Illumination-based Real-Time Contactless Synchronization of High-Speed Vision Sensors

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Abstract—**To acquire images of a scene from multiple points of view simultaneously, the acquisition time of vision sensors should be synchronized. In this paper, an illumination-based synchronization technique derived from the phase-locked loop algorithm is proposed. Both Simulation results and experimental results show that the operation of vision sensor can be successfully locked to the corresponding edges of an intensity-modulated LED illumination signal in real time, as long as the feedback gain is empirically chosen with the help of MATLAB simulation.**

Index Terms—**Camera Synchronization, Phase-Locked Loop, Visible Light Communication**

I. INTRODUCTION

The emphasis on the vision sensor technology becomes more and more evident in various fields such as automotive, human machine interface, surveillance and security, and industry control. When vision sensors are used to take multiple points of view simultaneously, the acquisition time of the sensors should be synchronized. Usually this synchronization is done through a dedicated bus or a wired network [1], [2].

In this paper, the authors explore into an illumination-based synchronization, rather than the conventional synchronization based on wired buses. This breakthrough is believed to contribute to convenient distribution of vision sensors, meanwhile reducing the propagation delay of synchronization signals as much as possible to ensure small synchronization errors.

To realize the illumination-based synchronization, an algorithm based on the phase-locked loop (PLL) theory [3] is proposed, which can generate steadily synchronized output signals in real time. Specifically, in the contactless illumination-based synchronization system, as shown in Fig. 1 the reference signal is an optical one, in a specific case, an intensity-modulated LED illumination. The output signal of PLL corresponds to a series of the electronic shutter timing of the vision sensor. If a phase error between the reference and the
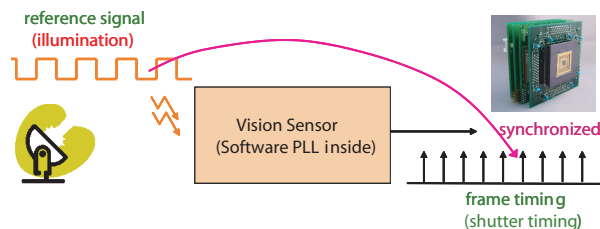

Fig. 1. Conceptual diagram of the proposed illumination-based synchronization.

output builds up, it will be negatively fed back to the frame time length of vision sensor in such a way that the phase error is again reduced to a minimum in real time. In this way, the vision sensor can fire automatically synchronized according to the properties of the modulated reference signal.

To implement the proposed technique, we require an illumination source which is intensity-modulated at a frequency on the order of the target vision frame rate (namely, half of the frame rate). If the target frame rate is, for example, 30 Hz, the illumination has to be modulated at 15 Hz and this kind of low-frequency blinking may be annoying to human eyes, and thus impacts on the popularization of the illumination-based synchronization technique. One way to address this issue is to use an invisible light such as an infrared light, and another way is to focus on high frame rate vision techniques [4] so that the modulation effect of illumination is not perceptible to human eyes at all. In this paper, the authors focus on the latter because the former is trivial, and also because synchronizing high frame rate vision sensors is particularly challenging comparing to the state of arts synchronization techniques.

II. SYNCHRONIZATION ALGORITHM

A. Digital PLL theory

PLL was introduced in 1932 by de Bellescize. Precisely, a PLL is a circuit synchronizing an output signal with a
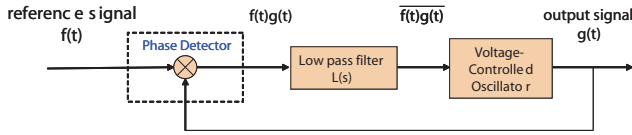
Fig. 2.   Block diagram of DPLL.

reference or input signal in frequency as well as in phase. In particular, a digital PLL (DPLL) is a PLL in which the
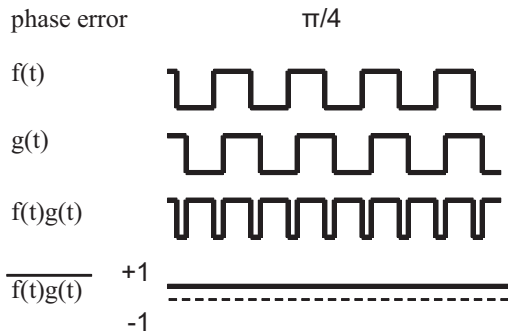

