Calculation stellar detection limit for active pixel sensor*

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Abstract: The stellar detection limit(SDL) of image sensor is a key parameter of star tracker. It plays an important role in the selection of guide stars and the star pattern identification. In order to calculate the SDL of CMOS active pixel sensor (APS), the model of star influx and the noise model of APS are presented. The main noise sources of APS are analyzed. If SNR and total noise of APS are given, the SDL of APS can be calculated based on the typical response of 0 magnitude visual star per second per mm^2. As an example, a specific SDL of APS is provided with given optical parameters and exposure time.

Key words: Detection limit; Active pixel sensor; Stellar radiation; Temporal noise

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有源像素传感器恒星探测极限计算方法*

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摘要:恒星探测极限是星跟踪器的一个关键参数,在导航星库的建立和星图识别过程中起着重要作用。根据恒星辐射模型和 CMOS 有源像素传感器的噪声计算模型,提出了一种在给定信噪比和有源像素传感器噪声条件下,计算星跟踪器恒星探测极限的方法。该方法利用单位时间内、单位面积上有源像素传感器对 0 星等恒星的响应来求取恒星探测极限。最后,在信噪比为 8 的条件下,结合星跟踪器的有关参数给出了一个计算恒星探测极限的具体实例。

关键词:探测极限; 有源像素传感器; 恒星辐射; 随机噪声

0 Introduction

Most spacecrafts use a star tracker to determine its 3-axis attitude[1]. CCD image sensor (CCDIS) has been successfully applied in the star tracker, while CMOS image sensor is more suited for the star-tracking application [1] than the CCDIS. It has many advantages such as lower cost, lower power consumption, bigger blooming threshold, higher dynamic range, highly integrated, and the flexible readout models. Unfortunately, CMOS image sensor also has some disadvantages, mainly due to noise performance and the nonuniformity.

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One key parameter of star tracker is the SDL of image sensors. It plays an important role in the selection of guide stars and the star identification. Most star trackers select guide stars using the magnitude filtering method, where stars those are brighter than or equate to a given visual magnitude threshold in a star catalog are chosen as guide stars[2].The selection of visual magnitude threshold must consider the SDL of image sensor. In addition, SDL is also needed in star identification, since brightness is usually used as the secondary information. The SDL of CCDIS has been studied clearly. The purpose of this paper is to investigate the SDL of CMOS APS.

1 Comparison of APS and CCDIS

CCDIS and APS have different configuration of amplifiers and operation models, which leads to their different performance in sensitivity and temporal noise. In general, CCDIS has low noise and high uniformity, because the charge from every pixel is sequentially converted to voltage signal by the same chip level output amplifier[3]. Unlike the CCDIS, APS adopts digital memory style readout, using the row decoders and column amplifiers. By this way, readout can be very fast and consumes very low power. Random access of pixel value becomes possible, allowing selective readout of windows of interest.

CCDIS and APS have different fill factors (FF) and quantum efficiency (QE), which is closely link to the SDL of APS. FF is a measure of the pixel's photons capturing sensitivity. Generally FF of CMOS APS is 10%~25% while it is 50%~80% for CCDIS[4]. Lower FF of APS brings a lower photons sensitivity. QE is the fraction of photons impinging on a pixel's photons sensitive area that are effectively converted into photoelectrons. For normal silicon processes, QE is in the range of 20%~40% for the visible band, depending on the actual pixel layout. Standard CMOS APS has lower quantum efficiency: typically 30%~40% against 80% for the best CCDIS[4].

2 Sensitivity of APS

Assuming the black body radiation model for star emission, its spectral distribution can be described by wavelength and radiation color temperature T_c[5]. The power influx from a star is given by[6]

$$E_S(\lambda,T)=\frac{2\pi hc^2}{\lambda^5[\exp(hc/(\lambda k_B T))-1]} \tag{1}$$

where $h=6.626\times10^{-34}$ Js, $c=2.997\times10^8$ m/s is the speed of light, and $k_B=1.38\times10^{-23}$ J/K is the Boltzmanns constant. λ is the wavelength in m and T is the temperature in Kelvin.

The energy of a photons is[6]

$$E_{ph}=\frac{hc}{\lambda} \tag{2}$$

where E_{ph} is the energy of photons in Joules.

