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An observatory for astronomical imaging: development and future prospects

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Abstract. Astronomical observatories provide a centralized facility for conducting astronomical observations. The observatory houses the telescope, mount, instruments and delicate equipment used to collect data about astronomical objects, and also allows a comfortable place for the astronomer and/or operator. Beyond professional observatories dedicated to scientific research, amateurs and astronomy enthusiasts also build and operate facilities for personal use. This paper details the development, construction and initial operation of an amateur astronomical observatory, whose primary objective is optical light astrophotography. The planning, design, materials selection and construction are discussed. Data and images collected during the build are presented, and show how a relatively simple observatory can be built to fit amateur budgets. Commissioning tests performed in early 2022 show promising results, including the characterisation of an amateur imaging system based on a consumer-grade DSLR camera and an equatorially-mounted 15cm reflective telescope. Some further activities that can be performed from the observatory are also highlighted, including the possible impacts of those facilities in pro-am collaborations and astronomy outreach.

Resumo. Observatórios astronômicos oferecem um local centralizado para conduzir observações astronômicas. O observatório abriga o telescópio, montagem, instrumentos e equipamentos delicados utilizados para coletar dados sobre objetos astronômicos, e também oferecem um local confortável para o astrônomo e/ou operador. Além de observatórios profissionais dedicados à pesquisa científica, amadores e entusiastas de astronomia também constroem e operam observatórios para uso pessoal. Este artigo detalha o desenvolvimento, construção e operação inicial de um observatório astronômico amador, cujo principal objetivo é o de astrofotografia ótica. O planejamento, projeto, seleção de materiais e aspectos construtivos são discutidos. Dados e imagens coletadas durante a construção são apresentadas, e mostram como um observatório relativamente simples pode ser feito para orçamentos amadores. Testes de comissionamento realizados no início de 2022 mostram resultados promissores, incluindo a caracterização de um sistema de imageamento amador baseado em uma câmera DSLR e um telescópio refletor de 15cm em montagem equatorial. Futuras atividades que podem ser realizadas do observatório também são destacadas, incluindo os possíveis impactos de tais instalações em colaborações profissional-amadora e na divulgação de astronomia.

Keywords. Instrumentation: miscellaneous – Miscellaneous – Site testing – Telescopes

1. Introduction

Astronomical observations – both scientifically-oriented data acquisition and amateur observations, including pretty pictures – impose strict quality constraints. High quality results require stability, repeatability and patience. Stability because the telescope must be precisely pointed, aligned, tracked and guided (so that stars can be exposed sufficiently long). Repeatability so problems can be systematically addressed and the imaging system optimized for its best performance, and so the data can be better compared and analyzed. Patience for astronomy requires time and effort to acquire and process data (again, both for scientific and artistic purposes).

As a traveller amateur astronomer and astrophotographer, the first author's experience with astronomy involved significant efforts. More than 50kg of equipment must be transported, setup and checked before observations could take place from a dark site away from the polluted urban skies of his home in São Paulo. The entire process is tiresome, not to mention error-prone: a seemingly harmless forgotten cable could end the prospect of an imaging night. For this reason, building an observatory in the author's rural property was a natural development, allowing the making of astronomical observations a more pleasing process yielding higher quality results. Most traveller amateur astronomers wish for a similar experience, as building a personal observatory is the dream project of many. Furthermore, it enables new and exciting projects, including the participation in scientific collaborations. In sum, the main reason why an amateur astronomer should build a personal observatory is to have the best quality results and relative comfort (Hicks 2016).

In this paper, we discuss important aspects to consider when pursuing such a project. A thorough description of how should an observatory be build is beyond our scope: the specific contingencies of each case must be considered, as is highlighted from the beginning of our framework. The textbook Hicks (2016) presents a thorough description of construction methods and techniques of two main observatory designs (dome and roll-off-roof, discussed in more detail in the next section). However, those designs (and others available online) typically use materials and techniques found on countries such as the United States, Canada or parts of Europe, which are usually not employed in the Brazilian context. As such, reporting the experience of building an astronomical observatory in Brazil can be insightful, and hopefully helps individuals or groups that wish to pursue a similar project.