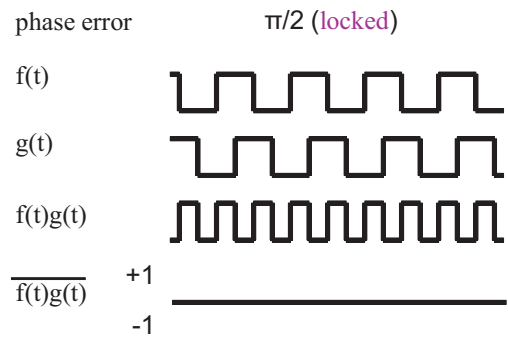Fig. 3.   Example of the computation of the phase errors, with pi/4 phase shift.

Fig. 4.   Example of the computation of the phase errors, with pi/2 phase shift.

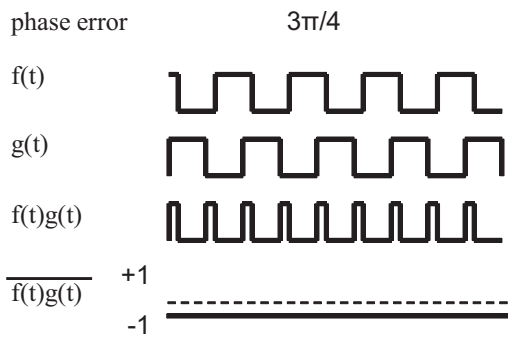

Fig. 5.   Example of the computation of the phase errors, with 3pi/4 phase shift.

input and the output are binary signals consisting of *HIGH* or *LOW* values. The block diagram of a standard DPLL is shown in Fig. 2. The function of the PD is to compute the product $f(t)g(t)$ of the reference signal $f(t)$ and the output signal $g(t)$. The average output $\overline{f(t)g(t)}$ of the phase detector, which is generated by the LPF, depends on the phase error θ_e between $f(t)$ and $g(t)$ as shown in Fig. 3, Fig. 4 and Fig. 5. The voltage-controlled oscillator (VCO) generates a square-wave signal of which the frequency is determined by the input $\overline{f(t)g(t)}$ in real time.

When the difference between the phases of the reference and the output signals is $\pi/2$, as shown in Fig. 4, $\overline{f(t)g(t)}$ is zero and thus the output frequency is stable at the central frequency of VCO. This state is called the locked state. Otherwise, as shown in Fig. 3 and Fig. 5, the average output of the phase detector $\overline{f(t)g(t)}$ exhibits positive or negative values, which makes VCO generate a higher or lower frequency than its central one so that the phase deference can converge to $\pi/2$ consequently after some running time.

At the present time, due to the large impact of microprocessors, the logic *and/or* arithmetic operations within the building blocks can be executed by software if the desired operation frequency is not so high. The algorithm proposed in the following parts of this paper is a software PLL for the most components, while the functions of the phase detector and part of the low pass filter are achieved by way of optical analog processing. Software-based function blocks of DPLL, such as phase detector, low pass filter, and digitally controlled oscillator can be designed according to its DPLL prototype.

B. Proposed algorithm

A digital PLL makes use of the average phase error between the reference signal $f(t)$ and the output signal $g(t)$, to adjust the output signal frequency. This average phase error can be expressed as a time-domain correlation integral

$$\frac{1}{T} \int_{t-T}^{t} f(\tau)g(\tau)\,d\tau \tag{1}$$

of them. Here, T is the period of the *correlation time window*, which should be sufficiently longer than a vision frame period. In a typical DPLL, both $f(t)$ and $g(t)$ are considered to be square waves of which the highest and the lowest values are 1 and -1, respectively.

However, when the reference signal is expressed in an intensity-modulated light, negative signal values are unachievable. Instead, the authors employ a square wave of which the low value is 0 and the high value is 1 as the reference signal. Let $f'(t)$ be the original square wave whose

amplitude set is $\{-1, 1\}$, then the new $f(t)$ is

$$f(t) = \frac{1}{2}f'(t) + \frac{1}{2} \qquad (2)$$

where the illumination is *on* (bright) while $f(t) = 1$, and *off* (dark) while $f(t) = 0$.

