RASI: the Robotic All-Sky narrowband Imager Postprint

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Abstract

We report a novel standalone robotic all-sky narrowband imager (RASI) for aurora and airglow research. RASI features innovative designs in both optical and electromechanical systems, offering low operating and installation costs, ease of deployment, and fully automatic operation. The novel optical system provides an all-sky field of view with excellent image quality and sensitivity. The innovative electromechanical system design enables a more compact device size and supports outdoor standalone deployment. We have also developed fully automatic data acquisition software based on solar elevation angle and all-sky cloud cover sensing. In summary, RASI offers significant advantages over traditional all-sky narrowband imagers and is highly suitable for large-scale intensity measurements of aurora and airglow distributions.

Full Text

Preamble

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RASI: the Robotic All-Sky narrowband Imager

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Abstract: We report a new standalone Robotic All-Sky narrowband Imager (RASI) for auroral and airglow studies. RASI features novel optics and an electromechanical system, low operation and installation costs, easy deployment, and fully automatic operation. The new optics provide an all-sky field of view with excellent image quality and sensitivity. The new electromechanical system design offers a more compact size and the capability for outdoor independent deployment. We have also developed fully automatic data acquisition software for RASI, which is based on perception of solar altitude and all-sky cloud cover. In conclusion, RASI demonstrates significant advantages over traditional all-sky narrowband imagers and is highly suitable for intensity measurements of large-scale aurora and airglow distributions.

Keywords: Robotic; All-sky imager; Auroras; Airglow; Optical imaging

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1. INTRODUCTION

The Earth’ s ionosphere (ranging from mesosphere to thermosphere, with an altitude of 60 to 1,000 km) serves as an interaction region between Earth’ s atmosphere and solar radiation (mainly ultraviolet and X-rays). It is rich in free electrons and ions and is the region where auroras and airglow occur. The study of atmospheric and astronomical phenomena benefits greatly from continuous, wide-field imaging of the night sky. All-Sky Imagers (ASI) have become essential tools for observing transient events such as auroras and airglow.

Auroras are created by interactions of air molecules with the solar wind [1,2]. The purpose of ASI measurements of auroras is to conduct studies on geomagnetic storms and geomagnetic substorms [3-9]. Airglow (nightglow and dayglow), the faint glow of the atmosphere, is caused by the self-illumination of the upper atmosphere via chemiluminescence processes. The nightglow (also called "Nocturnal airglow") results from the photoionization of atmospheric gases by ultraviolet sunlight [10]. It has been shown that airglow emissions are altered by gravity waves passing through certain layers of the atmosphere, making it possible to study atmospheric gravity waves (AGWs) and their sources through airglow imaging [11–16]. ASIs can also detect aircraft lights and contrails, satellites, meteors, local light polluters, atmospheric extinction, and transient astronomical objects [17,18].

Furthermore, auroras and airglows, along with starlight and the zodiacal light, all contribute to the brightness of the nonlunar night. As airglows can even outshine scattered moonlight in the near-infrared band, understanding Earth' s night-sky brightness requires good knowledge of the complex airglow emission spectrum and its variability [19].

Traditional broadband ASI provides valuable data on spatial and temporal variations in sky emissions [20–23] but lacks the spectral resolution needed to isolate specific chemical species or physical processes. Aurora and airglow emissions occur both as distinct bands and as continuum emission, spanning UV, visible, and near-infrared wavelengths. The aurora and night sky spectra are recorded by the Arizona Airglow Experiment during the flight of STS-53, December 1992. Narrowband imaging enables targeted observations of emission lines, which are critical for studying mesospheric and thermospheric dynamics [24–27].

Recent advancements in optical system optimization and automated data processing have significantly improved the efficiency of night-sky monitoring [28–31]. However, most existing ASIs are limited to remote control observation mode, and installation still depends on rooftops of astronomical observatories or private homes [9,32–35]. To address this gap, we have developed a standalone Robotic All-Sky narrowband Imager (RASI), designed for autonomous, high-resolution spectral imaging with minimal maintenance and standalone operation without requiring a rooftop. RASI employs a fixed single-filter or multi-filter design, optimized for optical and electromechanical systems, coupled with a high-sensitivity Electron Multiplying Charged-Coupled Device (EMCCD) or Scientific Complementary Metal-Oxide-Semiconductor Transistor (sCMOS) detector, and an automatic unattended software control system. It is perfectly suitable for multi-point networked monitoring projects of aurora or airglow emissions, such as the Mid-latitude All-sky-imaging Network for Geophysical Observations (MANGO) network [9], Time History of Events and Macroscale Interactions During Substorms (THEMIS) ground-based network [32], Super Dual Auroral Radar Network (SuperDARN) [34], and so on.