The remainder of this paper is structured as follows. Section 2 presents a general framework to guide the development of an astronomical observatory, highlighting the main aspects and design points that must be addressed. Section 3 presents the first author's personal amateur observatory, including its design, planning, building and initial operation. A cost analysis of the project is also included. Finally, Section 4 concludes and lists future opportunities envisioned for the presented observatory.

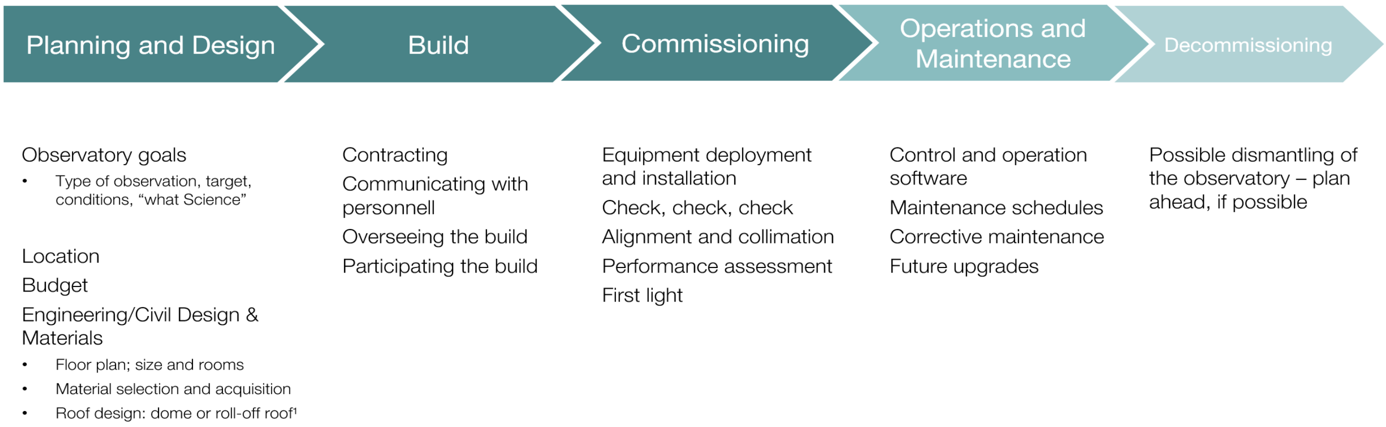


Figure 1. A framework for astronomical observatories

2. A Framework for the development of an astronomical observatory

Building an observatory is not a trivial task. The entire project goes beyond the simple build phase, and careful decisions must be made by the owner(s). To better conceptualize and systematize the process, the following framework, based on the project life-cycle was developed. It describes the observatory build from the perspective of an amateur astronomer, but similar concepts can also be applied or adapted even for professional astronomy contexts. It is graphically presented in Fig. 1, and explained in the following subsections.

2.1. Planning and design

This should be the first and most important phase of the entire observatory project. Foregoing careful planning and heading straight to the build can lead to rework, frustration and avoidable expenditure. As such, it must begin with the most important question to be answered by the observatory project owner: what are the goals for the observatory? In other words, the astronomer must determine what is the observatory going to be used for, what type of observation, object and science objective is going to be pursued. Clearly answering this question is critical.

Other important aspects to be considered during planning include the location, budget and engineering design. The location scouting and selection can be more or less sophisticated, depending on the goals and scope of the project. As examples, one can refer to the location scouting campaign for the Brazilian National Observatory (later Observatório do Pico dos Dias - OPD, managed by the Laboratório Nacional de Astrofísica - LNA), summarized in the report by Ferraz-Mello (1982). Further examples are ESO campaign that ultimately decided for Paranal as the site to the most advanced optical telescope in the world at the time (see Grenon (1990); Ardeberg (1983) for early surveys and Sarazin (1990) for the full report), along other more recent studies Aksaker et al. (2020); Vernin et al. (2011); Schöck et al. (2009). For amateurs, the location selection is typically more contingent, usually on their home backyard or in property they have access to.

