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Development of an allsky camera based on commercially available hardware and open-source software

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Abstract. All-sky cameras provide a live view of the sky visible from the location where they are installed. These speciality cameras feature a fisheye lens that projects a full hemisphere image into the imaging sensor, and are often used by professional observatories for sky condition monitoring. However, technological developments in recent years enabled increased availability of components and a cost reduction of such devices. This paper details the development, construction and initial results of an amateur allsky camera. It is based on commercially available components (camera, lens and controlling unit) and open-source software developed by an amateur community for managing and controlling those devices. The planning, design choices, materials selection and build are discussed. A prototype unit was built and deployed in a rural site located in Minas Gerais, being operational for several months since 2021. A cost analysis is presented, and shows that assembling the camera as do-it-yourself project can greatly increase the accessibility when compared to commercial allsky camera solutions. This could expand the sky monitoring network beyond professional observatories to more universities, schools and amateur astronomers, enabling new research and pro-am collaborations in areas that include meteor, satellite and light pollution monitoring.

Resumo. Câmeras all-sky (ou de céu-todo) oferecem uma visão de todo o céu visível do local onde são instaladas. Essas câmeras especializadas utilizam uma lente olho-de-peixe que projeta uma imagem hemisférica no sensor de imageamento, sendo frequentemente utilizadas por observatórios profissionais para monitorar as condições do céu. Porém, avanços tecnológicos recentes permitiram maior disponibilidade de componentes e redução de custos de tais dispositivos. Este artigo detalha o desenvolvimento, construção e resultados iniciais de uma câmera allsky. Ela baseia-se em componentes disponíveis comercialmente (câmera, lente e unidade de controle) e software de código aberto desenvolvido por uma comunidade amadora, para gerenciar e controlar o equipamento. O planejamento, escolhas de projeto, seleção de materiais e construção são discutidos. Um protótipo foi construído e instalado em um sítio rural em Minas Gerais, operando há vários meses desde 2021. Uma análise de custos é apresentada, e mostra como a construção da câmera como um projeto faça-você-mesmo permite aumentar a sua acessibilidade quando comparada a soluções comerciais. Isso pode expandir a rede de câmeras de monitoramento do céu além de observatórios profissionais, para mais universidades, escolas e astrônomos amadores, habilitando novas oportunidades de pesquisa e colaboração amadora-profissional em áreas que incluem monitoramento de meteoros, satélites e de poluição luminosa.

Keywords. Instrumentation: detectors – Instrumentation: miscellaneous – Site testing

1. Introduction

All-sky cameras are "devices designed to capture images of the full hemispherical sky and consist usually of a chargecoupled device (CCD) or a complementary metal oxide semiconductor (CMOS) sensor looking at a mirror or with a mounted fisheye lens" (Antuña-Sanchéz et al. 2021, p. 2202). As such, these specialty cameras can capture the entire sky visible form a particular location. The extremely wide angle hemispherical projection is typically accomplished either by a normal camera downward-facing a convex spherical mirror, or by directly projecting the image onto an imaging sensor with a fisheye lens. Some projects have also accomplished all-sky visibility by combining multiple wide-field cameras with partly-overlapping fields-of-view as an array (Talens et al. 2017). The focus of this paper is on cameras that use a fisheye lens.

There are multiple scientific applications of all-sky cameras. The devices have been used to monitor aurora activity (Rao et al. 2014), cloud formation and coverage (Tzoumanikas et al. 2016; Mommert 2020), meteors and satellites (Jenniskens et al. 2011), for observatory site characterization (Skidmore et al. 2011; Yu-Xin et al. 2020), and to analyze annual atmospheric-climate phenomena (Fruck et al. 2015; Johnsen et al. 2021). Recent projects even use allsky cameras to make photometric measurements of bright variable stars (Burggraaff et al. 2018) and exoplanet transits (Talens et al. 2017), and have also been used to characterize and monitor light pollution conditions (Rabaza et al. 2010; Jechow et al. 2017). Finally, astronomical observatories usually feature such cameras (e.g. Observatório do Pico dos Dias, La Silla, GTC have publicly available websites that display the all-sky cameras), assisting astronomers and telescope operators during night observations.