This paper presents the design, key technology, and initial results of RASI. Section 2 describes the instrument' s basic specification parameters, including two different versions: RASI-1 and RASI-2. Section 3 details the instrument' s optical system, mechanical-electrical design, and fully automated software architecture. Section 4 discusses preliminary observations, demonstrating the system' s ability to resolve fine structures in airglow and aurora layers. Finally, we summarize the article and outline future application prospects of the two versions of RASI.

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2. THE OVERVIEW OF THE RASI

RASI is based on the classic imager design influenced by Mende et al. [36], Hu et al. [37], and Bhatt et al. [9], and includes some traditional structures: fisheye lens, telecentric imaging lens, narrowband filter, imaging lens, and camera. However, RASI introduces new features in several aspects: a more integrated and efficient optical design, a new electromechanical design that enables low-cost, independent, and rapid deployment, and a software system capable of achieving intelligent and autonomous observation and operation.

We developed two versions of RASI (RASI-1 and RASI-2, Fig. 1 [Figure 1: see original paper]) to meet the requirements of various application scenarios. The main specifications are presented in Table 2 .

RASI-1 has an electric narrowband filter wheel with five positions, while RASI-2 employs a filter slot in which a narrowband filter can be manually inserted. Focusing in both versions is performed manually. RASI-2 is built as a standalone robotic system with a waterproof compact metal frame and an acrylic transparent hemispherical cover with anti-condensation and anti-frosting functions. By using all-sky cloud cover data provided by an external all-sky near-infrared cloud sensor [21], RASI-2 can autonomously determine and conduct scientific observations based on weather conditions. RASI-1 can only be installed inside a room or dome and conduct scientific observations via remote mode. The universal camera interface design enables RASI to install different types of cameras (sCMOS or EMCCD).

The RASI with sCMOS camera is more suitable for observing auroras and airglows at middle and low latitudes, while the RASI with EMCCD camera is more suitable for observing auroras and airglows at high latitudes. This is because all CCD sensors exhibit blooming and streaking artifacts when the charge in a pixel exceeds the saturation limit, whereas CMOS sensors do not. Additionally, the moon (the largest illuminated target in the night sky) has a lower altitude in high-latitude regions. The blooming effect will cause pollution to normal aurora and auroral glow areas, as shown in Fig. 2 [Figure 2: see original paper].

3.1. Optical System

The optical structure of the monochromatic ASI is much more complex than that of the color ASI. Since the radiation spectral lines of the Earth’ s ionosphere are all sharp and independent, it is necessary to conduct narrowband measurements to effectively eliminate the influence of radiation from other bands.

Figure 3 shows the transmittance curve of the narrowband filter with a bandwidth of 2.5 nm selected for the RASIs. If the filter is placed directly near the focal plane of the fisheye camera lens, the bandwidth at different field positions after passing through the filter will vary. To solve this problem, a pair of plano-convex lenses are added in front of the focal plane to transform the original optical path into an equidistant and telecentric optical path. As shown in Fig. 4 [Figure 4: see original paper], most of the light enters the narrowband filter perpendicularly, except at the 90° position. This basically ensures the consistency of a 2.5 nm bandwidth within a 180° field of view.

We have also redesigned the secondary imaging system (SIS, No. 4 in Fig. 5 [Figure 5: see original paper]) of the RASI instrument, which is completely different from traditional ASI. Firstly, due to the mismatch between the focal plane area of the fisheye lens and the target area of the camera (the plano-convex lenses added at the front merely change the angle of the incident light beam but do not alter the size of the focal plane), the SIS should have a focal reducer function to reduce the imaging area. According to Equation (1) of an ideal optical system, image height is in direct proportion to focal length and field of view:

$$h = f\tan(\theta)$$

Another advantage of the optical system after focal reduction is that it improves the system's sensitivity to weak signals, as the optics are much faster. For RASI, the theoretical detection sensitivity is expected to increase by 3.1 times due to the f-ratio change.

Secondly, the SIS also has the function to correct the aberration caused by the front optical system. Finally, the SIS includes the imaging function, and RASI no longer requires a second commercial lens like traditional ASI does.

The Modulation Transfer Function (MTF) curves of RASI for two observation bands (557.7 nm and 630 nm) are illustrated in Fig. 6 [Figure 6: see original paper]; the cut-off frequency is about 38 lp/mm. Figure 7 [Figure 7: see original paper] shows their spot diagrams. The Root Mean Square (RMS) spot size for the worst case of image quality is concentrated within 3 to 4 pixels, which is excellent for observation of auroras and airglow.

In summary, RASI features a more efficient and compact optical design, and its detection sensitivity and optical quality are both superior to those of traditional ASI.