The DPLL will work on this new reference signal $f(t)$ just in the same way as on $f'(t)$ as long as $g(t)$ is a 50 % duty-ratio square wave whose amplitude set is $\{-1, 1\}$ because

$$\frac{1}{T}\int_{t-T}^{t} f(\tau)g(\tau)d\tau \qquad (3)$$

$$= \frac{1}{T}\int_{t-T}^{t} (1/2f'(\tau) + 1/2)g(\tau)d\tau \qquad (4)$$

$$= \frac{1}{2T}\int_{t-T}^{t} f'(\tau)g(\tau)d\tau + \frac{1}{2T}\int_{t-T}^{t} g(\tau)d\tau \qquad (5)$$

$$= \frac{1}{2T}\int_{t-T}^{t} f'(\tau)g(\tau)d\tau \qquad (6)$$

where the integration result of $\frac{1}{2T}\int_{t-T}^{t} g(\tau)d\tau = 0$. This signal modification is commonly used in many optical implementations of the time-domain correlation [5], [6].

We assign the odd-number frames of vision sensor to the periods where $g(t) = 1$ and the even-number frames to $g(t) = -1$, referring to $g(t)$ as the frame state signal. This is shown in Fig. 6. Therefore, the frame rate of vision sensor will be twice the frequency of the illumination signal.

Next, we have to consider how the product $f(t)g(t)$ is computed. Most vision sensors operate in frame-based manners, that is, time-domain integral of incident light brightness over one frame time is obtained as a pixel value at the end of the frame time, and therefore the input value $f(t)$ or the product $f(t)g(t)$ at any arbitrary time instant is not available. However, by considering that $g(t)$ is a constant during one frame period, we can obtain the time correlation as

$$\frac{1}{T}\int_{t-T}^{t} f(\tau)g(\tau)d\tau \qquad (7)$$

$$= \frac{1}{T}\sum_{i}(-1)^{i-1}F[i] \qquad (8)$$

where i is the frame number index and $F(i)$ is the pixel value (more precisely, sum of the pixel values is used in the implementation) obtained within frame i. Whereafter, summation over a correlation time window normalized with the window size T is replaced by an IIR low pass filter:

$$\text{LPF}[i] = k \cdot \text{LPF}[i-2] + (1-k) \cdot (F[i-1] - F[i]) \qquad (9)$$

which is recursively computed every two successive frames, where k is the coefficient that determines the characteristics
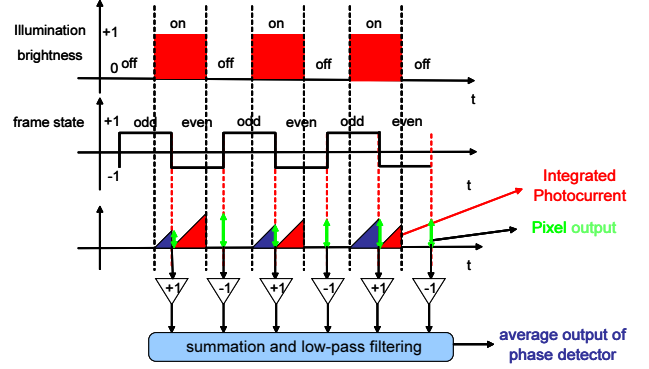

Fig. 6. The proposed algorithm.

of the filter, and LPF$[i]$ is the low pass filter output at the frame i. The term $(F[i-1] - F[i])$ expresses the phase error obtained over the recent two frames. The length of frame time is then adjusted according to this output of low pass filter.

The whole procedure is depicted in Fig. 6. To implement this algorithm, we do not need any dedicated pixel structures, unlike some prior proposals [5], [6]. The only issue we have to assume is that we can precisely adjust the frame time length of the sensor in real time, for example, with the help of built-in camera functions or by controlling external trigger signals. To put it the other way around, it is difficult to use the proposed method when there is no means to control the frame time length.

It should be noted that the blinking illumination does not disturb the visibility of the scene. This is because the vision sensor gets locked with the $\pi/2$ phase shift, the sensor operates so that a half of every frame time is covered by the period when the illumination is on, and the accumulated incident light within one frame time is always constant. Thus the synchronization can be done simultaneously with image acquisition.

