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THE INTELLIGENT OBSERVATORY

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RESUMEN

El Observatorio Astronómico de Sudáfrica (SAAO) se ha embarcado en un programa para mejorar tanto sus telescopios e instrumentos como el análisis de datos para que trabajen juntos de manera inteligente y coordinada. El objetivo no solo es ofrecer mayor eficiencia y agilidad, sino también permitir la exploración de nuevas oportunidades científicas, particularmente en esta era de la astronomía de multi-mensajeros y del dominio temporal.

ABSTRACT

The South African Astronomical Observatory (SAAO) has embarked on a programme to upgrade its telescopes, instruments and data analysis to have them intelligently working together in a coordinated fashion. The objective is to not only deliver greater efficiency and agility but to enable the exploration of new science opportunities particularly in the era of multi-messenger and time-domain astronomy.

Key Words: Robotic observatories — Autonomous follow-up — Transient Alerts — Multi-messenger astronomy

1. INTRODUCTION

The rate of astronomical transient discoveries and alerts is poised to increase dramatically in the coming years, driven by data-intensive surveys such as the Legacy Survey of Space and Time (LSST) at the Vera C. Rubin Observatory. In anticipation of this influx of transient alerts, the South African Astronomical Observatory (SAAO) has initiated the "Intelligent Observatory" or "IO" project (Väisänen et al. 2018; Potter 2021). The program involves the upgrading of the hardware of all the telescopes to permit autonomous operations with the corresponding development of software. Intelligent algorithms have also been developed in order to intelligently and autonomously respond to real-time alerts from other telescopes across the world and space based observatories. All this is overseen by an Observatory Control System that actively manages an observing queue in real-time. Here we summarize the achievements so far, particularly with the completion of one such SAAO telescope that is now fully integrated into the IO's daily operations[5].

2. DIVERSITY OF FACILITIES AND INSTRUMENTS AT THE SAAO

Situated at the southern tip of the Northern Cape province in South Africa, the South African Astronomical Observatory (SAAO) owns and operates four telescopes while serving as host to over 15 telescopes from various international partners. The SAAO-owned telescopes alone present a reasonable diversity, featuring instruments and aperture sizes ranging from the 1-meter Lesedi telescope to the impressive 10-meter South African Large Telescope (SALT). This diversity encompasses a broad spectrum of instrument capabilities, including optical imaging, optical and near-infrared spectroscopy, polarimetry, spectro-polarimetry, and high-speed photometry (refer to Figure 1). When including the capabilities of the various hosted facilities, the scientific endeavors at the observatory span a multifaceted array, encompassing transient science, near-Earth asteroid surveys, microlensing detection, exoplanet discovery, solar monitoring, to name just a few. The unique strengths of each telescope position the observatory to collectively serve as a potent "follow-up machine", particularly if autonomous robotic observing becomes the norm for each facility, supported by more cohesive and coordinated observing strategies.

3. THE IO PROJECT AND ITS VISION

The IO project is a comprehensive initiative within the SAAO that spans across all divisions, including astronomy, software, engineering, and instrumentation. The primary objective is to future-proof the SAAO and ensure its relevance in the