3.2. Electromechanical System

An obvious limitation of traditional ASI systems with sealed enclosures is frequent condensation during winter months due to temperature differentials between outside and inside the enclosure [9]. Through the innovative design of the electromechanical system of RASI (Fig. 8 [Figure 8: see original paper]), this condensation has been effectively eliminated.

RASI-2 is built as a standalone robotic system with a waterproof and thermal-insulated metal frame housing, whose sealing cover plate is made of lightweight and durable bakelite material to reduce weight (as shown in Fig. 1). At the top of the frame, a semi-spherical transparent cover installation interface plate with a sealing ring is designed, making installation and replacement of acrylic covers very convenient. At the bottom of the frame, a mechanical structure was designed that can adjust the tilt angle of the equipment. There are also four waterproof and low-temperature resistant plugs, which are used to connect power supply, network connection, external environmental temperature/humidity sensor, and the all-sky cloud cover sensor.

A wide-temperature industrial personal computer (IPC) is installed inside the frame. The operating system is Linux, and the programming languages are C++ and Python. The IPC is responsible for collecting various types of data and for intelligent control of the camera. Based on real-time collection of temperature/humidity data inside and outside the metal frame, and through auto-control of the heater and cooling fan, the acrylic protective cover achieves functions of avoiding condensation in high-temperature environments and anti-frosting in low-temperature environments.

Through robustness testing of the RASI system under wide temperature conditions in high and low temperature chambers (see Fig. 9 [Figure 9: see original paper]), we have verified multiple functions of the RASI system across a wide temperature range (-40°C to 40°C), including anti-condensation and frost-prevention functions, system self-starting and self-operating functions upon power restoration at low temperatures, and low-temperature resistance of the bakelite material.

Through optimized design of the optical system and innovative design of the electromechanical system, RASI has been equipped with the hardware conditions for fully automatic observation. However, the robotic software control system described below is also indispensable.

3.3. The Robotic Control System

Several projects studying the Earth’ s upper atmosphere have begun moving toward networked observation stages. MANGO employs twelve ASIs observing the 630.0 nm and 557.7 nm emissions [9]; the Chinese Meridian Project (Ground-based Space Environment Monitoring Network) established 15 comprehensive stations along 120°E longitude and 30°N latitude, with several dozen ASI devices deployed at these stations [38]. The RASIs will perfectly meet the requirements for networked operation of these projects.

The camera control software of RASI has achieved the ability to conduct scientific observations and data preprocessing independently based on solar altitude and weather conditions. Simultaneously, it has also realized automatic archiving and release capabilities for data.

The robotic control software workflow is shown in Fig. 10 [Figure 10: see original paper]. There are three main service threads: Core Main Service (CMS), Task Executor Service (TES), and Data Save Service (DSS). CMS is the main process of the software; it collects site information (station name, longitude, latitude, altitude, etc.) and task requirements (such as bias task, science data task, etc.) by loading the configuration file first. Then, based on information about solar altitude and all-sky cloud cover, corresponding observation tasks for TES are autonomously decided. The TES process reads various configuration files and starts the camera cooling function first, then carries out the data collection task second, and finally feeds back the execution results to CMS. Once CMS successfully receives the collected image data, it activates the data storage service thread—DSS. The main function of DSS is to convert the original image data into Flexible Image Transport System (FITS) format and simultaneously generate a compressed image with watermark information, which is convenient for real-time viewing and checking. FITS is the standard archival data format for astronomical data sets. All kinds of information related to data collection can be stored in the FITS file header, which is beneficial for image calibration and data processing.

The automatic software can also calculate solar altitude in real-time by using an astronomical calculation library (libnova[2]), which is conducive to intelligent execution of the TES and DSS services. Now, let us take Kjell Henriksen Observatory (Longyearbyen Station) in the Arctic and Lijiang Station of Yunnan Observatories, Chinese Academy of Sciences at lower latitude as examples to introduce the changing characteristics of sunrise and sunset throughout every day in a whole year. When we set solar altitude at -8° as the dividing point between day and night, we obtain the results shown in Fig. 11 [Figure 11: see original paper] and Fig. 12 [Figure 12: see original paper]. Obviously, Longyearbyen Station experiences polar day and polar night, but Lijiang Station does not. Another difference is that the lower the latitude of the site, the longer the observation nighttime will be. For example, in 2025, Lijiang Station' s nighttime has 3,893.5 hours, but Longyearbyen Station' s nighttime only has 3,163.8 hours.

In fact, the night sky is not always clear. To avoid collection of invalid data during bad nights, RASI achieves automatic data collection at clear nights based on acquisition and judgment of real-time cloud coverage data. The cloud cover data is obtained from the all-sky infrared cloud meter or the all-sky color camera developed by the authors; please refer to Xin et al. [21] for more details.