In the following simulation and experiments, the adjustment of frequency was realized by either prolonging or shortening every frame period in real time during the non-integration time of a frame. More specifically, a frame time is composed of an integration period in which photons are accumulated and an immediate non-integration period.

III. SIMULATION RESULTS

The authors carried out numerical simulation for the proposed algorithm to explore feasible parameters and analyze their behaviors.

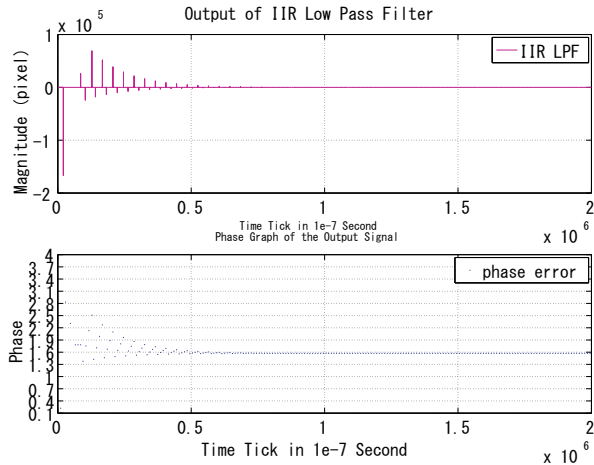The proposed algorithm was implemented in MATLAB (R2007a) along with the generation of input signal. Con-

Fig. 7. Simulated result of the case 2. The upper figure shows the low pass filter output and the lower shows the relative phase shift of the output signal to the reference.

sidering the specification of the vision sensor used in the real experiment described in the next section, we adopted the following setup parameters:

- basic reference frequency: 500 Hz (that is, the basic vision frame rate is 1,000 Hz),
- number of pixels: 64×64,
- pixel value when the illumination is on: 63,
- pixel value when the illumination is off: 0,
- low pass filter coefficient (k): 3/4.

The sum of all the pixel values in the images is computed and it is used as $F[i]$. At the primary stage, all sorts of background illumination is not taken into account. However, a comprehensive analysis and discussion will be carried out in the following section of this paper.

The setups for the simulation and the results are summarized in Table I. Here, the gain is the ratio of the frame time growth (in 10^{-6} s)[1] to the output of low pass filter.

One of the simulated results, with the case 2 where the gain = 0.04, is shown in Fig. 7. The upper figure shows the output of low pass filter and the lower shows the output phase relative to the reference signal. In this case, adjustment of frequency finally converged to the desired value after some slight vibrations.

As long as the gain value was within the correct range, the output signal of PLL got synchronized for the most cases. The optimal value will be determined later within this range when being applied to real hardware use. The ratio of the upper and lower limits of the gain with which the system

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[1]The reason the authors measure the time in 10^{-6} s is because it is the clock cycle time of the vision sensor used in the real experiment.
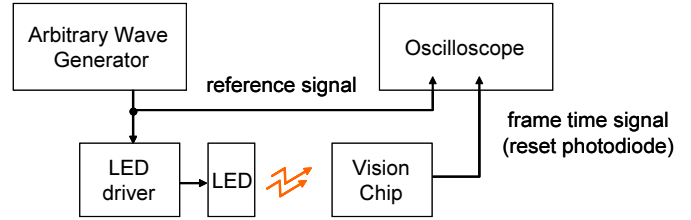

Fig. 8. Experiment set up.

was operational was 20, which means the system works well for a reasonably wide range of the gain setting.

As an exception, the case 4 exhibited an unstable behavior where the relative phase shift diverged, although the gain was within the correct range. The cause is not clear yet, and further investigation is needed.

IV. EXPERIMENT AND DISCUSSION

A. Structure of the experiment system

Figure 8 shows the block diagram of the experiment system. A high-speed vision system VCS-IV [4] was used as a vision sensor, which includes a digital vision chip, a CMOS image sensor each pixel of which has a programmable processing element. The reason the authors chose it is because it can operate at high frame rate (e.g. 1,000 fps) and also its frame time, either the integration period or the non-integration period, can be easily adjusted by software. Although it has a capability to execute pixel-parallel image processing programs on the focal-plane processing element array, it is not utilized in this experiment but instead only the summation of the digital pixel values over the array is computed on the focal plane. This pixel sum is used as $F[i]$ just in the same way as done in the simulation.