Based on the equation (1) and (2), the power influx of a star can be expressed in terms of photons by dividing the power influx by the photons energy. The number of photons n_{ph} is given by

$$n_{ph}=\frac{E_S}{E_{ph}} \tag{3}$$

where E_S is the power influx of star per unit area per second.

The number of photoelectrons n_{phe} generated by a single pixel of APS, due to the radiant energy collected and focused on it, can be modeled as[7]

$$n_{phe}=\Delta t_{sh}k_m\frac{A_{pix}}{A_{blur}}QE_{max}\times \int_{\lambda_{min}}^{\lambda_{max}}\tau_{op}R_{op}(\lambda)QE(\lambda)A_{ap}n_{ph}(\lambda,T_c)\mathrm{d}\lambda \tag{4}$$

where Δt_{sh} is the shutter time in seconds, $k_m<1$ accounts for motion distortion, the ratio A_{pix}/A_{blur} of the pixel area to the area of the blur accounts for defocusing, λ_{min} and λ_{max} are the minimum and maximum wavelength in sensor bandwidth, $\tau_{op}<1$ accounts for transmission loss in the optics due to absorption and internal reflections, R_{op} (λ) is the normalized spectral transmittance of the optics, QE_{max} is the sensor maximum absolute quantum efficiency, $QE(\lambda)$ is the sensor normalized quantum response, A_{ap} is the aperture area of optics and n_{ph} (λ,T_c) is the number of photons per unit area, per wavelength and per second.

3 Calculation model of noise in APS

The noise sources of APS are more than those of CCDIS, mainly due to the high dark current and the nonuniform. Such as shot noise, dark current noise, reset noise, readout noise, fixed pattern noise (FPN), $1/f$ noise, and flick noise [3]. The analysis of temporal noise in APS has been reported by several authors [3,8-10]. Their studies show that the largest noise component is due to the reset transistor noise at low illumination, and is due to the photons detector shot noise at high illumination.

Shot noise occurs when photoelectrons are generated and when dark current electrons are presented. The noise generated by photoelectrons is called photons shot noise. Dark current can be specified as a number of input-referred electrons generated per second in a pixel, or as a current per area unit[4]. Dark current generation is nonuniform over the focal plane array, leading to a fixed pattern offset in the resulting image. Dark current generation is a stochastic process, so it is also a source of shot noise. This type of noise is called dark current shot noise. The dark current induced by nonuniformity can be deduced by cooling the APS.Typically it halved with each 5~10 ℃ reduction of the imager temperature.

Fixed pattern noise refers to a temporal constant output offset that varies in a particular spatial pattern, where the term offset implies that this noise is independent of the integration time and the signal level. The fixed pattern noise can be decomposed into three components: a fully random per-pixel FPN, a per-column FPN, and a per-row FPN[11].There are two readout techniques for APS which implicitly remove (some) non-uniformities: double sampling and correlated double sampling.

The reset noise due to the reset transistor, which is sampled at the end of reset, is often quoted to be KT/C value. The readout noise is generated when reading out the pixel value. Generally, the readout noise and the $1/f$ noise due to the amplifiers can be deduced by means of double sampling technique or correlate double sampling technique.

The total noise of APS can be summarized as the photons shot noise which is inherent to any light stimulus and the shot noise caused by dark current, the reset noise, the fixed pattern noise, $1/f$ noise, photons response non-uniformity and the quantization noise. The total number of noise electrons in mean square root (RMS)n_{no} is given by

$$n_{no}=\sqrt{n_{shot}^2+n_{reset}^2+n_{FPN}^2+n_{PRNU}^2+n_{quant}^2} \tag{5}$$

4 SNR and SDL

To the star tracker, the star can be regarded as a point target, since it is far away from the star tracker. Generally, the image of star point in APS contains several pixels, which can be represented as a two-dimensional Gaussian[11]. If the optimum detection principle is given, the detection of star point can be expressed by

$$SNR \geqslant T_{SNR} \tag{6}$$

where SNR is signal and noise ratio, T_{SNR} is the threshold of SNR. The SNR is defined as[1]

$$\frac{S}{\sqrt{S+N^2}} \geqslant T_{SNR} \tag{7}$$

where S is the signal of star quantized in equality value photonelectron, N is the noise also quantized in equality value photonelectron.