Budgeting is obviously an important concern with any project, and should also be included for the personal observatory build. It is a particular characteristic of each individual, and drives the options in design and materials used.

Finally, the engineering project must be completed. It is in this phase that the floor plan, material selection and general design is developed. Here there are several design choices involving important trade-offs. The engineering project can be made by the owner or by a contracted third party (usually civil engineer or architect). It is also important to check local regulations to ensure compliance (e.g. building permits). Again, it is worth reminding that the design *derives from* the science goals, and not the other way round.

2.2. Build

The build includes personnel contracting, materials acquisition and the heavy civil works. It is very important for the project owner (in the case of not doing the construction thyself) to ensure adequate, precise, clear and frequent communication with the team working in the build. The builders must understand the requirements so they can actually perform as expected.

2.3. Commissioning

Commissioning includes the deployment and installation of equipment once the build is complete. The goal is to have best possible performance so that image quality is maximized. In this phase the components are accurately aligned, positioned and balanced. The performance is assessed using various metrics, depending on the science goals. It ends with the first light.

2.4. Operations and Maintenance

This long-term phase includes the continual operation of the observatory in carrying out astronomical observations and its support activities. The type of operation can be either local (with the astronomer operating the system *in loco*), or remote and even automatic). In general, developing and operating an observatory for automatic remote observations is much more complex than local operation, including safety, monitoring and support subsystems. Devising maintenance schedules is recommended, to keep track and manage such activities (e.g. check and adjusting collimation once a month).

2.5. Decommissioning

Included for the sake of completeness, it is worth considering the end of the observatory's life-cycle. In case of a house move, e.g., the disassembly and moving of the observatory with the astronomer should be planned ahead. How it can be repurposed or recycled, shall it be necessary, is also worth thinking about.

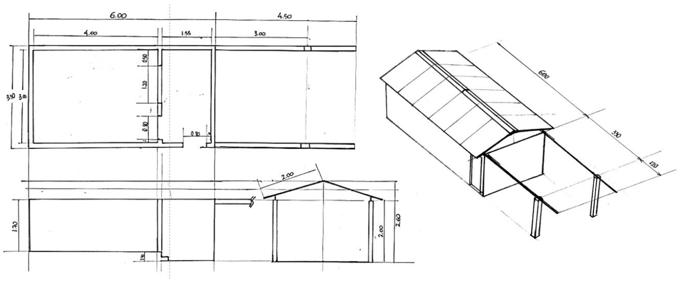


Figure 2. Floor plan (left) and isometric view (right) of the observatory.

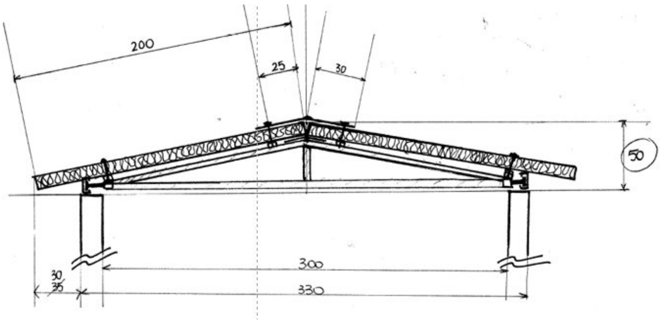


Figure 3. Detailed view of the observatory roof plan with key design parameters. The final roof structure was designed and executed by the contracted metalworker, and thus is not identical to the original design shown here.

