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Exploring Capabilities: Characterising Solar System Objects with SAAO Telescopes

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Abstract. This paper presents an overview of follow-up observations of small bodies in the Solar System conducted at the South African Astronomical Observatory's (SAAO) observing site near the town of Sutherland, Northern Cape, South Africa. It highlights the instruments and capabilities of SAAO telescopes and describes a new initiative: the SAAO's Intelligent Observatory (IO) program, which enables fully automated follow-up observations through a robotic, queue-scheduled mode on select telescopes, ensuring rapid and efficient response. The paper also discusses future plans, including potential follow-up activities with the Southern African Large Telescope (SALT) and the increased utilization of currently under exploited on-site facilities.

Keywords. near-Earth asteroids, main-belt asteroids, follow-up observations, photometric characterisation

1. Introduction

With its headquarters in Cape Town, the South African Astronomical Observatory (SAAO) serves as the national center for optical and infrared astronomy in South Africa. The telescopes managed by the SAAO are located at its observing site in the southern tip of the Northern Cape province, about 350 km northeast of Cape Town, which also hosts numerous telescopes from various international partners. The SAAO-owned professional facilities alone offer significant diversity, featuring a broad range of instruments and aperture sizes ranging from the 1-metre Lesedi telescope to the 10-metre South African Large Telescope (SALT). This diversity encompasses a broad spectrum of capabilities, including optical imaging, optical and near-infrared spectroscopy, polarimetry, spectro-polarimetry, and high-speed photometry (refer to Fig. 1).

When including the capabilities of the various hosted facilities, the scientific endeavors at the observatory cover a wide range of research areas within the galactic and extra galactic science fields such as transient science, near-Earth asteroid surveys, microlensing detection, exoplanet discovery, and solar monitoring, to name just a few. The diversity and unique strengths of each telescope position the observatory as a potential highly effective "follow-up machine," (Erasmus et al. 2024a) especially if autonomous robotic observing becomes standard across more facilities, supported by more integrated and coordinated observing strategies.

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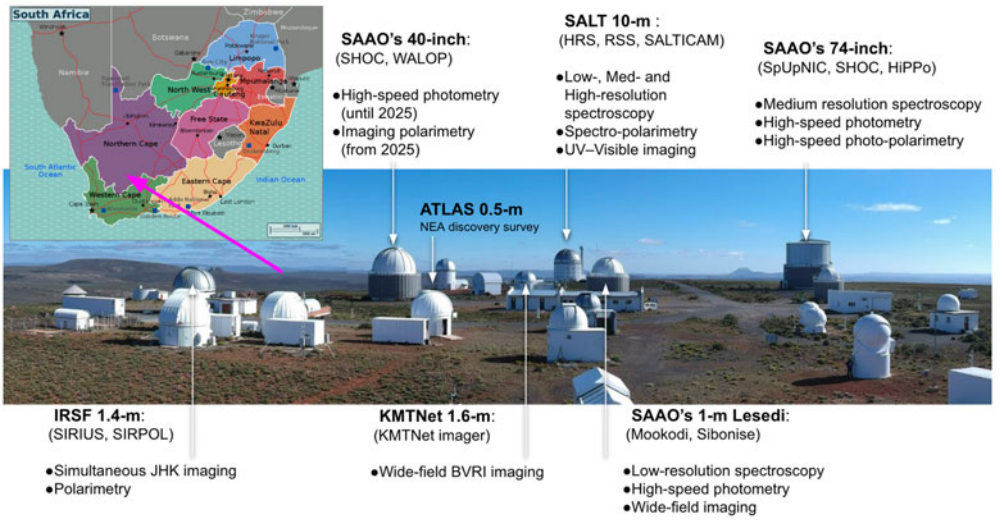


Figure 1. Panoramic view of the South African Astronomical Observatory's site in Sutherland, Northern Cape, showcasing the 40-inch, Lesedi, and 74-inch telescopes under the ownership and operation of the SAAO. Additionally, the Southern African Large Telescope (SALT) and InfraRed Survey Facility (IRSF) 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.

In the sections that follow, the telescopes and instruments located at the SAAO site that have specifically been used for observations of small bodies in the Solar System, along with some of the notable scientific achievements in this field over the past few years are highlighted.