The illumination system consists of a Nissin Electronics LDR-90 LED arrray and an LPR-30W-D power supply system, which are externally driven by a Tektronics AFG3102 arbitrary wave generator. The operation of the vision system was measured by observing the pixel reset signal of the sensor, whose positive edge corresponds to the beginning of a frame, with a Tektronics TDS3034 oscilloscope. If the operation of the vision system is locked to the illumination, synchronized waveforms of the pixel reset and the reference signal are observed in the oscilloscope.

B. Experimental results

According to the proposed algorithm, the flowchart of the experimental algorithm is shown in Fig. 10.

When the LED light directly shed on the vision sensor, as shown in Fig. 9, as long as appropriate parameters such as

Table I

SIMULATION SETUPS AND TRACKING RESULTS

case	reference frequency	gain	initial phase difference	output frequency	state
1	500 Hz	0.002	$1/5\pi$	1,000 Hz	locked
2	500 Hz	0.04	$1/5\pi$	1,000 Hz	locked
3	500 Hz	0.05	$1/5\pi$	fluctuant	unlocked
4	500 Hz	0.031	$1/5\pi$	fluctuant	unlocked
5	500 Hz	0.04	$(n+3/2)\pi$	1,000 Hz	locked
6	510 Hz	0.04	$1/5\pi$	fluctuant	unlocked
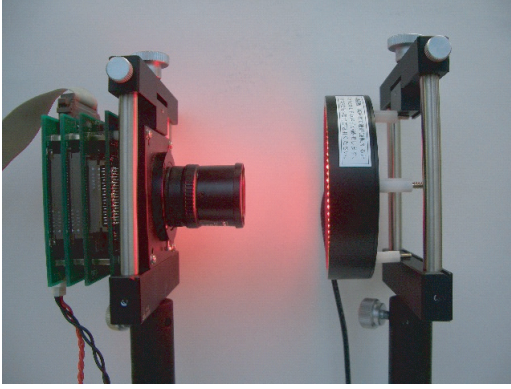
Fig. 9. Experimental setup of a direct LED illumination case.

Fig. 10. The flowchart of the algorithm.

the gain were selected, the electronic shuttering time of the vision sensor got synchronized with the $\pi/2$ phase shift and twice the frequency of the input signal as shown in Fig. 11.

The peak-to-peak jitter of the output signal was also measured with the help of oscilloscope. Although the jitter varied depending on experimental conditions, its typical valve was 32.0 μs, as shown in Fig. 12, Since the expected frequency of vision frame is 1,000 Hz, the jitter is 3.2 % of the frame time, which approves the possibility of illumination-based synchronization.

The ranges of appropriate parameters depended on the experimental conditions such as the illuminance on the focal plane, as is instinctively anticipated.

Because the proposed algorithm takes difference of pixel values in successive frames as its input, the results do not depend on background illumination, and thus the synchronization was also successful even when the sensor was indirectly illuminated, that is, when the vision sensor observed a scene illuminated by the LED, as long as all the parameters were chosen appropriately.

In virtue of the proposed algorithm, the synchronization is robust to small internal frequency errors. Actually, the operation of the vision sensor was stable when the frequency range of the modulated LED light was between 343 Hz and 606 Hz. However, the larger the frequency difference is, the larger the steady-state phase error becomes.
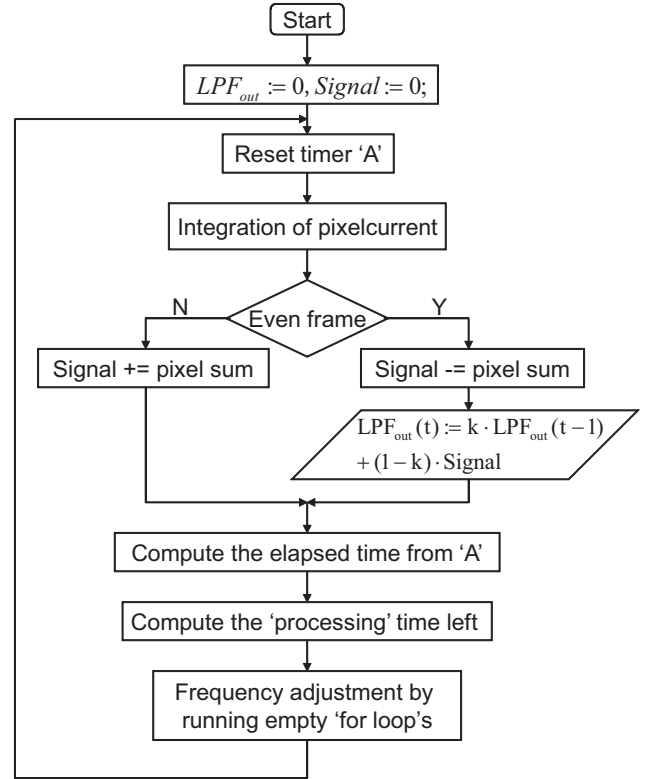
The most fatal problem in the proposed system is that it is not robust to changes in illumination signal brightness because the gain parameter must be set in accordance with it, as shown in Fig. 13. This situation can easily happen, for example, when the scene includes moving objects or the vision sensor is moving. This problem must be overcome by introducing a signal normalization technique.