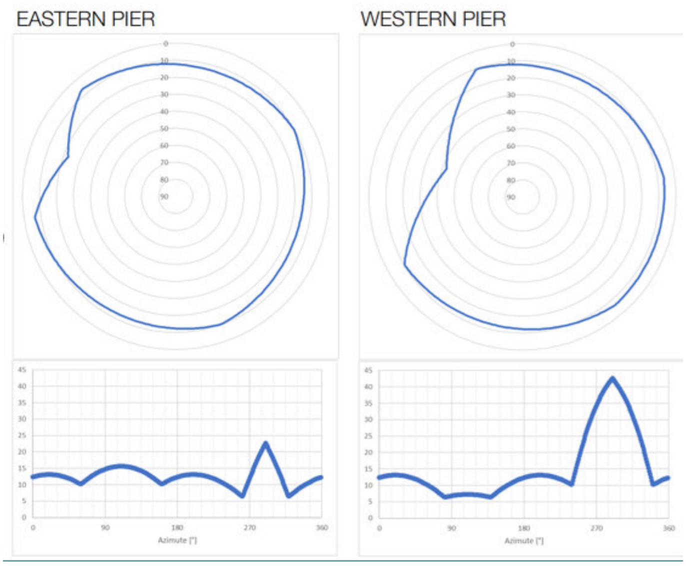


Figure 4. Horizon clearance as simulated for the eastern and western piers of the observatory. The expected maximum zenithal angle is about 70-80°, except towards the Western horizon, where the open roof is located.

3. The observatory project

This section details the construction of an actual observatory project, the first author's personal amateur observatory, in light of the framework devised in the previous section, with special emphasis on the first three phases (planning to commissioning).

3.1. The planning and design of an observatory

The author's observatory main goal was astronomical deep-sky imaging, that is, creating images of galaxies and nebulae primarily with artistic purpose (however, the data can also be used for scientific projects beyond outreach activities). Furthermore, as part of the requirement list, was the simultaneous operation of two systems (two telescopes/cameras/mounts/piers), the use for widefield imaging (angular field of view of 10-20° and wider), being a cost-effective project to fit an amateur budget, and serving as a learning hands-on and do-it-yourself experience. The location was a given for the project, in the author's family rural site in Southern Minas Gerais, Brazil (1220m altitude, Bortle 3).

The observatory features two separate "rooms". One observing room, where two concrete piers are located, and from where the observations are carried out. The second room is a control room (sometimes referred to as "warm room"), where equipment can be stored and where the operator can be shielded from the cold outside temperature during the winter.

The selected roof type was for a roll-off roof. Contrary to a traditional dome, the roll-off allows the operation of multiple instruments under the same roof, the near-allsky visibility (important for wide fields of view), and is generally easier and cheaper that a dome of equivalent size. Fig. 2 presents the floor plan for the observatory project, and Fig. 3 presents a detailed view of the roof design.

The roof tile material is an important consideration. For the project, thermoacoustic roof tiles (also known in Brazil as "telhas sanduíche" or "telhas termoacústicas") were selected. They allow a higher acoustic, and, more importantly, thermal stability inside the observatory when compared to simple metal sheet tiles. For this reason, they are recommended for observatories, despite their higher cost.

The wall design of the observatory aimed at maximizing the sky visibility, minimizing horizon obstruction. A simulation tool was developed, so that the horizon clearance could be compared using different wall/roof design parameters. Fig. 4 presents the simulated horizon view in azimuthal projection for the eastern and western piers, showing that the horizon is clear from about 20° altitude, except for the region where the roof is positioned.

3.2. Building an observatory

The project was executed in three phases, two of which were already fully completed. It was executed by local contractors and workers. The first phase happened in early 2020, and was comprised of the terrain preparation, markings and build of the two concrete piers and the observing concrete slab around them. The second phase consisted of the heavy civil works, including construction of the brick walls and control room (phase 2.1), the assembly of the metal roll-off roof (phase 2.2) and finishing (phase 2.3). It was the most labour and cost-intensive phase, taking place between September 2021 and early 2022.