2. Telescopes and Instruments

The SAAO-owned 74-inch (f/18) and 40-inch (f/16) telescopes are commonly referred to as the "1.9-metre" and "1.0-metre" telescopes, and they can be equipped with various instrument options. The 74-inch telescope currently hosts three instruments: a high-speed imager, a medium-resolution spectrograph, or a high-speed photo-polarimeter. With the new "instrument selector" in place, the high-speed imager is always available and co-mounted with either the spectrograph or polarimeter, depending on which is mounted at the time. As of this writing, the 40-inch telescope is equipped only with a high-speed imager identical to the one on the 74-inch. An imaging optical polarimeter is planned for permanent installation on the 40-inch starting in early 2025. Neither the spectrograph nor the polarimeter have been extensively used for small-body science, making the Sutherland High-speed Optical Camera (SHOC, Coppejans et al. 2013) on the 74-inch and 40-inch telescopes the primary instrument currently employed in this field. When mounted on the either 74- or 40-inch telescope, SHOC currently offers users a field of view of just under 3×3 arcmin^2 ($\sim$0.18 arcsec/px)† with the possibility of GPS-triggered high-precision time stamped frames. Frame rates of several frames per second, with almost negligible dead time due to the frame-transfer technology of the Andor iXon 888 employed in the instrument, can be achieved, making SHOC ideally suited for obtaining high-cadence light curves to resolve rapid phenomena (e.g., fast asteroid rotation periods) or brief events (e.g., stellar occultations of TNOs). The SHOC systems

† The mounting configuration on the 74-inch includes a focal reducer.

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are also equipped with two filter wheels populated with a full set of Sloan and Bessel filters, respectively. The filter wheels use robust "Geneva mechanisms", making them suitable for continuous high-cadence filter cycling for long periods (e.g., hours), which is ideal for cases where multi-filter light curves with interspersed filters are required (e.g., for multi-filter light curves of objects with ever-changing brightness, such as rotating asteroids).

The SAAO's Lesedi telescope (Worters et al. 2016) is a 1-metre f/8 alt-azimuth Ritchey-Chrétien telescope equipped with two Nasmyth ports that can accommodate two instruments: Mookodi (Erasmus et al. 2024b), a visible-wavelength low-resolution spectrograph with multi-filter imaging capabilities, and Sibonise (Worters et al. 2016), a wide-field imager. The science beam can be directed to the desired port by rotating a motorised tertiary mirror. Both the telescope and the Mookodi instrument, which can switch between spectroscopy (400–800 nm, R≈350) and imaging mode (10×10 arcmin^2, full Sloan filter set) at the click of a button, are available in fully robotic mode, making them ideal for rapid automated responses (e.g., same-night follow-up of newly discovered near-Earth asteroids). As of this writing, the Sibonise wide-field imager ($\sim40\times40$ arcmin^2) is still under commissioning and has not yet been used extensively for science. However, its wider field of view (compared to Mookodi's) will be useful for follow-up observations of newly discovered NEAs whose orbits are not refined enough for accurate ephemerides.

In addition to the SAAO-owned telescopes, several hosted facilities are accessible to the South African astronomical community and have been utilized for small-body science. The South African node of the Korea Microlensing Telescope Network (KMTNet, Kim et al. 2016) and the InfraRed Survey Facility (IRSF, Glass and Nagata 2000) have also contributed to this field. The 1.6-metre KMTNet telescope, with its 2×2 deg^2 field of view (mosaicked with four 9k×9k e2v CCDs at 0.40 arcsec per pixel, employing Johnson-Cousins filters), is best suited for observing large areas of the sky, which is useful for capturing multiple objects simultaneously (e.g., mini-surveys) or capturing asteroids with large position uncertainties (e.g., newly discovered NEAs). The IRSF 1.4-m telescope is unique among facilities on site in that it can observe in the JHK near-infrared (NIR) bands ($\sim7\times7$ arcmin^2) with its Simultaneous-color InfraRed Imager for Unbiased Survey (SIRIUS) camera (Nakajima et al. 2002), and it can do so simultaneously, making it highly efficient for multi-filter light curve observations.

The SAAO also hosts the third unit (of four) of the Asteroid Terrestrial-impact Last Alert System (ATLAS) network† (Tonry et al. 2018), which specializes in discovering Potentially Hazardous Asteroids (PHAs). The co-location of ATLAS with the robotic Lesedi telescope makes this pairing a good fit for same-night rapid follow-up of new small-body discoveries, where immediate observation is critical (e.g., follow-up characterization of newly discovered near-Earth asteroids).

Finally, the SAAO has recently initiated their "Intelligent Observatory" (IO) program‡ (Potter 2021; Potter et al. 2024; Erasmus et al. 2024). This initiative aims to upgrade the hardware and control software of all SAAO telescopes to enable autonomous operations, thereby enhancing the efficiency of follow-up observations for transient alerts (e.g., near-Earth asteroid discoveries). The program focuses on increased integration, robotic capabilities, and automated external observation requests, with the ultimate goal of becoming part of a globally coordinated network. Lesedi with the Mookodi instrument is already incorporated into the IO's software ecosystem.