A worldwide expansion of such devices, forming a true network of cameras, was simply not possible until recently. Commercial all-sky cameras solutions have prohibitive costs to a significant number of amateur astronomy enthusiasts. The cost of commercial allsky systems available for online retail range between 1500 and 2500 US dollars (Alcor System 2022; Starlight Xpress 2022). The Brazilian context has additional entry barriers, including the dependence on the import of such devices, further increasing the cost for amateurs or institutions that wish to operate an allsky camera.

However, these characteristics presented unique opportunities for the development of amateur all-sky camera projects. These projects can be great learning experiences, and also feature significant cost reduction, enabled by recent (i.e. since mid 2010s) cheapening in astronomical cameras. Amateur community-based open-source software projects have also been developed, allowing users with little programming experience to effectively control and operate the cameras. Finally, such

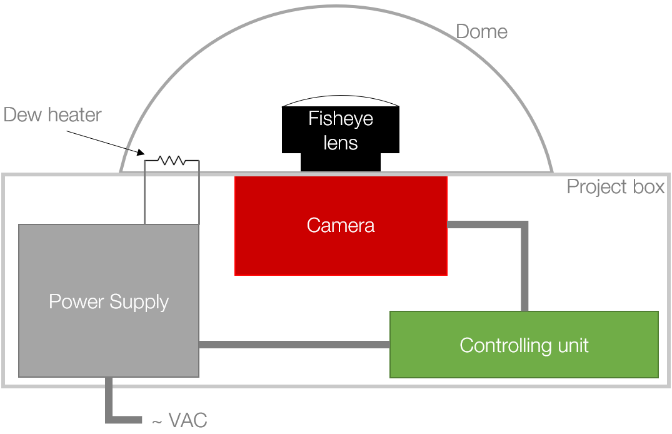

Figure 1. All-sky camera architecture.

projects can be valuable teaching tools for schools and institutions, developing competences in areas including engineering, astronomy, programming and maker-skills. This paper discusses the design, construction and lessons learned from building a do-it-yourself all-sky camera.

The remainder of the paper is structured as follows. Section 2 presents the basic design choices on both hardware and software for such cameras. Section 3 presents the build of the prototype unit, drawing from the design choices presented before. Section 4 presents the main results of the prototype, operational for more than 500 nights at the time of writing. Section 5 concludes and offers insights on further research using all-sky cameras.

2. Designing an All-sky camera

This section discusses the main design parameters, requisites and choices when developing an allsky camera. Recommendations and guidelines are also presented.

2.1. Basic architecture

The basic (hardware) architecture of an allsky camera system, highlighting the main subsystems or components is presented graphically in Fig. 1.

The device design centers around the **camera**, understood in the strict sense as the component which houses the imaging sensor. To the camera is mounted the **fisheye lens**, responsible for projecting the hemispherical image on the sensor. The camera is also connected to the **controlling unit**, which is responsible for data acquisition, control and communications, effectively an embedded computer. The components are housed in an **enclosure**, which should be resistant to being exposed to the environment 24/7, and also provide a clear opening so the lens-camera can see the hemispherical sky, accomplished with a transparent dome. Finally, additional **peripherals** offer power and auxiliary functions for the all-sky camera, such as preventing the formation of dew on the dome.

All steps when choosing the components have great potential to be learning processes, either personally (in the case of an amateur astronomer build), or for students (in the case of a school or university class). The following subsections discuss the main components and their design.

Table 1. Camera comparison

	ASI120MC	ASI224MC	ASI178MC
Sensor Model	AR0130CS	IMX224	IMX178
Sensor Size [mm]	4.8 x 3.6	4.9 x 3.7	7.4 x 5.0
Resolution [MP]	1.23	1.27	6.4
Pixel Size [um]	3.75	3.75	2.4
QE [peak]	65%	75%	75%
FWC [e-, peak]	14500	19200	15000
Readout noise [e-]	6.0-3.5	3.0-1.0	2.2-1.4
Cost	US$150 R$800	US$200 R$1100	US$270 R$1600

2.2. The camera

The selection of camera, being the central component of the device, should be the first step in the development of the camera. The primary design choice is between a monochrome or color sensor. The latter feature a special matrix in front of the sensor creating pixels that are sensitive to red, green or blue light. In general, color sensors obviously capture three-channel color information, but are typically less sensitive to monochrome chips, which can be fitted with a clear filter (maximum light throughput) or different-band filters (including photometric filters).