It is worth mentioning that it is currently in a third phase, comprised of the activities towards automation and remote operation of the facility, which is not discussed in this paper. The main build phases and milestones are presented in Fig. 5, and the finished observatory is presented on Fig. 6.

3.3. Commissioning an observatory

The observatory commissioning tests were performed in mid-2022. Once the heavy civil works were finished, equipment was setup and performance-optimized. Current equipment include two setups, as previously mentioned, one extremely wide field system based on a camera lens as the main optics (135mm focal length), and one deep-sky astrograph telescope. The character-

Figure 5. Observatory build photos and milestones. The leftmost column shows the first build phase in early 2020 (terrain, dual concrete piers and observing slab); the center column, the first part of the second phase in Sep. 2021 (walls and heavy civil construction); the right column shows the second part of this phase in Dec. 2021 - early 2022 (roof assembly and finishing).

Figure 6. The finished observatory.

Item	Details
Mount	Sky-Watcher HEQ5 (German equatorial)
Telescope	Newtonian reflector, 150mm, custom-made
Correcting Optics	3-element TS Coma Corrector
Imaging camera	Canon T5 DSLR (w/ enhanced Ha sensitivity)
Filters	Photographic RGB (Bayer color filter array)
Eff. focal length	710mm (f/4.8)
Pixel scale	1.08 "/px
Field of view	1.8 x 1.2°
Image resolution	18MP (c.a. 5000 x 3500px)

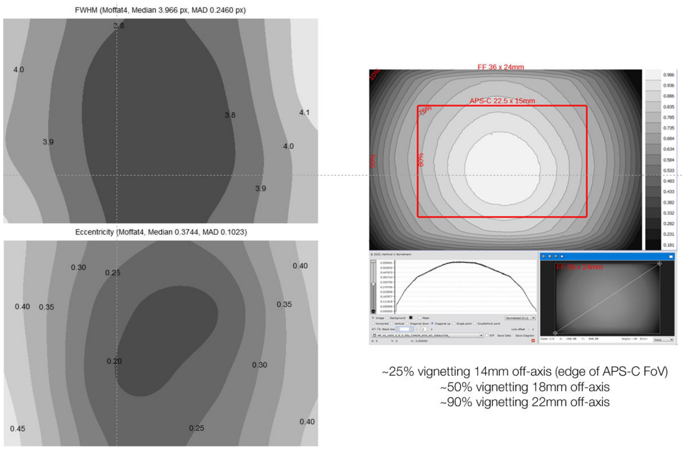
Table 1. Main equipment data

ization and assessment focused on the telescope performance, since it is the most demanding optically and mechanically.

Table 1 presents the main characteristics of the current equipment installed in the deep-sky setup. It includes a newtonian telescope optimized for astronomical imaging and a consumer-grade digital single lens reflex camera.

The current imaging system operates at a pixel (plate) scale of 1.08"/px, which can be considered slight undersampling under median seeing conditions. Once the telescope was collimated, a flat field analysis was performed to check vignetting, and a starfield analysis was performed to assess star shape and quality across the field. The results are presented in Fig. 7.

The median FWHM of the system is about 4". The field shows acceptable spatial variance in both star size (FWHM) and eccentricity. Analysing the flat field shows good field illumination across the main imaging sensor (APS-C sized, 27mm diagonal). Tests were also performed using larger sensors (Full-frame sized, 44mm diagonal): the extreme corners suffer from severe vignetting, but usable images can also be acquired with this setup.



~25% vignetting 14mm off-axis (edge of APS-C FoV)
~50% vignetting 18mm off-axis
~90% vignetting 22mm off-axis

Figure 7. Star quality and flat field analyses. Star FWHM (top left), eccentricity (bottom left) and vignetting (right) are plotted.