† https://www.fallingstar.com/
‡ https://io.saao.ac.za/

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3. Science Highlights of Solar System Objects

Occultations by outer Solar System Objects: The SHOC cameras were primarily designed for short-duration occultation events and have been extensively used for this purpose. One of the exciting areas to which this instrument has contributed is the study of size, shapes, and discovery/characterization of ring systems around outer Solar System objects. For example, that of the centaur (10199) Chariklo (Bérard et al. 2017; Leiva et al. 2017), the New Horizons spacecraft's extended mission target (486958) Arrokoth (Young et al. 2018) and the centaur Chiron (Braga-Ribas et al. 2023; Sickafoose et al. 2023b). Multiple observations of occultations by Pluto have also been conducted to study its evolving atmosphere (Sickafoose et al. 2023a). A recent MSc thesis also utilized SHOC data to report on numerous stellar occultations by outer Solar System bodies (Genade 2018).

Characterisation of main-belt Asteroids: Using KMTNet data originally intended for a near-Earth asteroid study, multi-band photometry of nearly a thousand main-belt asteroids (MBAs) that were serendipitously observed in the same fields could be "mined" due to the wide field of view of KMTNet's camera (Erasmus et al. 2018). This dataset was subsequently supplemented with additional targeted observations of MBA fields using KMTNet for a study on taxonomic diversity of asteroid families (Erasmus et al. 2019).

Follow-up observations of near-Earth Asteroids: In recent years, telescopes at the South African Astronomical Observatory (SAAO), including both SAAO-owned and hosted facilities, have actively participated in several observational campaigns organized by the International Asteroid Warning Network (IAWN)†. These campaigns serve as simulated exercises aimed at enhancing global coordination and preparedness for potential near-Earth Asteroid (NEA) impact threats. During the "2012 TC4" campaign (Reddy et al. 2019), both KMTNet and IRSF contributed multi-band photometry, which helped in determining the asteroid's rotation period and taxonomic classification through photometric color analysis. In the subsequent campaign targeting the well-known NEA, Apophis (Reddy et al. 2022) the three telescopes: Lesedi, the SAAO's 40-inch and KMTNet; again provided multi-band photometric data. For the most recent "2023 DZ2" campaign (Reddy et al. 2024), Lesedi, equipped with its new Mookodi instrument, delivered $g'r'i'$ photometry, aiding in the characterization of this asteroid.

The population of small NEAs (<300 meters in diameter), and specifically their taxonomic distribution, has been extensively studied through a study using KMTNet (Erasmus et al. 2017) and two MSc theses utilizing multi-filter photometry from the Lesedi and 40-inch telescopes (Janse van Rensburg 2021; Ngwane 2024). The latter thesis also made significant contributions to the confirmation of discoveries by performing same-night rapid follow-up astrometric observations of newly discovered NEAs, particularly those detected by the ATLAS-STH survey, located at the SAAO site.

Finally, several telescopes at the SAAO were crucial contributors to the ground-based observing support of the Double Asteroid Redirection Test (DART) mission. The Las Cumbres Observatory, which include three 1-metre telescopes at the SAAO site was instrumental in measuring the pre- and post-impact orbital periods (Thomas et al. 2023). ATLAS-STH and the Lesedi telescope, successfully observed and monitored the resultant plume ejected from the asteroid shortly after the DART spacecraft's impact on the asteroid Dimorphos (see Fig. 2 and Fitzsimmons et al. 2024).

4. Conclusion and Outlook

We have provided an overview of the telescopes and instruments at the South African Astronomical Observatory (SAAO) that have been used for follow-up observations of

† https://iawn.net/index.shtml

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Figure 2. Shown is a stacked r'-filter exposure (30 × 1-second exposures) of the fast time-series photometric data collected by SAAO's 1-m Lesedi telescope during the Double Asteroid Redirection Test (DART) spacecraft's impact with the asteroid Dimorphos. The resulting plume from the impact is clearly visible and the time-series data successfully recorded the temporal evolution of this plume.

small bodies in the Solar System in recent history. We also highlighted a few key science results in this field.

Looking forward, while SALT has been used for some small body science (e.g. Earth mini-moons, Kwiatkowski et al. 2009), asteroid spectroscopy (Oszkiewicz et al. 2014), and NEA observations (Kwiatkowski et al. 2010; Trilling and Sickafoose 2015), it should become a more utilised small-body follow-up facility in the era of LSST, where more numerous fainter discoveries will require follow-up observations with larger aperture telescopes like SALT. Additionally, the SAAO is now home to the new 1.8-m PRime-focus Infrared Microlensing Experiment (PRIME) telescope†. With its wide-field camera ($\sim$1.3×1.3 deg^2, Durbak et al. 2024), PRIME could play a key role in near-infrared follow-up of small bodies. Lastly, already existing and well-established instruments such as the high-speed photo-polarimeter on the 74-inch telescope hold valuable potential for further characterization of small bodies using underutilized polarimetric methods available at the SAAO.

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† http://www-ir.ess.sci.osaka-u.ac.jp/prime/about/telescope.html

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