Research status and key technologies of all-day star sensor

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Abstract. The all-day star sensor can complete the star detection throughout the day to solve the problem that the sky signal is overwhelmed due to excessive sky background radiation during the daytime. In this paper, a comprehensive analysis of the status quo of the all-day star sensor is presented, and the technical indicators of the typical all-day star sensor at home and abroad are introduced. In order to improve the detection ability of daytime stars, based on the factors affecting the detection performance of star sensors throughout the day, short-wave infrared technology is used to detect weak star signals. The small field of view lens design is adopted, and the hood in the optical system is optimized to achieve an extinction ratio of $8.65 \times 10^{-6}$. Low-contrast star map processing is performed using spectral filtering methods. The target of daytime stargazing is achieved.

1 Introduction
Star sensor is based on optical, machine vision and information processing. It is an optical attitude sensor with high precision, strong anti-interference, and no attitude accumulative error. However, as an optical attitude sensor, the star sensor is highly susceptible to background stray light, and the background light in the atmosphere is complex and the sky background radiation is extremely strong under the condition of daytime sky, The star's weak starlight is easily submerged, and the application of star sensors in the atmosphere is greatly limited. Therefore, the development of an all-day star sensor that can be applied under conditions of daylight is receiving increasing attention.

2 The development history and research status of star sensors in all-day time

2.1 Foreign development history
2.1.1 NAS-26 system. In the early 1980s, Northrop developed the NAS-26 system, and its star sensor optical head is shown in Figure 1. The star sensor can track magnitude from -1.46 to +3.5 in daytime conditions, providing a position output better than 25", with high reliability and equipped with B-1 and B-2 bombers. The bomber greatly improves the navigation accuracy, significantly reduces or eliminates the dependence on radar correction, and provides a valuable reference for the development of the following full-time star sensor [1].

2.1.2 HERO System. In 2000, the HERO (High Energy Replicated Optics), as shown in Figure 2, was used to make the star sensor work in the R and I bands (600-1000 nm). The design of the limiting
magnitude was 9, but due to the influence of the longitudinal color of the lens, the actual observation limiting magnitude is 8.7\(^2\).

2.1.3 BLAST system. In 2005, the BLAST (Balloon-Borne Large-Aperture Submillimeter Telescope) used a pair of redundant star cameras consisting of CCD, optical lens, optical filter and information processing computer. Its structure is shown in Figure 2-3. Under typical daytime conditions, the observable magnitude of BLAST is 9 and provide absolute accuracy better than 5\(^\circ\), and the data update rate is 1Hz real-time positioning information\(^3\).

2.1.4 DayStar System. In 2006, Microcosm successfully developed the DayStar system for observation magnitude of 7.1 at sea level throughout the day\(^4\), as shown in Figure 2-4. The DayStar system uses a multi-head star sensor.

2.1.5 EBEX telescope. A number of units such as Columbia University's Joint Jet Propulsion Laboratory (JPL) designed a pair of mutually redundant star cameras for EBEX\(^5\). The structure is shown in Figure 5. The star sensor uses a CCD imaging system with a Hoya 25A red filter in front of the lens to filter out stray light with a wavelength of less than 600 nm, reducing the impact of the sky background on the star camera. The star camera is equipped with a helium gas pressure package to reduce the influence of temperature changes on optical components and electronic components, improving accuracy and reliability, and the observed limit magnitude is 6.1. At the extreme, the observations are shown in Figure 6.