	Cost [R$]
Phase 1	4076
Construction material	629
Terrain preparation	540
Civil labor	1510
Pier adapters and electric materials	1397
Phase 2	25658
Construction material	3332
Civil labor	2100
Roof tiles	6021
Roof structure and installation	9496
Roof accessories	521
Woodwork (doors/window)	2643
Electric accessories	943
Finishing and paint	602
Total cost	**29734**

Table 2. Observatory project cost analysis

Additional guiding tests allowed the determination of a maximum unguided exposure length of about 2 minutes, with a mount RA periodic error of about 8 arcseconds, which is considered acceptable for the consumer-grade equatorial mount. It is worth noting that the imaging system is run with autoguiding, providing a guiding tracking performance RMS of c.a. ±1". Pointing accuracy is better than 2' (with software plate-solving).

3.4. First light

The first light of the finished observatory was on 30 June 2022. The telescope was pointed to the Carina Nebula and exposed a 2-panel mosaic for 80 minutes of total integration time. Fig. 8 presents the final processed image of the first light, fully displaying the large and bright nebulosity of hydrogen gas in a dense starfield of the Southern Milky Way.

3.5. Cost analysis of the observatory project

Cost accounting was performed throughout the project. The summary of the project cost is presented in Table 2.

The absolute numbers are prone to regional variability and market conditions, affecting construction material and labor

Figure 8. First light image of the observatory.

cost. The latter was also reduced in the reported project since a significant portion of the work was performed by the first author himself. Nonetheless, it can be regarded as a general figure that may be used as an estimate for similar amateur projects.

It is worth noting the significance of the roof cost in the overall project. It was responsible for 54% of the total cost of the project (R$ 16038), which highlights the importance and responsibility in its design and execution. The roof is followed by the civil construction labor and construction materials costs. Furthermore, the phases also show a significant cost difference: building the piers and concrete slab was a relatively simple process. Phase 2 presented a greater challenge, effort and cost.

4. Conclusion and next steps

This paper discussed the design and build of an amateur astronomical observatory, including general considerations summarized in a framework, and presented the project of the first author's personal observatory.

The roof was found to the most significant and complex subsystem of the project, and also the most expensive. For this reason, special attention should be devoted to its design. A lesson learned in the case of the author's observatory regards more careful consideration of the need and of the layout of the control room. The roof has a 20m^2 footprint, but only 12m^2 are useful observing space, because the control room represents area in the roof footprint. A smaller movable roof could represent significant cost savings. Conversely, fully utilizing the existing roof area could allow for an extra instrument or two to be installed.

Four take home messages could be derived from the observatory project experience. Firstly, it is crucial to set clear goals for the project – once that is clear, the following design choices, project alternatives and trade-offs are much more manageable. Secondly, plan ahead as much as possible, for identifying (and tackling) problems early, during the planning phase, is much more efficient than solving them during (or after) the build. Thirdly, find good and reliable contractors, preferably local, and communicate the project clearly with them, working in close collaboration. The workers and professionals involved in the project execution must understand the project requirements. Finally, an observatory is much more than a telescope (or even its building): thinking systemically is critical, especially for larger and more complex projects.

Complemented by professional assistance when required, getting involved and doing things yourself can be beneficial in two fronts: cost savings and learning experience. We argue the first generally not the most important. Despite the monetary benefit, some rework and iteration is inevitable in a learning process. It is also extremely time and effort intensive. However, what is learned with the experience is invaluable, both in terms of hard, practical and soft skills: from planning, designing, communicating with stakeholders and workers, and managing the build.

Current and future exciting projects for the author's observatory are already on course or being currently planned. It is expected to continue to deliver high-quality deep-space pretty pictures. The development of the automation systems towards remote operation is ongoing, and includes an all-sky camera presented in other paper also on this Proceedings of the XLV RASAB (Rodrigues Santos & Ederoclite 2022). Furthermore, the fixed observatory enables future scientifically-oriented projects in pro-am collaborations, e.g. the photometric monitoring of variable stars, exoplanet transits and near-earth objects. Astronomy outreach activities with the local community are also in consideration, along with projects in light-pollution monitoring and awareness raising.

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