Some important parameters that should be considered are the sensors' quantum efficiency, pixel size, overall size and resolution, full-well capacity and noise characteristics (including read noise and dark current shot noise). For a comprehensive review on this parameters, readers are referred to Howell (2006).

Chinese astronomy equipment manufacturer ZWO ASI (ZWO 2022) produces a wide assortment of cameras using CMOS-sensors, being widely used by amateur astronomers. Despite not being the only possible choice, the software support and competitive prices make their cameras suitable choices for allsky cameras. A comparison of three popular models is presented in Table 1.

All three models are well suited for simple generic all-sky cameras, but depending on the use case, one option can be preferred. All are supplied out-of-the-box with a simple fisheye lens, that, despite not being highly optimized, can be used for initial allsky camera tests, dispensing the purchase of additional components. In simple terms, the first option, ASI120MC is the budget choice. It is the cheapest camera model from the manufacturer, but has generally inferior sensor parameters and more noise. Nonetheless, it can be used for simpler all-sky camera systems, and is recommended for projects with utmost budget constraints. The second option is based around ASI224MC, which feature a similar-sized sensor, but improved noise and sensitivity characteristics. This option is generally a well recommended balanced price/performance choice. The third option, ASI178MC, features a larger sensor, with higher resolution than the previous options. This allow for more detailed images, but at a higher cost (and processing power requirements). It is recommended as the top performing choice.

2.3. The fisheye lens

The fisheye lens should be selected jointly with the sensor used. The camera (sensor) and lens should be thought of as a system, so that their parameters can be optimized. As for the lens connection to the cameras, ZWO models feature a CS-mount adapter included in the box. CS-lenses are typically used for industrial applications, and can be found on online retail directly from Chinese distributors. However, there are relatively few wide angle models available, priced in the $50 to $80 range. Conversely, one can buy lenses that use a smaller mount, M12, typically used for security cameras, that can be fit into ZWO cameras with an additional CS-M12 adapter. There are more fisheye models to choose from, and these lenses can be found for as low as $10.

Important parameters when selecting the lens include the projection field of view (some lenses project less than 180°, while others can project as wide as 220°), image circle dimensions (that should be matched to the sensor size and desired image characteristics) and back-focal length (it must be able to focus on the sensor surface). Another choice is to have the lens fitted with a IR-cut filter. The filter limits the wavelength passband to the visible spectrum, thus allowing more natural colors, and preventing excessive infrared sky background contamination, and is generally recommended for all but special purposes. A more detailed comparison between lenses in the prototype unit is presented in section 4.1.

2.4. The controlling unit

A small computer has adequate hardware performance for controlling the all-sky cameras. The choice of controlling unit also depends on the software and platform used. Some software applications are exclusive to Linux, whilst others run on Windows PCs.

A popular and cost-effective controlling unit is a Raspberry Pi (RPi), especially suited ton run the allsky software by Thomas Jacquin. Choose a full-sized board (Model 3B+ or, better, Model 4), with at least 1GB of RAM (preferably 2GB or more). However, under limited availability for the maker market, the board prices have recently skyrocketed (reaching more than triple the MSRP). Other boards that run Linux systems can also be considered and adapted to run that software, but their configuration is less straightforward. These boards can be found from circa $50, and are the cheapest option for low-budget high-tinkering projects.

Regardless of board type, having extra GPIO pins can be an useful feature for expanding the capabilities of the system (e.g. controlling extra heating elements or acquiring additional sensor readings).

2.5. The enclosure and peripherals

There is great freedom in designing the enclosure. It can be built using different materials, using a custom 3D printed design, or adapted from existing plumbing or electronic mounting boxes. Regardless of design, it should allow the secure fitting of all components inside, and resist the weather events for outside operation, including direct sunlight and rainfall. A highly reflective outside color such as white is desired, due to the reduced heat absorption, but having the lens/dome area darkened and flocked reduces unwanted reflections.