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[5]`https://io.saao.ac.za/`

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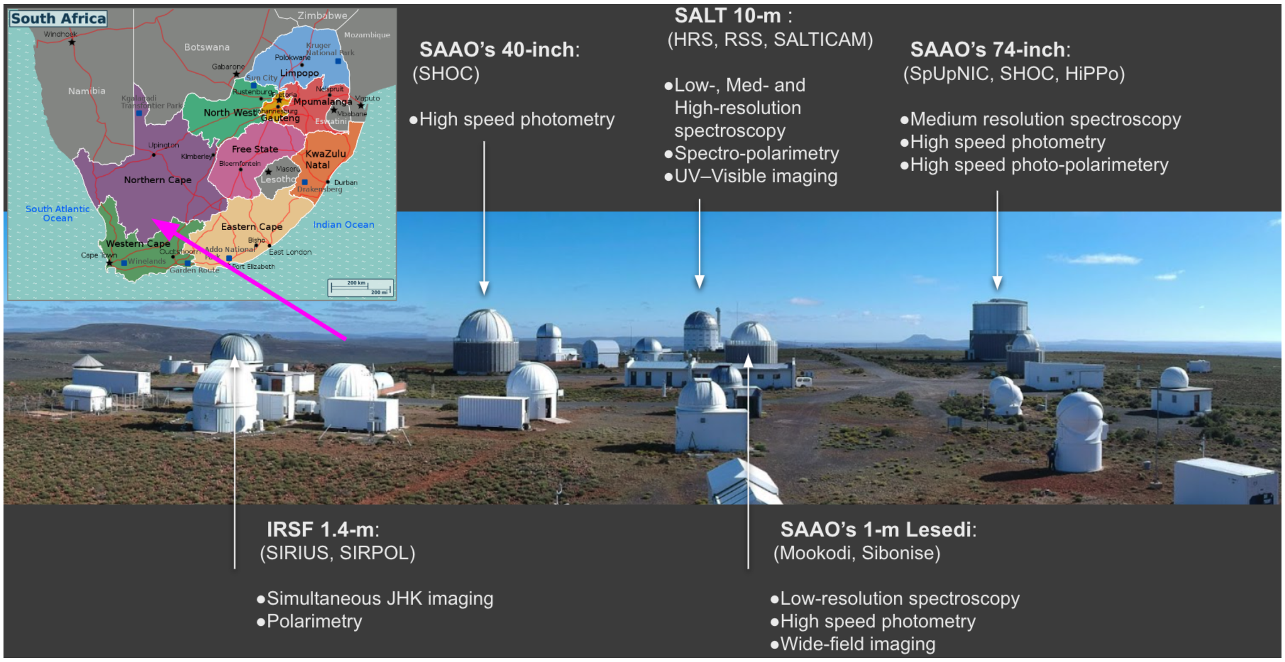

Fig. 1. Panoramic view of the South African Astronomical Observatory's site in Sutherland, Northern Cape, showcasing the 40-inch, Lesedi, and 74-inch telescopes under the ownership and operation of the SAAO. Additionally, the Southern African Large Telescope (SALT) and InfraRed Survey Facility (IRSF) are also highlighted with their respective available instruments and capabilities. The photograph captures the presence of many of the other telescopes from international partners contributing to the collaborative astronomical efforts at the site.

rapidly evolving astronomical landscape (Buckley 2019). Open to all capable contributors within the organization, the project maintains a core IO team utilizing a modified "Scrum" methodology as a framework for effective work execution toward the ultimate goal. The project envisions the integration of as many telescopes as possible into the IO system, fostering more coordinated scientific efforts across telescopes in the era of multi-messenger astronomy. This integration aims to strengthen national and international partnerships while propelling the SAAO into the realm of the fourth industrial revolution (4IR). Such advancements will enhance the SAAO's service to the astronomy community and users, enabling features such as the submission of proposals at any time, science on various timescales (i.e. not restricted to the classical 1-week blocks), manually performing remote observing from Sutherland, Cape Town, or anywhere globally, robotically queued observations, improved responsiveness to transient alerts, and the facilitation of computer-generated observing requests for rapid response.

4. CURRENT STATE OF THE IO PROJECT

While we envisions the integration of as many telescopes as possible into the IO system, for now the IO activities have mainly focused on the telescopes fully owned by the SAAO with no external partners. This mainly includes the almost 80-year old 74-inch telescope, the roughly 60-year old 40-inch telescope, and the newly installed 1-m Lesedi telescope that was purchased and installed with robotic operation in mind from the onset.

