SALT Mini-Tracker Feasibility Study Report

Submitted by

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with

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1 Introduction

At the Southern African Large Telescope (SALT) Board meeting on 16 November 2019 in Pune, India, and at the request of the Board, a proposal was presented to perform a study to determine the feasibility of designing and building a device called a "mini-tracker" (MT) for the telescope. By taking advantage of SALT's large uncorrected field of view, the mini-tracker would enable the telescope to acquire and independently observe more than one astronomical object at a time, including objects widely separated from the SALT target under observation. The scientific motivation for the project is to address the problem of transient follow-up of large astronomical surveys both in operation now and approaching first light in the next few years.

The device would be replicable, so that upon the successful demonstration of a prototype MT, more could be built and deployed on the telescope with minimal additional engineering design cost. The project is thus often referred to as "the mini-trackers".

2 Executive Summary

A feasibility study was performed over the period 1 January 2020 to 31 May 2020, and a summary presentation of the study results was delivered to the SALT Board on 28 May 2020. The study was comprised mainly of mechanical and optical design efforts. The mechanical design phase focused on developing 1) a practical means of attaching the MT to the existing tracker, and 2) a deployment mechanism to position a mini-spherical aberration corrector (MSAC) within the primary mirror field of view. From the MSAC, auxiliary optics route starlight to a low-resolution spectrograph mounted on the tracker carriage. The optical design phase focused on developing a variety of MSAC designs of different apertures. A very preliminary strawman budget and schedule were produced. A science case for the MTs was also developed.

At this early stage of "pre-concept" design, it appears that mechanical solutions exist for the mini-trackers, and optical solutions for the MSAC are within reach. The project appears to be sufficiently feasible to pursue through the concept design phase. More work also needs to be done to ensure that the science goals envisioned for the project match the better understood capabilities of the MTs.

Given the unusual nature of this project, including the fact that it is a retrofit to the existing tracker adding significant mass and moment arms to the payload, there is general agreement that funding, designing, building, and testing a prototype device is the most reasonable course of action at this point.

Finally, owing to the onset of the global coronavirus pandemic during this period, several areas of the study could not be completed as planned. Among these areas were the post-MSAC optical systems including the focal expander and wavefront sensor, characterization of the required software effort, and additional work with the Technical Operations team in Sutherland to develop installation, operations, and maintenance scenarios. Additionally, many potential vendors were partially or completely shut down in April and May (and some still are). Most of our team was confined with stay-at-home orders from late March, so planned travel to HET and other vendor sites was prohibited. As a result, the budget and to some extent the schedule lack the fidelity we had hoped for.

In spite of these challenges, the study was completed to the extent possible, and we have indicated throughout the report where additional work is needed to round out the effort and proceed to a complete concept design level and beyond. We sincerely hope that the Board finds the study helpful in deciding on a path forward for this exciting new capability for SALT.

3 Purpose of the Feasibility Study

The purpose of the feasibility study was twofold. The first being to explore the MT design space by creating conceptual designs for the most important elements of the device, and thereby gain a better understanding of the true scope, risk areas, and cost of the project.

The second purpose of the study was to be in a position to recommend a path forward for the project, based on what was learned in the process. We have a much better understanding now of what is possible and what will be required to bring the mini-tracker concept to a working reality.

The structure of this report thus contains descriptions of the work performed and results obtained, followed by "next steps" in the context of each report section. General recommendations are made near the end of the report. The report summarizes the design work performed over the period of 1 January to 31 May 2020.

4 Study Activities

In the sections below, we summarize the activities undertaken and results achieved during the study. These include the development of the science case for the mini-tracker concept, the mechanical design work to explore different mounting and deployment concepts for the mini-trackers, the optical design and analysis work performed to create several spherical aberration corrector (SAC) configurations of different entrance apertures, a rough order of magnitude (ROM) cost estimate, and a notional schedule.