The dome is an important component, allowing the lens to effectively see the daytime or night sky. Acrylic domes are commonly used for underwater action cameras or security cameras, and can be sourced in Brazil or directly from China, but keep in mind their toll on optical image quality is an unavoidable weakness. It must be securely mounted and sealed, preventing water leaking inside the enclosure.

Peripherals are additional important, but sometimes forgotten components. These include at the very least the power supply for the controlling unit, but a dew heater for the dome is also a potentially critical part. The cold night air condenses in the outside surface of the dome, completely fogging and obscuring the field of view. To prevent it, a heating element is placed inside the dome, to keep its temperature above the dew point and prevent condensation. The element can be build from resistors or nichrome wire. Our experience is that about 3W of power is sufficient to keep the dome gently above dew point, but testing is recommended. The heating control can be simpler (e.g. constantly on) or more sophisticated (e.g. incorporating active control with dew point measurement). The heat should be enough to prevent dew formation, but it should not damage internal components or cause excessive thermal noise on the camera.

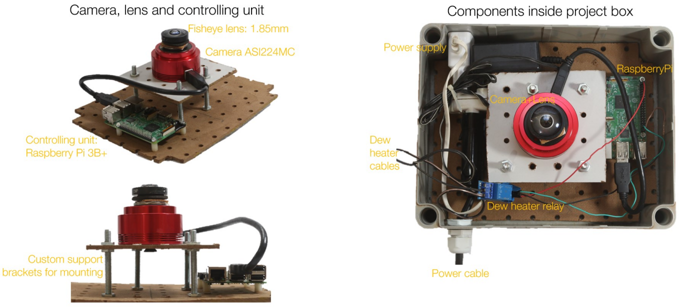

Figure 2. Prototype main components (left) and the components fitted inside the enclosure (right).

2.6. Control software

There are a few options of control software specifically developed for amateur all-sky cameras. The authors highlight three. The first is the allsky project, originally developed by Thomas Jacquin, and further expanded by a community of active developers (Jacquin et al. 2022). It runs on a Raspberry Pi, and features automatic exposure, ZWO/RPi camera control, file management and a high degree of flexibility. It can generate time lapses, startrails and keyograms, as well as upload the data to a website accessible through the internet. The second option is the INDI allsky project, which is inspired by the former and offers similar functions,is built upon the INDI library running on Linux machines, supporting a greater variety of camera and astronomy equipment (Morris 2022). Both these options are actively developed open-source projects. As a third option, there is the Windows software application AllSkEye, offered as freeware standard version (and a paid PRO version with additional features), that can also control all-sky cameras automatically (AllSkEye 2022).

The choice of control software should consider the use case and required functions, as well as the degree of custom desired. Thomas Jacquin's and INDI allsky software can be modified with additional functions programmed by the user. AllSkEye is a more plug-and-play solution for non-programmers Windows users. Note that dedicating a Windows PC to running the all-sky camera can be more expensive than simpler boards that run Linux systems.

3. Building an All-sky camera prototype

A prototype unit was built by the authors. The build featured ZWO ASI224MC, a 1.85mm M12 fisheye lens projecting a 185° horizontal fisheye image, and an enclosure based around an off-the-shelf waterproof electronic component box. A 6" acrylic dome was used. Fig. 2 shows the build and components, and Fig. 3 shows the finished unit before being deployed in the first author's personal amateur astronomical observatory in a rural site in Minas Gerais.

Figure 3. Finished prototype project box.

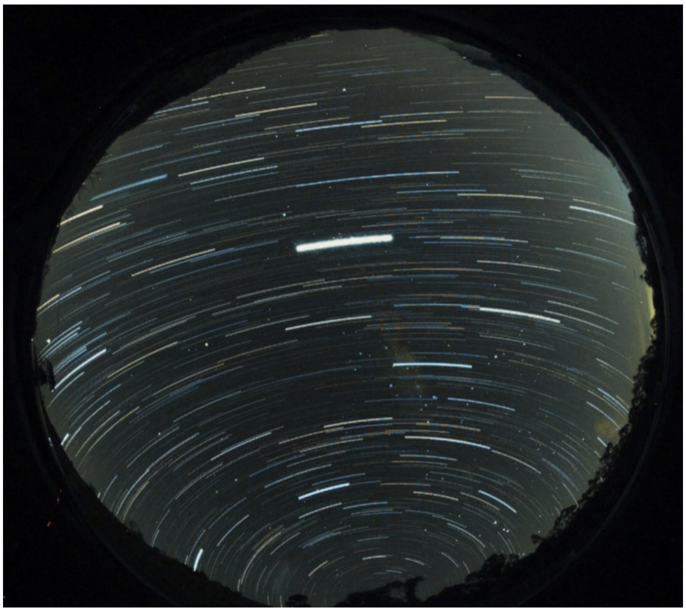

Figure 4. Startrail image generated by the co-addition of allsky camera frames. Total exposure of about 2 hours. The brightest trail North of center is Jupiter.