4.1. *Remote Observing*

A crucial initial stride towards achieving fully autonomous observing, particularly with the two older telescopes, involves the implementation of remote observing capabilities. Over the past decade, a concerted effort has been dedicated to upgrading various electronic and mechanical components, as well as control software for the telescopes and domes, to facilitate remote observing. Currently, all telescopes operated by the SAAO are accessible remotely from the dedicated remote observing room at the SAAO's headquarters in Cape Town. In principle, they are remotely operable from any computer worldwide equipped with a web browser and appropriate access credentials. It's noteworthy that this is not merely through desktop remote connections to the control PCs but via web-based graphical user interfaces (GUIs) that communicate with GUI-independent back-end software services running

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on the control PCs. The back-ends are accessible through an application programming interface (API), future-proofing for robotic algorithmic control of the telescopes and instruments.

The implementation of remote observing has already proven valuable for certain science programs that require only a single night or even a portion of a night (e.g stellar occultations of solar system bodies), rather than an entire week, demonstrating the flexibility and more efficient use of telescope time of the upgraded system.

4.2. *Robotic Observing with Lesedi*

Lesedi (Worters et al. 2016) meaning "light" or "enlightenment" in Sesotho, is the name of the SAAO's 1-m alt-az telescope, which features two Nasmyth ports equipped with field derotating and autoguiding capabilities. Installed on one of the ports is Mookodi (Erasmus et al. 2024) - meaning "rainbow" in Sesotho a low-resolution (R = 300) spectrograph operating in the visible wavelength range (400−800 nm). Both Lesedi and Mokoodi were designed and constructed with robotic operation in mind from the outset, making them the obvious initial telescope and instrument combination for full integration into the IO's system. Mokoodi utilizes an imaging mode for astrometrically-driven automated target acquisition[6] on the spectrograph's slit, and this imaging mode can also be used for scientific operations because it employs the same science-grade detector as the spectroscopy mode. The instrument is equipped with a full Sloan filter set (see caption of Figure 2 for more detail on Mookodi). The capability to rapidly switch between spectroscopy mode and photometric imaging mode makes Mokoodi an attractive instrument for the SAAO's IO initiative since this is essentially two instruments in one that can cater for various science cases. The telescope and instrument have been in full robotic operation for over a year, and the science cases presented in Section 5 are performed by this duo.

4.3. *Observatory Control System*

The IO Project has chosen to leverage proven technology, utilizing the recently open-sourced Observatory Control System software (OCS) [7] developed by the Las Cumbres Observatory (LCO) to manage user-submitted observing requests and schedule observations into a dynamic queue. The LCO's OCS is already AEON (Astronomical Event Observatory Network) compatible, aligning well with the goals of the SAAO's IO project. AEON aims to create a network of world-class telescopes accessible on demand, specifically for swift follow-up observations in the LSST-like survey era. Currently, the SAAO's version of the OCS has implemented the Mookodi instrument, with plans for more instruments in the future. Users can submit observation requests manually through a web form or programmatically via the provided API. Figure 3 shows a screenshot of the web-front end of the OCS showing the submitted observation requests. The OCS dynamically schedules requests into a queue that can be rearranged or appended as new requests are submitted. A continuous-running in-house developed "poller" on the observation control PC retrieves the latest version of the queue every minute, executing the top request by translating observation details into commands for our developed back-end software for Mookodi and the Lesedi telescope.

