Infrared Physics & Technology 81 (2017) 305–312

Contents lists available at ScienceDirect

Infrared Physics & Technology

journal homepage: www.elsevier.com/locate/infrared

Regular article

High spatial resolution shortwave infrared imaging technology based on time delay and digital accumulation method

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HIGHLIGHTS

- SWIR imaging is possible to achieve 1 m GSD in 500 km orbit height.
- TDDA method could enhance image quality due to better uniformity and sensitivity.
- A prototype of SWIR imaging system based on a large format area InGaAs detector is designed and has good imaging results.

ARTICLE INFO

Article history:
Received 8 September 2016
Revised 20 January 2017
Accepted 20 January 2017
Available online 27 January 2017

Keywords:
SWIR
TDDA
SNR
High spatial resolution
InGaAs

ABSTRACT

Shortwave infrared (SWIR) imaging technology attracts more and more attention by its fascinating ability of penetrating haze and smoke. For application of spaceborne remote sensing, spatial resolution of SWIR is lower compared with that of visible light (VIS) wavelength. It is difficult to balance between the spatial resolution and signal to noise ratio (SNR). Some conventional methods, such as enlarging aperture of telescope, image motion compensation, and analog time delay and integration (TDI) technology are used to gain SNR. These techniques bring in higher cost of satellite, complexity of system or other negative factors. In this paper, time delay and digital accumulation (TDDA) method is proposed to achieve higher spatial resolution. The method can enhance the SNR and non-uniformity of system theoretically. A prototype of SWIR imager consists of opto-mechanical, 1024 × 128 InGaAs detector, and electronics is designed and integrated to prove TDDA method. Both of measurements and experimental results indicate TDDA method can promote SNR of system approximated of the square root of accumulative stage. The results exhibit that non-uniformity of system is also improved by this approach to some extent. The experiment results are corresponded with the theoretical analysis. Based on the experiments results, it is proved firstly that the goal of 1 m ground sample distance (GSD) in orbit of 500 km is feasible with the TDDA stage of 30 for SWIR waveband (0.9–1.7 μm).

1. Introduction

In recent years, SWIR has been used widely for earth observation, mineral exploration, astronomy, and other fields because of its fascinating features [1–3]. Although SWIR has advantages on many applications, it still has a gap in spatial resolution compared with that of VIS. However, higher spatial resolution will sacrifice SNR of system [4]. Furthermore, high spatial resolution imager often requires high frame frequency and low integration, which decreases SNR too, seriously affects image quality. So solutions manners or methods to increase sensitivity of system are needed. Imager can enlarge aperture to improve SNR, but that adds weight and cost of satellite. For example, the SWIR imager of WorldView-3 of America achieved 3.7 m GSD with 1.1 m aperture in orbit of 617 km [5], if it wants to reach 1 m GSD and keeps the same SNR, the aperture will be amplified to 4.07 m. Some remote sensing satellites use image motion compensation technology to improve SNR [6–8], however, it leads to blind observation, requires additional control mechanism and increases system complexity.

In this paper, TDDA technology is proposed to enhance SNR of system and make SWIR imager get higher spatial resolution without enlarging aperture or additional control mechanism. The scanning frequency is controlled to match with the frame frequency of detector, objects are exposed and readout to digital numbers by pixels of adjacent lines of detector in different frames, finally these

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http://dx.doi.org/10.1016/j.infrared.2017.01.017
1350-4495/

digital numbers are averaged to lower the noise of the system. Because TDDA technology needs not complicated readout circuit and can realize accumulation of any stages, it is more flexible and suitable for high spatial resolution spaceborne infrared imaging system than analog TDI technology [9–11]. A SWIR imager consists of opto-mechanical, 1024×128 InGaAs detector, and electronics was designed and two experiments were completed to demonstrate TDDA method. Experiment results indicate that TDDA method can enhance image quality due to better sensitivity and uniformity, which is good for SWIR to achieve high spatial resolution.

2. TDDA technology

In addition to image motion compensation technology, another common technique of raising sensitivity of system is time delay and integration (TDI) technology. TDI technology is analogous to taking multiple exposures of same object to add integration time. Therefore, sensors can receive more energy and improve sensitivity of system. Fairchild proposed this technology firstly and used it in Charge Coupled Device (CCD) reconnaissance camera of remote slope photography in 1979 [12]. After decades of development, TDI technology has been used extensively in various CCD devices, such as the 6U cubic star of the United Kingdom [13] and Deimos-2 satellite of Spain [14].