4.1 The Team

Following a positive response by the SALT Board to the mini-tracker proposal presented at the November 2019 Board meeting, the first order of business was to identify team members with the requisite technical skills to perform the feasibility study. These skills included optical design and analysis (ideally with a good knowledge of aberration theory), and mechanical design using 3-D modeling techniques (with knowledge of and experience with the SALT tracker design being a big plus). Our initial plan was to include additional talent, including mechatronics and software design assistance, but that did not pan out as hoped.

Our team is featured in the below image from the Board presentation in May 2020:

Retha Pretorius was the Principal Investigator for the study. John Booth was the project manager. Melanie Saayman was the optical engineer who created the various mini-SAC designs and together with John worked with optical vendors to cost the designs. Wouter Lochner was the mechanical designer, creating the models of the mechanical devices and assemblies found in this report. Lisa Crause worked as our general project scientist and advisor, contributing much local knowledge about SALT, and about the resources available from SAAO and SALT. Freya Bovim worked with Retha to begin analyzing tracker data, and to create an "illumination calculator" for the telescope and the MTs. Francois Strümpfer volunteered to join our team because of his keen interest in SALT and in astronomy in general. Francois is an optical scientist and SALT veteran now working for Spaceteq, and was a key member of the team that fixed the SALT image quality problem a decade ago. His invaluable contribution to the current effort is greatly appreciated.

4.2 The Global Pandemic

As noted in the Executive Summary, midway through the study period, the global pandemic began to limit our ability to work together as effectively as we had earlier in the year, as well as hampering/delaying communication and interaction with potential vendors who had reduced operations or shut down over this period.

As a result, we were unable to complete some of the work we had planned over the course of the study. We have therefore provided more detailed descriptions of the completed work, and more detailed "next steps" (and more of them) in this report than we had originally anticipated, in an attempt to capture more of the information developed, and in order to proceed as efficiently as possible to the next project phase whenever work can resume, with Board approval.

Some of the "next steps" would have been within the original pre-pandemic scope of this study, but many others, while beyond the scope of the study, became obvious paths to follow as the study progressed – as ones that should be included in the concept design and preliminary design phases of the project.

5 The Science Case

The science case for the MTs was developed by Retha over the course of this study, and is included in Appendix A. It is summarized in the paragraph below.

The constraints that limit the science that can be done with MTs are the patrol field that each MT can access (about 100 deg^2) and the flux limit (probably a bit deeper than 21^{st} magnitude, for low-resolution spectroscopy). MTs are therefore suitable for any science program that requires spectra of large numbers of bright objects, but at sky densities of a few per 100 deg^2. Identification spectroscopy of optical transients is an obvious example. LSST will discover a few transients brighter than 21^{st} magnitude per 100 deg^2 per night. This means MTs can produce an unbiased sample of transients with ID spectra. Sources that are identified as individually interesting from the MT data can then be put in the main SALT queue, for additional time-constrained monitoring of their evolution.

The "few transients per 100 deg^2" result is far fewer than we had understood to be the case when the 2018 SPIE paper (included in Appendix B) was written. Thus an extension of the effort to better quantify the number density of interesting targets available to the MT's "grasp" (patrol area size and mini-corrector aperture) will be a logical next step for the project.

6 The Basic Mini-Tracker Concept and Operation

A review of the basic mini-tracker concept may be useful here before addressing the detailed elements of the mechanical and optical sections of the study.

6.1 Mechanical Concept

The basic concept of the MT is to mount a mechanical device to the main SALT tracker that can support and position a small SAC anywhere within a defined MT "patrol area". The patrol area is a subset of the SALT primary mirror 35 degree diameter uncorrected field of view. In order to track an astronomical object, the tracker must drive the entire payload precisely along the focal sphere. Anything attached to the payload, in this case the MT, will be automatically driven along the focal sphere as well, albeit at a different location in the field. Hence the main tracker does nearly all of the motion control work to keep the MT's optical corrector positioned and tracking on SALT's large focal sphere, simply by tracking the SALT target along the sphere as it currently does. The MT makes local guide corrections autonomously using a guide camera, wavefront sensor, and a small hexapod which supports the mini-SAC (MSAC).