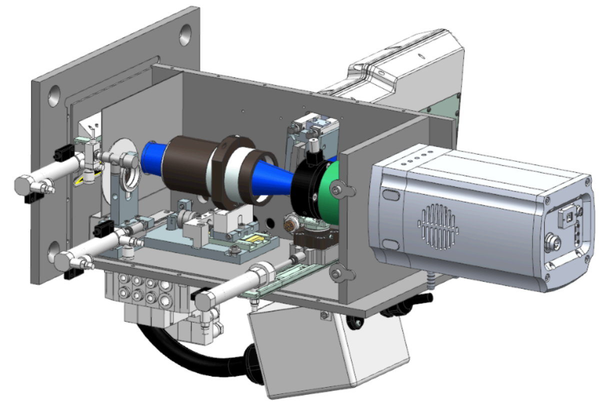

Fig. 2. CAD render of the Mookodi instrument (Erasmus et al. 2024), a low-resolution spectrograph. The incorporation of a grism enables a linear optical design, facilitating the movement of specific optical components (such as the slit and grism) out of the beam without beam deflection, transforming the instrument into an imager. The inclusion of photometric filters (cover of filter slides visible protruding into the page at the back) allows for multi-filter imaging. This dual functionality makes the instrument versatile, serving as both a low-resolution spectrograph and a multi-filter imager.

4.4. *Monitoring of hardware, software services and observations*

In addition to the control software for the telescopes and instruments we have developed, we have

[6]Two options are available for automated target acquisition: 1) acquisition based on the astrometric solution of the acquisition frame and the provided RA and Dec, and 2) the same as option 1 with an additional search for any nearby detected source. The second option is recommended when the exact coordinates are uncertain.

[7]`https://observatorycontrolsystem.github.io/`

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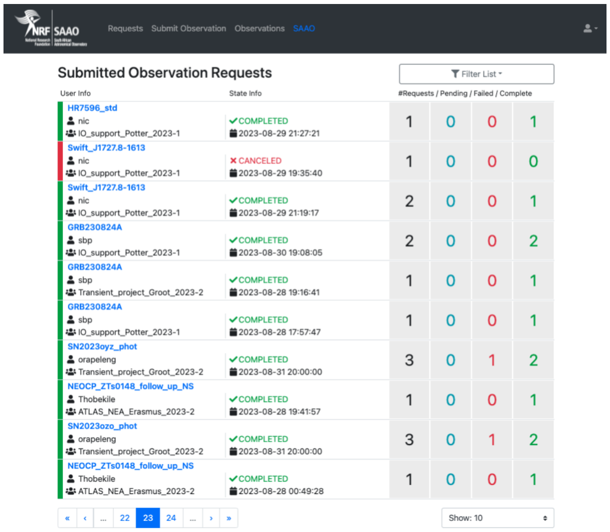

Fig. 3. Displayed is the web-based user interface of the Observatory Control Software (refer to Section 4.3 for implementation details), enabling registered users with approved proposals to submit observing requests through a web-form. Additionally, this platform allows users to monitor the status of submitted requests.

also created user-friendly overview platforms to monitor the state of hardware and services crucial for successful autonomous observing. Our team has access to an "overview dashboard" (refer to Figure 4), which serves as a centralized tool for monitoring. This dashboard enables us to intervene promptly when a specific service is disrupted or hardware is in a faulty state, ensuring the smooth operation of the observing system.

Finally, we have also developed a "schedule viewer" that enables operators and astronomers to visualize the observing queue generated by the Observatory Control System (OCS), indicating the status of each observation as "COMPLETED", "PENDING", or "IN PROGRESS" (refer to Figure 5). Currently, this feature is available for Lesedi, but there are plans to implement separate viewers for each telescope in the near future.

5. SOME EXAMPLE USE CASES

While the telescopes incorporated into the IO project will remain available (with sufficient motivation) for manual observing by astronomers in the more traditional week-long blocks, particularly for science cases better suited to such an approach, the showcased use cases here emphasize the system's true power and efficiency in fully automated robotic operations.

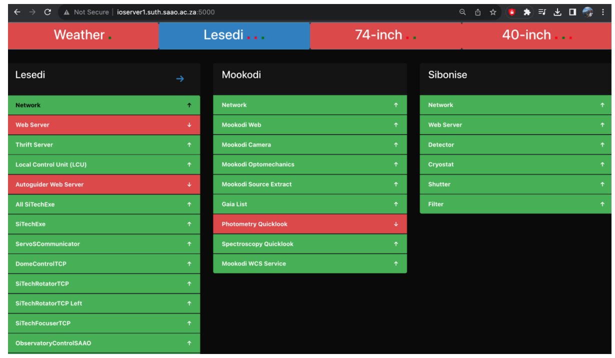

Fig. 4. The "overview dashboard" designed for monitoring the status of all hardware and software services. A color-coded system is employed, where green signifies normal operation, while red indicates a potential fault. Each telescope is organized into distinct tabs, offering dedicated sections for different instruments and relevant components related to that telescope. In this example, the Lesedi telescope's tab is selected (indicated with a blue color).