The core service also includes a data post-processing section, which mainly involves merging bias images and then subtracting the master bias from scientific data. The dark current values of the cameras are very low (Table 2), which can be ignored.

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4. RESULTS AND DISCUSSION

The RASI-1 with Andor EMCCD iXon888 was installed inside a sliding roof at Lijiang Station since March 2024, and an all-sky color imager has been installed not far from RASI-1 since 2018. A sample airglow image taken with a narrow-bandpass filter of 630 nm with 4 s exposure is shown in Fig. 13A [Figure 13: see original paper]. The color all-sky image captured simultaneously with 59 s exposure is shown in Fig. 13B. The yellow bright line in the color all-sky image comes from the sodium laser guiding star system. As its central wavelength (589 nm) is not within the detection range (630 ± 1.5 nm) of RASI-1, we cannot see it in the narrowband image.

Although rotation and translation are not applied to the images in Fig. 13, the fields of view are almost centered with north upwards. In these two images, the Ursa Major constellation in the upper left corner and the Orion constellation in the lower right corner are both very prominent. By comparing color and narrow-band images, the airglow structure is very obvious, and the quality of starry patterns in narrowband images is also much higher than that in color images. This indicates that the system focus of RASI is excellent and the image quality is good, although it is slightly blurred at large zenith angles.

The RASI-2 with Andor EMCCD iXon888 was installed on an outdoor platform at Longyearbyen Station since August 2024, and the color all-sky imager was installed simultaneously next to RASI-2. A sample aurora image taken with a narrow-band filter of 557.7 nm with 4 s exposure is shown in Fig. 2A. The maximum time resolution of RASI-2 in continuous acquisition mode is 5 s. The color all-sky image with 20 s exposure is shown in Fig. 2B. By comparing color and narrow-band images, the aurora structure can be clearly displayed in the narrow-band image, but it appears very faint in the color all-sky image. Affected by moonlight, the blooming effect of the CCD will impact aurora measurements in certain areas.

To study the positional and temporal patterns of auroras or airglow, image spatial position calibration is necessary. We can obtain the internal and external parameters of the RASI fisheye imaging system by identifying bright stars with known positions across the entire sky. However, simply specifying the temporal-spatial characteristics of auroras or airglow is insufficient; we also need to know the radiation intensity (flux in Rayleighs [39]) to better understand their physical radiation processes. Traditional laboratory flux calibration methods are no longer capable of meeting precision requirements. Baumgardner et al. [40] proposed an improved method, and we have proposed an in-situ calibration method based on photometric standard stars. All calibration results will be presented in the next issue of this publication series.

The RASI system still has some limitations. The RASI-2 version can only conduct robotic measurement for a single narrowband band. If three bands need to be measured simultaneously, three RASI-2 devices are required. Although RASI-1 can achieve multi-band observation by switching filters through an electrically rotating filter wheel, focus still needs to be manually adjusted (the next version will be upgraded to electric focusing), so it can currently only conduct single-narrowband observations.

5. SUMMARY

We developed a new type of standalone RASI with a completely new integrated design of optics, mechanics, and electronics, along with a robotic control system. The new optics utilizes a commercial fisheye lens, a telecentric optical lens, a narrowband filter, a secondary imaging system with focal reducer, and a cooled digital CCD camera or sCMOS camera, which provides an all-sky field of view with good image quality and sensitivity.

Two versions of RASI (RASI-1 and RASI-2) are developed. RASI-1 has an electric filter wheel and an sCMOS camera, which should be installed in a room with a transparent dome and operate in remote mode. RASI-2 is built as a standalone robotic system with a waterproof and thermal-insulated metal frame housing. Through adaptive control of temperature and humidity inside the housing, the transparent hemispherical protective cover achieves functions of avoiding condensation and frosting within a wide temperature range. By conducting real-time calculations of solar altitude and all-sky cloud cover, RASI-2 can be installed independently outdoors and achieve intelligent and fully automatic observation. Given that sCMOS detectors have an advantage over CCD detectors regarding the blooming effect, RASI-1 is more suitable for observing airglows at middle and low latitudes, while RASI-2 is more suitable for observing auroras at high latitudes.

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AI DISCLOSURE STATEMENT

AI-assisted technology is not used in the preparation of this work.

AUTHOR CONTRIBUTIONS

Yuxin Xin and Zejun Hu conceived the main ideas, implemented the study, and wrote the paper. Baoli Lun conceived the robotic control system ideas, implemented the study, and wrote the paper. Yue Zhong designed the optical system and implemented the study. Kai Ye and Yuxin Xin designed the electromechanical system ideas and implemented the study. Yuxin Xin and Hongying Xu performed the observations, collected and processed the data. Yufeng Fan, Bin Li, and Dehong Huang participated in the installation and testing of RASIs. All authors read and approved the final manuscript.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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