2.1.6 Comparison of typical foreign all-day star sensors. As can be seen from Table 1, foreign research institutions have adopted a single field of view scheme in the early stage, but in order to overcome the problem of inconsistent triaxial precision in single-field star sensors, and in-field
observation using small field of view To the few defects of the number of stars, the multi-field scheme was adopted later. Accuracy continues to increase, and application platforms are becoming more widespread, covering sea level to near-Earth space.

| Development unit | Model  | Field of view | Magnitude | Precision | Platform |
|------------------|--------|---------------|-----------|-----------|----------|
| Northrop         | NAS-26 | single-field  | 3.5       | 25"       | Airborne |
| NASA             | HERO   | single-field  | 8.7       | /         | Balloon  |
| UPENN            | BLAST  | single-field  | 9         | 5"        | Balloon  |
| Microcosm        | DayStar| Multi-field   | 7.1       | /         | Shipborne|
| JPL              | EBEX   | Multi-field   | 6.1       | 1.5"      | Balloon  |

2.2 Research status in China
After entering the 21st century, as the application environment becomes more and more complex, the all-day star sensor has also attracted the attention of Chinese researchers, but there is still a gap with foreign research results.

2.2.1 Optical system. Wang Yang et al.\[^6\] have designed an optical lens for an all-day airborne star sensor. The optical system is excellent in performance through optical design and aberration analysis. The parameters are shown in Table 2, and the structure is shown in Figure 7. Pan Yue et al.\[^7\] designed the Cassegrain mirror and the refracting structure of the calibrated lens, and the structure is shown in Figure 8. The point map and energy concentration diagram after defocusing are shown in Figure 9.

Table 1 Comparison of typical all-day star sensor in foreign countries

Table 2 Optical performance parameters

| Angular resolution | distortion | Diameter of diffuse spot |
|--------------------|------------|--------------------------|
| 2"                 | <3%        | 7.6μm                    |

Fig. 7 Optical design structure Figure 8 Optical structure
2.2.2 Hardware System. He Jiawei [8] proposed the use of high-sensitivity EMCCD imaging technology to solve the detection problem under strong daytime background. The EMCCD system imaging scheme is shown in Figure 10, using complementary FET switch circuit and The driver circuit design of the high-frequency and high-amplification of the clamp circuit is shown in Figure 11. Zhong Xing et al. [9] used the "FPGA+DSP" electronic processing overall scheme, As shown in Figure 12.

2.2.3 Algorithm Research. Xia Mengqi et al. [10] used multi frame pseudo star elimination algorithm to effectively eliminate the pseudo star points. Hu Xiaodong et al. [11] proposed a star point centroid extraction algorithm based on frame accumulation. the result is shown in Figure 13.

3 Key Technologies for All-Day Star Sensors
The all-day star sensor measures the position of the star by means of imaging and then performs attitude measurement. Therefore, the main factors affecting the detection capability are as follows:

(1) Detector performance. To achieve weak signal star detection under strong background radiation, choose a detector with high sensitivity, large dynamic range, wide spectral response, low readout noise and low dark current noise.

(2) Optical system. Increasing the aperture of the imaging system maximizes the reception of radiation from the target, and obtains a large target illumination, that is, a large aperture is beneficial to improve the signal-to-noise ratio of the star sensor imaging system; but the background received by the star sensor The intensity of the radiation is related to the field of view. The larger the field of view of the star sensor, the more background radiation is received.

(3) Background radiation. For all-day star sensors, background radiation is a factor that must be considered. During daytime observation, strong sky background radiation causes the weak star signal to be submerged. As the height of the observation decreases, the contrast of the target-background decreases exponentially.
3.1 Weak star signal detection technology
In fine weather, the background light of the sky is dominated by short-wavelength, with a peak value of about 450nm~550nm, as shown in Figure 14. The spectral curve decreases rapidly with increasing wavelength, and the spectral energy is very low outside 900nm. Therefore, short-wave infrared technology can be used to detect weak star signals during the day.

To this end, based on the analysis of the target characteristics of the daytime stellar star, combined with the requirements of the index, a short-wave infrared InGaAs detector Sofradir SNAKE-SW was used for research, as shown in Figure 15. The main parameters are shown in Table 3.