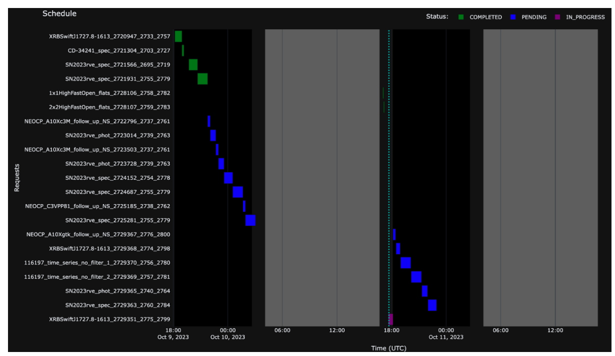

Fig. 5. An overview of the observing queue for the Lesedi telescope, depicting the past and upcoming 24 hours. Daytime is represented by light gray areas, twilight in dark gray, and black areas indicate available observing hours. The vertical cyan dotted line denotes the present time. Hovering over each block, which represents a scheduled observing request, provides additional details such as exposure times, the number of exposures, and selected filters. Completed, pending, and ongoing observations are denoted by green, blue, and purple blocks, respectively.

5.1. *near-Earth asteroid follow-up*

One of the best use cases that demonstrates the full capability of the systems developed by the IO is the swift follow-up of newly discovered near-Earth asteroids (NEAs). In this program, a "watchdog service" continually queries the publicly available Near-Earth Object Confirmation page[8] (NEOCP)

[8] `https://www.minorplanetcenter.net/iau/NEO/toconfirm_tabular.html`

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of the Minor Planet Centre (MPC), which consolidates discoveries from various asteroid surveys and serendipitous discoveries by others. These automated queries don't query the MPC directly but rather utilize NASA's JPL Centre for Near-Earth Studies (CNEOS) Scout service[9], offering real-time NEOCP updates but with more easily accessible additional information, such as on-sky uncertainties, through a well-documented API. When a new discovery appears on CNEOS Scout that is observable from Sutherland using Mookodi (filtered based on magnitude and on-sky position uncertainty limits), the service promptly sends an observing request to the IO's Observatory Control System (OCS) also via a well documented API provided by developers at LCO. Since the OCS is able to receive observing requests for non-sidereal objects as well, the autonomous "watchdog service" only needs to provide the orbital parameters, and the OCS dynamically calculates RA and DEC on-the-fly to accommodate non-sidereal objects in a dynamic observing queue. Figure 5 illustrates some of these "NEOCP observing requests" in a queue.

Operating since early 2023, this program has successfully executed follow-up observations for nearly 300 near-Earth Asteroids (NEAs) in its inaugural year, all without human intervention, including the submission of observing requests to the OCS. Approximately 63% of these completed observations were deemed successful, meaning the asteroid was captured in the frame and sufficiently bright for detection in the reduction pipeline. Of these successful observations, the astrometry of 75% was submitted to the Minor Planet Center (MPC) in time to contribute to the Minor Planet Electronic Circular (MPEC) demonstrating the program's rapid end-to-end success from triggering on a discovery to submitting measurements to the MPC. Many of these follow-ups and subsequent submission occurred within the same night as the discovery.