For reference, the 35 degree diameter focal sphere is about 8 meters in diameter and lies halfway between the primary mirror and its center of curvature. An arcsecond on the sky here at uncorrected prime focus is about 63 microns. One degree is about 227 mm. One square meter is about 20 square degrees of sky.

6.2 MT Operation

Once a target for the main tracker has been selected, the MT software selects an available MT target from a list based on a number of criteria, including the target availability in the MT patrol area, target priority and magnitude, and guide star availability. As the main tracker moves to position to intercept its selected target, the MT simultaneously moves to a position within its patrol area by rotating the swing arm and positioning the translation stage (trolley) along the arm, and waits for the tracker to arrive at its target. Acquisition of each target is accomplished, and the MT begins an exposure for (typically) an identification spectrum of the selected MT object. Once a MT spectrum is obtained, if there is sufficient track time remaining, the MT may select, acquire, and observe another target. In full operation, all of these functions will be robotic, with little or no human intervention.

7 Deployment Mechanism Mechanical Design

The mechanical deployment of the MSAC was the least understood element of the MT concept at the beginning of this feasibility study. A total of five different deployment concepts were identified in the 2018 SPIE paper, and the most promising two of these were explored in more detail for the study using mechanical design modeling software.

In February 2020, John met with Wouter Lochner, our mechanical designer, and Francois Strümpfer at the telescope to begin work on the mechanism design. We worked closely with members of the Tech Ops staff as well (Eben Wiid and Jonathan Love) to evolve this design.

There are three major challenges with the deployment mechanism design. The first is finding a way to mount it to the tracker. The second is devising a means of supporting the corrector and accurately positioning it over a wide patrol area to acquire astronomical objects. The third challenge is to provide a means of fine guiding, maintaining optical alignment, and tracking the component of motion of objects not accomplished by the main tracker.

7.1 Mounting the MT to the Tracker

From the standpoint of minimum MT complexity, the "best" way is to mount the MT directly to the upper hexapod ring which carries the Non-Rotating Structure (NRS), the main SAC, and the various instruments, collectively known as the payload. By mounting the MT here, the main tracker accomplishes all the necessary motions to track an astronomical object across the focal sphere for the MT, except for de-rotation of the sky. Sky de-rotation is accomplished by very slow tracking movement of both the swing arm and the trolley during an observation. Mounting the MT to the hexapod ring turns out to be quite difficult in practice, and for a few days we abandoned this effort to look at a carriage-mounted option.

7.1.1 Hexapod Ring Mounted Concept

The carriage-mounted option turned out to present even more difficulties, and we returned to the hexapod ring mounting concept shown in Fig. 1. Eventually we were able to find a way to create a mounting base assembly that threads its way through the hexapod legs supporting the payload. The assembly is bolted to the upper steel hexapod ring at a total of eight locations, and is braced against a lower ring which is attached to the NRS. With widely separated upper and lower attachment points, this is meant to be a stiff, semi-permanent mounting base for the MT swing arms.

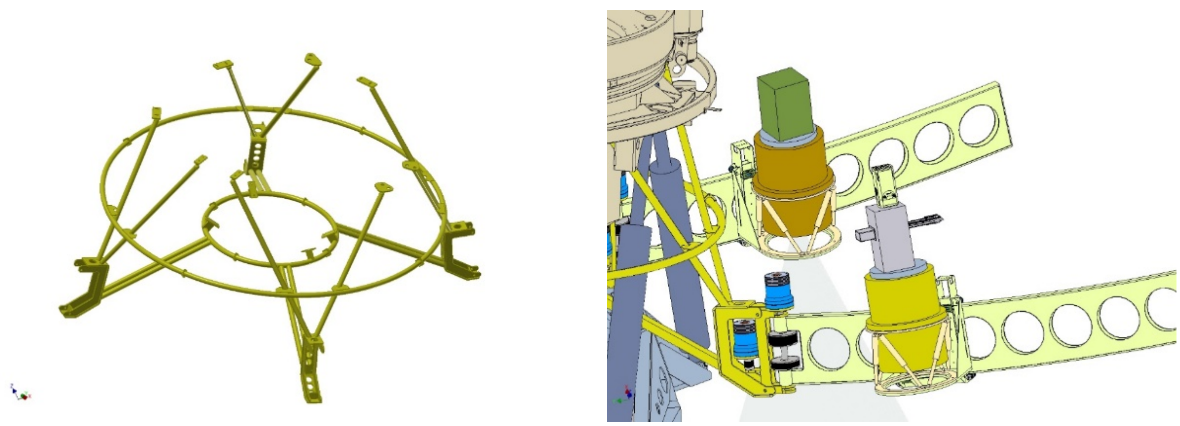


Fig. 1: The mounting base assembly.

