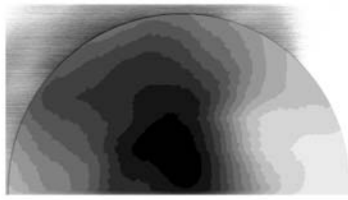


(3) IR stray light enhancement image

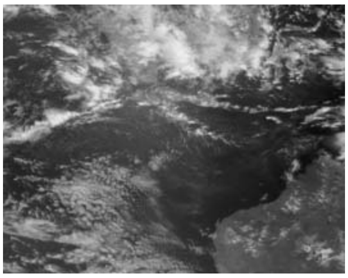
(4) WV semi-disc raw image



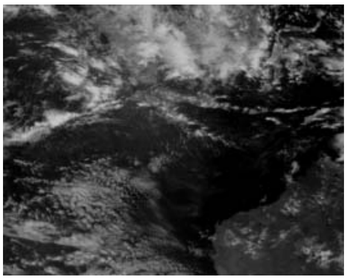
(5) WV semi-disc stray-light-free image



(6) WV stray light enhancement image



(7) VIS raw area image



(8) VIS stray-light-free area image

(9) VIS stray light area enhancement image

Figure 7. The contrast of the analysis of the stray light of IR, WV and VIS channels

Figure 7-3 and 7-6 are the estimation of the stray light in IR and WV images respectively. Apparently, the total trends of the estimated stray light are degressive in quantity from west to east outside of the earth and appear some larger values inside of it , which represent some gradual distributions and are almost complied with the principle analysis (illustrated in the Figure 2) and the simulations in lab, while the visual effects have been improved significantly. Moreover, at the noon of the satellite local time, because of the increased albedo, the Australia continent and its near sea area, which are closed to the subsatellite point, are covered with a layer of heavy white gauze, namely the stray light effects, shown in Figure 7-7. However, the processed stray-light-free VIS image in Figure 7-8 is better in sight and its definition has been improved greatly.

Furthermore, the restored results from multiple times and multiple sample combinations of the outside of the earth region of each channel, show that the restored mean error of the stray light is less than 1 bit in IR and WV channels as well as less than 2 bits in VIS channel.

5. ANALYSIS OF THE MODEL PERFORMANCE

5.1. Edge-detection of each channel effects on the performance of the stray light estimation

In effect, the base of FFOV stray light estimation model is to learn the pre-known knowledge of the stray light outside of the earth region. Obviously, the first step is to get the positions of the earth edge. The relative edge-detection algorithms can be seen in reference [3] and be omitted here.

For the IR and WV channels, because what VISSR gathers are radiation energy from the objects of the earth, the earth edge will not change with the transform of the relative positions among the satellite, the earth and the sun, and the edge profile is basically normal. So the mean difference between the edges from this model and the accurate navigation information is less than 2 pixels, which can be depressed by the quality control method used in the learning of the pre-known stray light.

However, for the VIS channel, because what VISSR gathers are reflection energy from the objects of the earth, the actual earth edge will change with the transform of relative positions among the satellite, the earth and the sun daily. And at about 06:00 and 18:00 of the satellite local time, for the solar incident angle is very small, the edge of the earth, which is farther from the sun, is ambiguous greatly and could not be detected accurately. To solve the problem, it should be done that the solar illuminating areas of each acquisition time is gained by the relative positions among the satellite, the earth and the sun ahead of time, which will be benefit to the accurate edge detection and must be considered in the following operations.

5.2. Model errors effect on the performance of the stray light estimation

In theory, when gathering the input eigenvector of the folding mirror direct reflection area of the current position, the analyzed objects must be the true object information of the earth, but in fact, they are substituted with the pixel values of the image with additional stray light information. This is main error of the model.

In order to remove the model error, the $m \times n$ stray light information input error matrix $\mathbf{E}$ is introduced and the equation (1) can be overwritten by:

$$(\mathbf{S}_0 + \mathbf{E}) \cdot \mathbf{A} = \mathbf{S}_Z + \mathbf{e} \tag{4}$$

The matrix $\mathbf{E}$ in equation (4) is regarded as a disturbance added on the $\mathbf{S}_0$, so it is necessary to use the total least squares (TLS) method to solute the equation. The basic way can be summarized as follows: disturbing $\mathbf{S}_0$ and $\mathbf{S}_Z$ simultaneously to adjust the existent noises in both matrixes, while remaining the norm-square of the disturbances minimum.

5.3. Choice of the model input eigenvalues effects on the performance of the stray light estimation

In order to describe the mapping between the statistical eigenvalues and the stray light distribution on the corresponding position accurately, it is very important to choose the reasonable and integrated input eigenvalues of the model. The real results show that, in the stray light function matrix **A**, the model coefficients of the high order statistical eigenvalues, namely the third and the fourth ones, are almost 102 order times larger than that of the first and the second order statistical eigenvalues. So, selecting the high order statistical eigenvalues is exactly right.

6. CONCLUSIONS

Based on the analysis for the principle of the stray light of the FY-2 meteorological satellite, the main component of the stray light, generated from the folding mirror direct reflections, is physically modeled. By learning the pre-known knowledge of the stray light outside of the earth region as well as extracting the high-order statistical eigenvalues of the designated objective areas, the stray light function matrix, **A**, can be calculated using the TLS method, which is applied to the inside of the earth region, and the FFOV stray light estimation can be produced in the end efficiently.

The estimation method offers a feasible approach to restore, analyze and evaluate the performance of the stray light of the on-orbit imager from the images directly. With relative algorithm and software engineering optimizations, the estimation method will be used in the operations of the FY-2 and its subsequences in the near future and provide the possibility of improving the performance of the quantitative applications of FY-2 meteorological satellite on ground in some degrees.

7. REFERENCES

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