The remaining 37% of unsuccessful observations were attributed to various factors: 1) faint objects not detectable in the frame despite correct exposure (14%), 2) incorrect telescope pointing leading to the asteroid being out of frame, mostly due to growing on-sky uncertainty and a large delay in the observations since the observing request was sent (13%), 3) lack of visible stars in frames due to weather or technical issues, such as unexpected dome closure or clouds appearing without timely automated shutdown (7%), and 4) cases where the discovery was suspected to be artificial (e.g a satellite) or not real, subsequently removed from the NEOCP but unfortunately only after our observation request trigger (2%).

Impressively, these 300 completed observations only consumed approximately 75 hours of telescope time (15 minutes per observation), equivalent to about one traditional one-week block. Achieving this volume of observations in a traditional one-week block would have been totally unfeasible.

5.2. *Transient Name Server follow-up*

Another use case aligned precisely with the IO's vision of rapid follow-up characterizations involves triggering spectroscopic observations of transients reported to the Transient Name Server (TNS). To provide an additional service to the SAAO transient astronomer community, we developed an additional "TNS watchdog" that continuously queries the TNS for any transients discovered in the past 24 hours within the limiting magnitude of a 600-second exposure of the Mookodi instrument in spectroscopy mode. The concept is that these quick-look, low-resolution spectra from Mookodi can better inform the community about the likely type of transient and whether further follow-up, such as with the high-resolution spectrograph (HRS) on the 10-m SALT, is warranted. Although this specific case wasn't triggered by our autonomous "TNS watchdog", the workflow and methodology described in the Astronomer's Telegram #16369 (Buckley et al. 2023), involving quick-look follow-up spectra of the LMC transient ASASSN-23ii (AT 2023ygp) with Mookodi superseded by more detailed follow-up spectroscopy using SALT's HRS, perfectly exemplified the type of use case envisioned by this program.

Figure 6 depicts the acquisition image illustrating an instance of fully automated spectroscopic follow-up for SN 2023yoo conducted by our "TNS watchdog." This supernova was discovered by ATLAS on 2023-11-28 at 00:50:48 UT, with a magnitude of 17.3. Our systems promptly triggered a spectroscopic observing request at 2023-11-28 11:00 UT[10] following the ATLAS team's report of the discovery to the TNS at 2023-11-28 10:36:43 UT[11]. The observation was submitted as a "rapid-response" request, prioritized at the forefront of the queue and

[9] `https://cneos.jpl.nasa.gov/scout/#/`

[10] at the time of this trigger the TNS was being queried every 30 min but this interval can be reduced for more rapid response in future

[11] we rely on TNS alerts for triggering so our response time is constrained by the reporting timeline of the relevant discovery team. In this instance, the ATLAS team reported the discovery to the TNS several hours after the discovery exposure.

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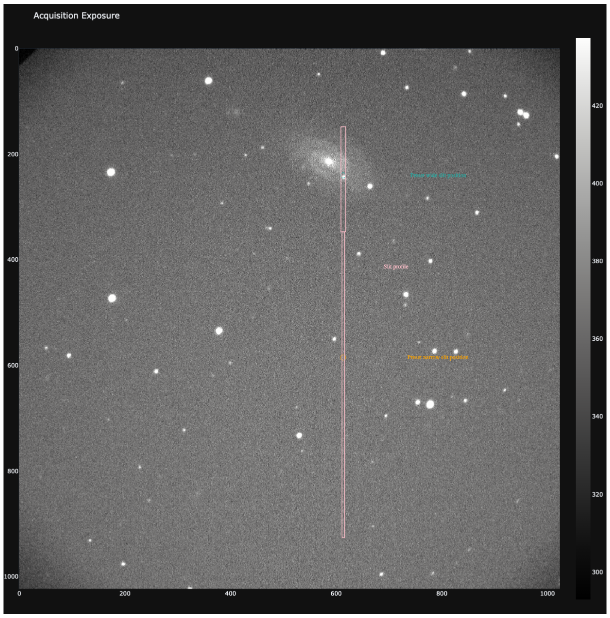