7.1.2 Y-Carriage Mounted Alternative Mounting Concept

An alternative mounting position is on the tracker Y carriage (see Fig. 2), which we explored during the early part of the study, and which was discussed briefly at the Board presentation in May. The problem with this concept is that while the carriage provides a very rigid base, the MT is then responsible for following the focal sphere through a large "Z" (focus) change (about 0.3 m), as well as large tip/tilt angles (+/- 6 degrees). The mechanical solution to this problem became complicated and unwieldy, and was eventually abandoned in favor of the current simpler hexapod-mounted concept shown in Fig. 1.

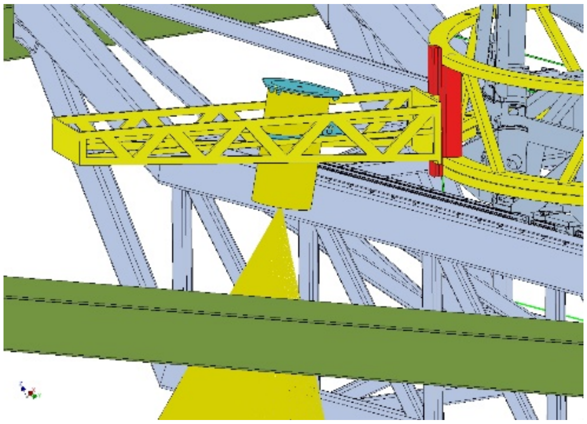


Fig. 2: The Y-carriage mounted concept.

7.2 The Positioning Device

7.2.1 Swing Arm Concept

We explored several different positioning device concepts, but in the end a swing arm pivoting about an axle on the mounting base, and using a small trolley that carries the MSAC and moves along the length of the arm, appeared to be the simplest idea (Fig. 3). This arrangement can sweep out a large area within the focal sphere, and hence produces a large MT patrol area. The size, shape, and orientation of these areas are shown in section 7.4 for four MTs. Cable and drum drives similar to the drive for the tracker rho stage are used to rotate the arm, and to drive the trolley linearly along the arm. A precision rotary encoder tracks the rotary position of the swing arm, and a linear encoder mounted along the swing arm tracks the position of the trolley.

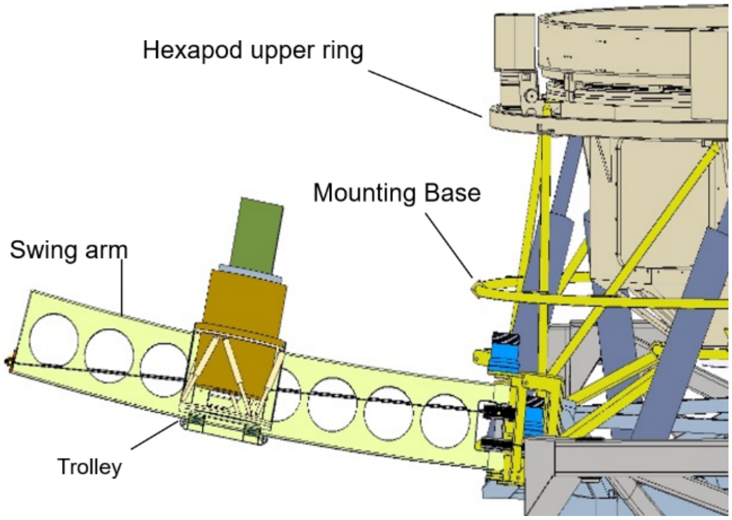


Fig. 3: The swing arm positioner (cable and drum drives in blue).