4. Results

The prototype has operated under a dark sky (i.e. low light-pollution) for over 500 nights since March 2021, and produced over 150GB of data. Although a full photometric calibration of the cameras has still not been performed, *ex-post* analysis of images show that in a moonless night it can detect stars down to about magnitude 6 (in a 60s exposure). It can also detect the brightest meteors, the Milky Way band and the outline of constellations and asterisms. More images of the night sky photographed by the system are presented in the lens comparison section. A startrail image, automatically generated by the control software by the co-addition (maximum operator) of about 2h of exposures is also included in Fig. 4, showing the apparent motion of the stars across the night sky.

4.1. Lens comparison

Three fisheye lenses were compared, as presented on Fig. 5. All were compared with the same camera (ASI224MC). Daytime images highlight the difference in field of view between lenses. Nighttime images compare the effects of the IR-cut filter on the same lens. It is possible to identify the main constellations, the Milky Way band, as well as light pollution from nearby cities. The brightest point light-source in the image is Jupiter.

Table 2. Prototype cost analysis

Component	Cost [R$]
Imaging camera - ASI224MC	1200
Fisheye lens - 1.85mm M12 12MP	120
Controlling unit - Raspberry Pi 3B+	400
Enclosure - Project Box	100
Enclosure - Acrylic Dome	80
Peripherals - Power supply	50
Peripherals - Dew Heater	10
Peripherals - Mounting accessories	40
Total cost	**2000**

4.2. Cost analysis

An analysis of the prototype's cost is fully presented on Table 2. The numbers (rounded to the nearest meaningful ten or hundred) are a reasonable cost estimation for future projects based around the prototype, but some variability is expected depending on the selected components, exchange rate and market conditions.

The overall cost of the prototype was around R$2000 or US$400. This represents 20-40% of the cost of commercial allsky systems (MSRP, no taxes), highlighting the potential of the expansion of such projects to a broader audience and user base.

4.3. Lessons learned

The first key takeaway point from designing, building and operating an allsky camera is that it should be designed as a system. The device is more than just a camera and lens. The design should also consider the enclosure, mounting and peripherals.

The second takeaway is that water is conspicuous, and should be very carefully addressed. The first version of the prototype did not feature a dew heater, and condensation formed on the outside of the dome. Furthermore, the seal between dome and box had leaks that allowed rainwater inside, fortunately detected early, preventing damage to the components in the enclosure.

Finally, doing things yourself can be beneficial twofold. It represented significant cost savings for this project (about 70%), thus increasing availability of devices to a broader user base. Furthermore, the process of doing it is a learning experience unparalleled to buying a product - there is great potential for personal skills development, including in a teaching context.

5. Conclusion

It is possible to develop capable and cost-effective all-sky cameras. This paper has discussed the design, build and results of a successful all-sky prototype. The camera has operated for more than a year, and is already being integrated as part of the remote monitoring system of the first author's personal observatory (more details on the observatory are presented in a second paper by the authors in this edition of the Proceedings of the XLV RASAB).