Fig. 6. Presented is the acquisition image from the rapid spectroscopic follow-up of SN 2023yoo using Mookodi. The robotic system utilizes Mookodi in imaging mode, coupled with astrometric calibration to precisely and automated position the requested RA and DEC within the appropriate section of the spectrograph's slit. In this instance, RA=22:01:03.150 and DEC=-13:16:28.99, and the request specified the use of the "wide slit" (depicted by the pink outline, illustrating the location of Mookodi's stepped-slit, with a ∼6-arcmin-long "narrow slit" of 2 arcseconds and ∼2-arcmin-long "wide slit" of 4 arcseconds). The resulting spectrum can be viewed on the Transient Name Server (TNS) at: `https://www.wis-tns.org/object/2023yoo`.

executed immediately after twilight on 2023-11-28 at 18:57:23.939 UT. Subsequently, the spectra were processed, and a classification report[12] was submitted to the TNS (Mogawana et al. 2023). We aim to streamline and automate certain aspects of the reduction and TNS reporting processes in the future.

5.3. *General Coordinates Network follow-up*

Similar to the the "TNS watchdog" discussed in section 5.2, we have established a service that monitors notifications from the General Coordinates Network (GCN) operated by NASA. To achieve this, we utilized and expanded the provided example Kafka Client Python code with the instructions outlined by GCN[13]. While the GCN offers real-time notices for various instruments our current focus, for testing purposes, is on alerts generated by the instruments of the *Neil Gehrels Swift Observatory*: the Burst Alert Telescope (BAT) with multi-filter photometry follow-up, the X-Ray Telescope (XRT), and the Ultraviolet/Optical Telescope (UVOT) with spectroscopy follow-up. The decision between whether to purse photometry or spectroscopy follow-up is determined by the source position accuracy provided by each instrument. Only XRT and UVOT offer source location accuracies sufficient for positioning the source within our widest selectable 4-arcsec slit of Mookodi when in spectroscopy mode. In the future, we aspire to broaden our scope by responding to additional alerts provided by the GCN (e.g., from instruments on the Fermi Gamma-ray Space Telescope). The future strategy would also involve submitting requests to instruments/telescopes integrated into the IO project best suited to meet the specific alert constraints (e.g., factors like magnitude and position uncertainty).

6. WORK IN PROGRESS, FUTURE PLANS AND CONCLUSION

Our future focus is on seamlessly integrating more SAAO-operated telescopes into our IO system, likely starting with the larger 74-inch telescope. This telescope will soon feature a remotely operated "instrument selector", allowing the permanent pairing of the SHOC (imager) instrument with either SpUpNIC (spectrograph) or HiPPo (photo-polarimeter). Our initial objective is to establish the 74-inch telescope, along with SHOC, as a fully robotic-enabled system, enhancing our automated photometric follow-up capabilities for fainter objects. Simultaneously, we aim to optimize rapid-response observations for Supernovae and Gamma-Ray Bursts, collaborating with experts within the SAAO. Looking ahead, we plan to diversify our observational portfolio with time-critical but not necessarily rapid-response projects that could benefit from robotic automation, such as occultations of Solar System objects and exoplanet transits.

Currently, we support several data pipelines for our various instruments, enabling users to manually extract calibrated spectra and photometry from images. In the future, we aim to automate some of these processes to provide users with publish-ready data products. For example, we plan to implement real-time astrometric and photometric calibration for each frame as it is created, thereby generating corresponding catalog files containing calibrated photometric data for all detected sources. We are actively exploring several approaches to achieve this.

[12] `https://www.wis-tns.org/object/2023yoo/classification-cert`

[13] `https://gcn.nasa.gov/docs/client`

In conclusion, we have successfully demonstrated an end-to-end telescope and instrument system that aligns with the SAAO's "Intelligent Observatory" vision of fully automated, rapid-response of transient objects. This achievement paves the way for future integration of additional telescopes into the IO framework, further advancing astronomical research at the SAAO.

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