7.2.2 Alternative Swing Arm Concept

Inevitably called "the desk lamp concept", we briefly looked at an alternative swing arm concept that employs two four-bar linkages as shown in Fig. 4. There may be an arrangement of hinge points that allow for a single drive screw to position the MSAC along the sphere, but we were unable to explore this further within the limitations of the study. It is included here to potentially explore in future design work.

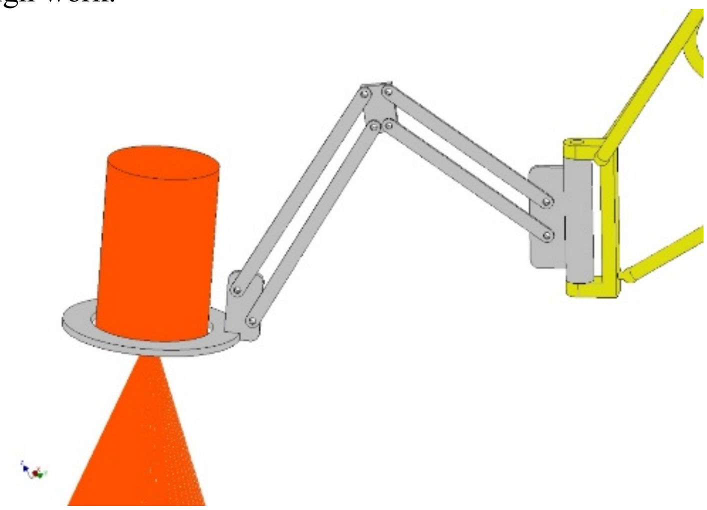


Fig. 4: The "Desk Lamp" concept.

7.3 Summary – Evolution of the Design

The left-hand panel in Fig. 5 is the simple diagram of the MT concept as it existed at the November 2019 SALT Board meeting, showing the basic elements of the device. On the right is a similar view of an MT (Fig. 3 repeated here for comparison), but showing some of the changes and improvements that were incorporated as a result of the design work performed for this study.

The pivot point has moved from the hexapod ring to the end of the lateral swing arm, and crucially, the axis of the pivot now tilts to pass through the primary mirror center of curvature. This keeps the corrector on the focal sphere regardless of swing arm position. While still attached to the upper hexapod ring, the lower part of the mounting base assembly is now braced against the Non-Rotating Structure (NRS). The swing arm profile is now much taller, for stiffness, and curved to match the focal sphere curvature, which allows the travel range of the small MSAC hexapod to be minimized.

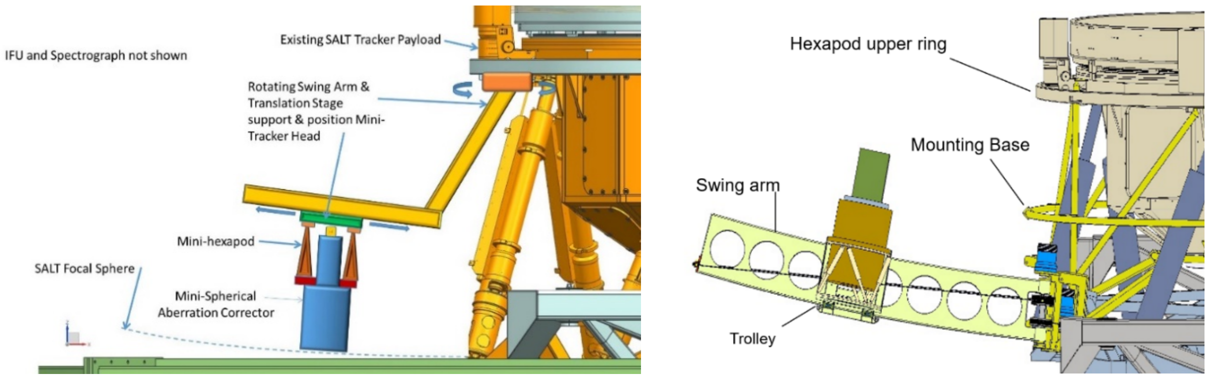


Fig. 5: The evolution of the design.