Due to current readout circuit of infrared focal plane array (IRFPA) detectors mostly use CMOS readout circuit, so it is difficult to use TDI technology to accumulate charges like CCD devices in infrared imaging system. Some people use specific circuit blocks to implement cumulative analog signal, which is called analog TDI technology. However, this method needs complicated circuit blocks and the accumulative stage is limited. The principle of TDDA is shown in Fig. 1: the object A is exposed by the pixel P_{1j} of detector, and then it is readout and quantized to digital number $DATA_1$ in the integration time of $Frame_1$, $DATA_2$ is obtained by the pixel P_{2j} which also exposes for object A in $Frame_2$, and so on, $DATA_m$ is obtained by the pixel P_{mj} in $Frame_m$. All digital numbers are averaged to lower the noise of the system, which also improves the SNR of the system.

2.1. TDDA technology can increase SNR of system

In classical SNR model, generally method of calculation is the ratio between the number of electrons converted by target signal and the number of electrons converted by noise. The number of electrons converted by target signal can be expressed as:

$$N_s = \phi_q \cdot \eta \cdot t_{\rm int} \quad (1)$$

where N_s is the number of electrons converted by signal, ϕ_q is the photon radiance flux of photosensitive surface, η is the quantum efficiency of detector, and t_{int} is the integration time.The main noise of system is shot noise, readout noise, and electronics noise:

$$n_{noise} = \sqrt{n_{shot}^2 + n_{readout}^2 + n_{electronic}^2} \quad (2)$$

where n_{noise} is the number of electrons converted by total noise, n_{shot} is the shot noise, $n_{shot} = \sqrt{N_d + N_s + N_b}$, N_d is the number of electrons converted by dark current noise, and N_b is the number of electrons converted by background radiation.

The SNR model is:

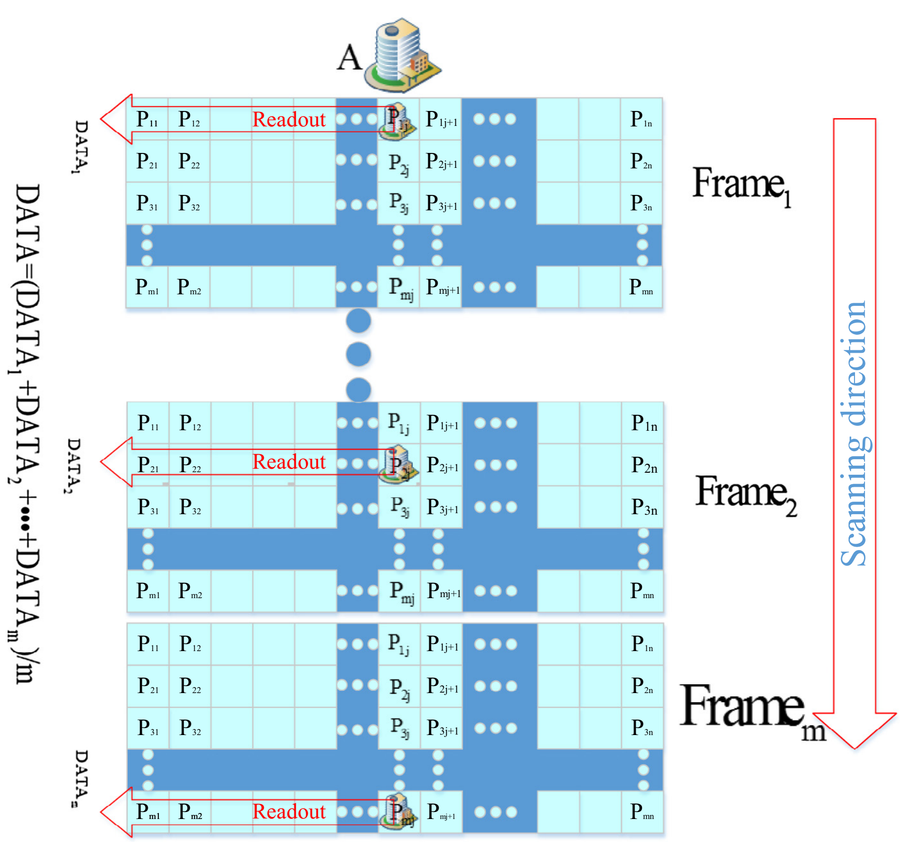

Fig. 1. The principle of TDDA. The scanning frequency is controlled to match with the frame frequency of the detector, object is exposed and readout to digital numbers by pixels of adjacent lines of detector in different frames, finally these digital numbers are averaged to lower the noise of the system.