It has been shown that the incident energy from a M_v=0 star on an area of 1 mm^2 is 1.3 kW/m$^2\times10^{-6}$mm^2/ $4.2\times10^{-10}=2.96\times10^{-14}$ W [1]. Hence, the response of a magnitude M_i star per second per mm^2 aperture can be given by

$$S_{phe,M_i} = \frac{S_{phe,M_0}}{2.5^{M_i - M_0}} \tag{8}$$

where S_{phe,M_0} is the sensitivity of 0 magnitude star in photoelectrons, S_{phe,M_i} is the sensitivity of M_i magnitude star in photoelectrons.

SDL is the minimum M_v of APS, it is determined by the amount of signal electrons for a given photons excitation, and by the total noise of APS as well. A star can be detected easily with a *SNR* of 8 [1].The relation between the sensitivity and the noise is shown in Fig.1 with *SNR* of 8. If the *SNR* of APS and the total noise

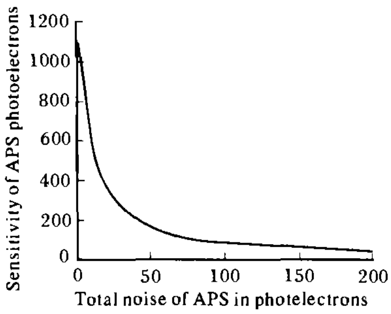

Fig.1 Sensitivity of APS with *SNR*=8

ar e given, the sensitivity of APS can be calculated based on the equation (7), the SDL of APS can be deduced by the equation (8). The variety of SDL with respect to the total noise is shown in Fig.2. It is shown that SDL of star tracker increases with the decreasing of total noise of APS.

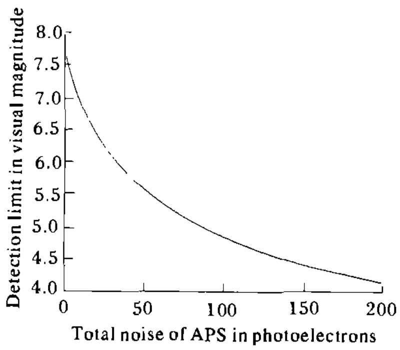

Fig.2 SDL of APS with *SNR*=8

5 Example

The paramters of optical for star tracker and APS chip are given in order to calculate the SDL of a specific APS. As depicted before, the sensitivity of 0 magnitude star is 13000 photoelectrons per second per mm^2. If exposure time is 100 ms and the aperture is 25.5/1.45=17.6 mm ,the aperture area is 243 mm^2. So the sensitivity of this specific star tracker will be 13000×0.100×243=315900 photoelectrons per exposure per mm^2 for a magnitude 0 star.

The average dark current of one APS is 4750 photoelectrons/s. If the exposure time is 0.1 s, then the dark current noise is $\sqrt{4750\times0.1}$ =21.7 photoelectrons. Readout noise is 76 photoelectrons/s. Fixed pattern noise is 18 photoelectrons. Photons response nonuniformity is 38 photoelectrons, the quantization noise is 9 photoelectrons, and the $1/f$ noise is ignored. So the total pixel noise of APS is 82 photoelectrons based on the equation (5).

With *SNR* of 8 and total noise of one pixel is 82 photoelectrons, the sensitivity of one pixel of APS is 688 photoelectrons based on equation (8). If the 90% energy of the star is contained within an area of 2×2 pixel, that is at least 90% ×1/4 =22.5% of the star energy will be in the brightest pixel. Therefore the sensitivity of APS is 688/22.5%=2756 electrons. As we known, the response of the APS for the 0 magnitude is 315900 photoelectrons. So the SDL of this APS is 5.1 M_v based on the equation (9).

6 Conclusion

The sensitivity of CMOS image sensor is worse than that of CCD image sensor. The stellar detection limit of APS should be set at a higher level of brightness than that of CCD image sensor. If the signal noise ratio and the total noise of APS are given, the stellar detection limit of APS for star tracker can be calculated theoretically based on the typical response of 0 magnitude visual star, where both the starlight and

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用制造工艺、封装工艺研究,为微小型技术研究积累一些必要手段,今后将着重开展MOEMS设计技术、兼容性制作技术、专用封装技术研究。面向应用重点发展与现有技术兼容共用的项目,加速发展关键技术和急需应用项目;总体应用技术和元件技术要平衡发展。

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temporal of APS are quantized in equality value photoelectron. Reducing the noise of APS by the correlate double sample technology can increase the stellar detection limit.

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