7.4 MT Patrol Area

The swing arm concept results in the "patrol areas" relative to the main tracker payload shown in Fig. 6. Each patrol area is approximately 100 deg^2 in size. Depending on the main tracker position, the position of each swing arm, and the final size of the corrector, the effective aperture of the MT can vary from approximately 3 m up to the full size of the MSAC over the course of an observation. Note that the "170 deg" and "177 deg" shown in the diagram refer to the angular range of the swing arm, not the patrol area.

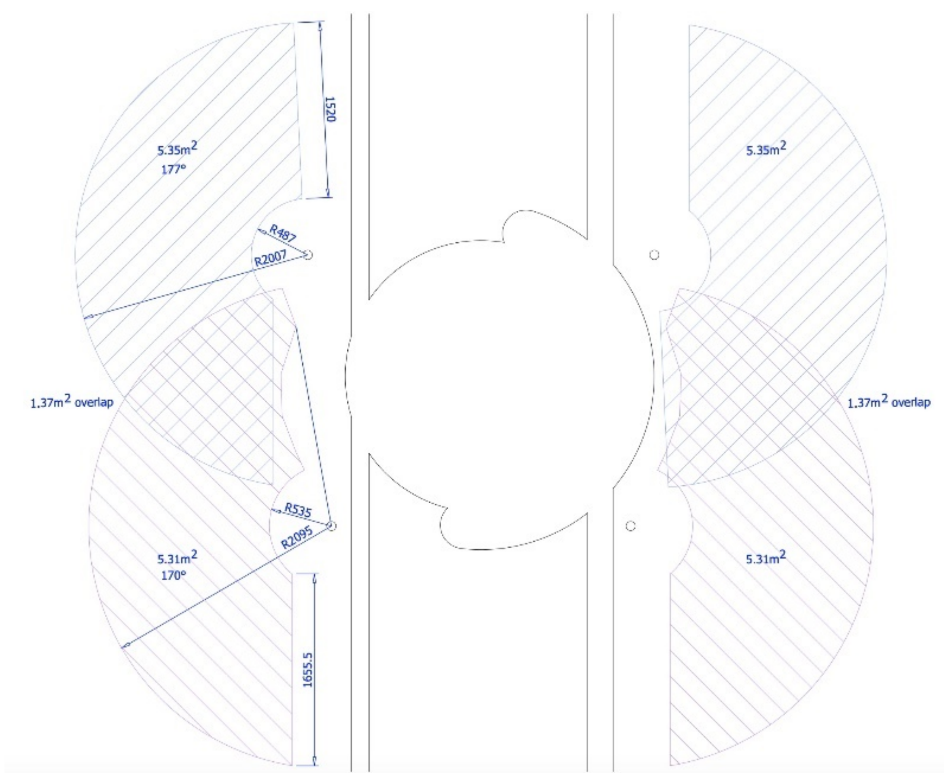


Fig. 6: Patrol areas on either side of the main tracker. Each area is about 100 deg^2 on sky.

7.5 Target Acquisition, Fine Guiding, and Tracking Sky Rotation

Once a target has been selected and the swing arm and trolley have been moved into position, the target must be acquired, tip/tilt and focus positions adjusted, guiding started, and the acquired, in-focus target observed. This is similar to the slewing, setting, and acquisition and guiding procedure for a conventional telescope. In the case of the MT, the swing arm and trolley will provide the "slewing" capability, and a hexapod carrying the MSAC, coupled with an acquisition/guide camera and wavefront (WF) sensor, will provide the positional sensing and fine motions needed to place the target image on an IFU or fiber and perform an observation.

With the current design configuration, it will also be necessary for the swing arm and trolley to be driven very slowly during an observation, in order to take out the global sky rotation across the telescope. (Thanks to Janus Brink for this insight.) In the extreme case, this motion could amount to as much as 0.4 m of travel for a one-hour exposure.