The authors strongly believe such projects, based on commercially available hardware and open-source software, can enable unprecedented expansion of such devices to a much broader audience, not only astronomy enthusiast individuals, but also in-

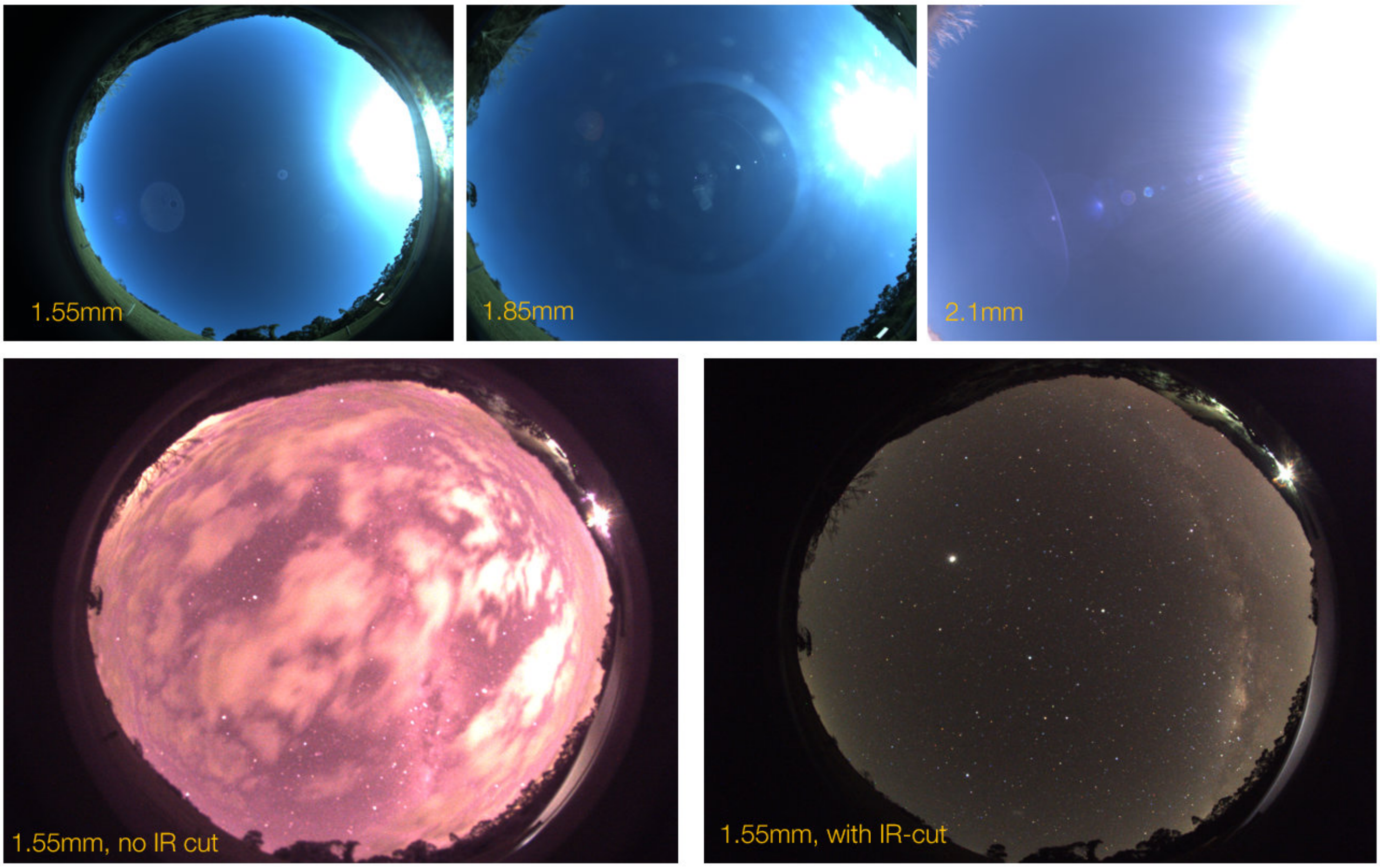

Figure 5. Fisheye lens comparison.

stitutions. Middle and high-schools and universities can build institutional all-sky cameras, which also posit great learning opportunities for courses and classes, integrating STEM and maker-related fields, including concepts in astronomy, engineering, design and programming.

Further research and improvements to the project are envisioned, including the full prototype integration in an observatory automation system, automatic detection of clouds, events, meteors and satellites, as well as a full astrometric Barghini et al. (2019) and/or photometric calibration of the system (e.g. Román et al. (2012)). The latter could allow precise site characterization and long-term light pollution monitoring. Finally, a broader network of allsky cameras could enable scientific research in various areas, by triangulating data from nearby cameras, and contribute effectively to the understanding of night sky phenomena.

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