Table 3 main parameters

| factory | type       | Resolution | pixel size | spectrum | framerate | quantum efficiency | dark current | Nonuniformity |
|---------|------------|------------|------------|----------|-----------|--------------------|--------------|---------------|
| Sofradir | InGaAs    | 640×512    | 15 µm      | 0.9µm~1.7µm | 300Hz     | >70%               | 30fA         | <4%           |

3.2 Optical system
Considering the effects of sky background radiation, using a small field of view lens design (8°×6°), in order to eliminate the effect of temperature effects on the lens optical system, the use of no heating design. The main parameters and indexes are shown in Table 4. It has great improvement in achromatism, dispersion, correction system aberration, optical image quality and so on. Figure 16 shows the optical path diagram and diffuse spot diagram.

Table 4 main parameters and indexes

| Serial number | parameter          | index                   |
|---------------|--------------------|-------------------------|
| 1             | focal length       | 76 mm                   |
| 2             | Field of view      | 8°×6°                   |
| 3             | Center wavelength  | 900 nm                  |
| 4             | distortion         | ≤0.18%                  |
| 5             | lateral color      | ≤±2µm                   |
| 6             | Diffuse spot       | Φ≤0.04 mm               |
| 7             | working temperature| −40°C～+70°C             |
| 8             | mass               | ≤200g                   |

Fig.14 Spectrum curve Figure
Fig.15 InGaAs detector SNAKE-SW
Fig.16 optical path diagram and diffuse spot diagram.
The hood is the most direct module to suppress stray light, while also minimizing the impact of daytime sky background on the star sensor. The configuration has a total of 6 layers of light blocking rings, which are installed in a diagonal ring manner. The hood body is divided into upper and lower parts, and the lower part is a hood base of titanium alloy material for heat insulation. The overall effect and cross-section of the hood are shown in Figure 17.

![Fig.17 3D illustration of the hood](image)

The hood is simulated and verified by extinction ratio. The input conditions are: the coating absorption rate is 0.99, the reflectance is 0.05, and the scattering rate is 1. According to the situation, the incident light is 4000000 (2000×2000) (the energy of each light is 1 unit), the incident light intensity is 100 units/mm². When the incident light is 25°, the extinction ratio reaches 8.65×10⁻⁶.

### 3.3 Low-contrast star map processing technology

During the daytime, the sky background is not only high in intensity, but also affected by the comprehensive effects of the atmosphere. The background undulation is extremely noisy, and as the observation height decreases, the target-background contrast decreases exponentially.

As shown in Figure 18, when under daytime conditions, the uniformity of the background distribution of the star map is destroyed, the background gray value is raised to a higher level, and the signal-to-noise ratio of the image is lowered. When white clouds enter the field of view, the background undulations become larger, which is not conducive to the extraction of star point targets.

![Fig.18 Star map background](image)

(a) Cloud map during the day  (b) 3D gray map of the star map with clouds during the day

Therefore, a background filtering method is employed. Firstly, according to the processing power of the FPGA, the star feature template size is determined, and the mean value of the template edge pixel is used as the background estimation value. Then, the weight coefficient is added to suppress the residual low frequency part after the template processing; finally, the background difference method is used to extract Star point. The processing result is shown in Figure 19.

![Fig.19 Star map processing results](image)

(a) original star map  (b) background image  (d) extracting star points
4 Conclusion

This paper summarizes the development history of foreign all-day star sensors, introduces several typical all-day star sensors in the process of foreign development, and introduces the domestic research results around the composition of all-day star sensors to detect the influencing factors of performance are the entry points. The analysis analyzes the key technologies that need to be studied and solved in short-wave infrared in the all-day star sensor. At the same time, the corresponding solutions are given, and the verification results are given through experimental simulation. In the future, the all-day star sensor will continue to develop in the direction of high precision, high dynamics, high update rate and high reliability. Therefore, it is an urgent need in China to conduct more in-depth research on the all-day star sensor and realize practical, productized and industrialized.

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