V. CONCLUSION

An illumination-based synchronization technique based on PLL for high-speed vision sensors has been described. Experimental results show that the sensor operation can be successfully locked to an LED illumination signal as long as
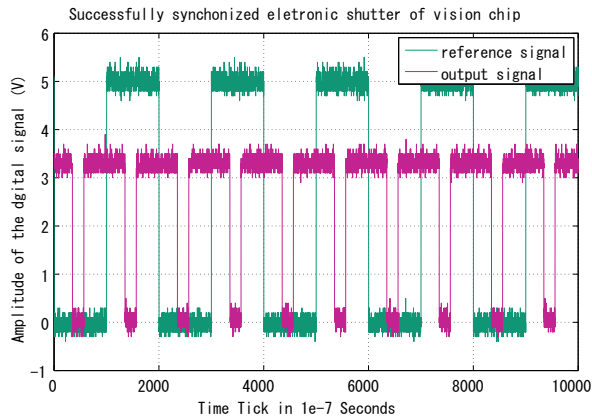
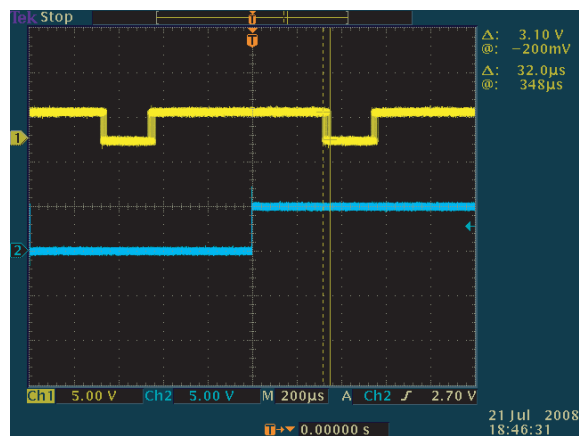Fig. 11. Successfully synchronized electronic shutter, compared to the reference signal.

Fig. 12. Peak-to-peak jitter (△ readout) of the vision frame.

the gain parameter was carefully chosen to fit the illumination signal brightness. This dependency should be removed in
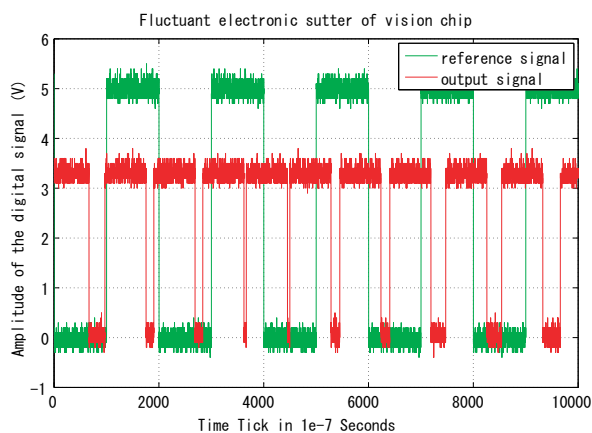
future work.

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Fig. 13. Fluctuant electronic shutter of vision chip because of dynamic disturbance that affected the integration value of average brightness.