7.6 MT Mass, Moment, and Obscuration

With the current concept as described above, the mass of four MTs mounted on the telescope is estimated to be in the vicinity of 500 kg. Clearly the existing tracker assembly will need to be evaluated to see if any modifications need to be made to accommodate this additional mass.

In addition, as the MT range around their patrol areas in operations, this will presumably result in small deflections of the main tracker beam itself. These small deflections will translate into small optical misalignments (focus, tip/tilt) that must be guided out in the main tracker assembly. It should be possible to map out the bulk of these effects during testing and shakedown of the MTs, and "pre-mitigate" these misalignments in the tracker mount model. Residual misalignments can be corrected in real time using the MT wavefront sensors, and the main tracker autocollimator.

Obscuration of the main corrector beam due to the MTs is shown in Fig. 7. For the portion of an MT that extends beyond the 4.6 m diameter central obscuration of the main SAC, the obscuration is calculated to be 0.38 m^2. For reference, a single SALT mirror segment area is 0.866 m^2.

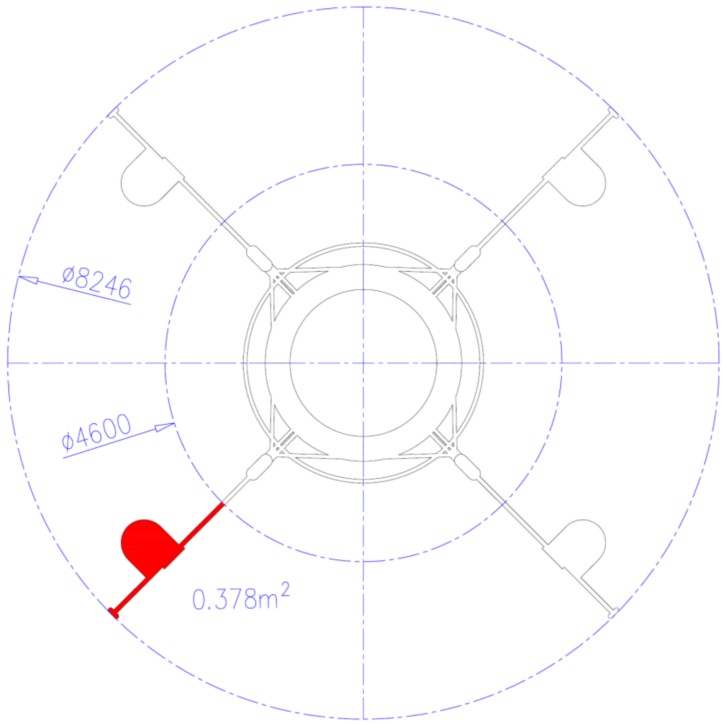


Fig. 7: MT obscuration beyond the main SAC central obscuration.

7.7 Assembly, Testing, Installation, and Telescope Integration

During the next design phases of the MTs, a robust process will need to be developed for the assembly, integration, and extensive testing of each MT on the ground, before installation and on-telescope integration and testing is considered. Whether the MTs are built in the SAAO Mechanical Workshop or by an outside contractor, there will need to be a phase of in-house testing during which the hardware and software are thoroughly vetted, and the device is tested for reliability, accuracy, and repeatability.

This shakedown and testing program will require a large mobile test stand that can support the mass and moment of a single MT, similar to the test stand/carts for the payload and the RSS. Fortunately, the SAAO Mechanical Workshop has a large coordinate measuring machine, which may be used to measure and test the various coarse and fine motions of an MT.

7.8 Next Steps

The mechanical design concept for the MTs that was developed in the course of this study solved the basic problem of mounting an MT to the main tracker hexapod, thus simplifying the motion requirements for the device. It employs a swing arm and trolley assembly to create a patrol area of about 100 deg^2, with minimal primary mirror obscuration.

However, there is much work to do to bring the design to a stage that it can be built and tested. For example, the design was not optimized or analyzed for structural stiffness. The cable drives are at this point notional, and stiffness of the pivot drive is another concern. Many other design areas will need attention in the next phase of design work. The following next steps are therefore recommended:

1) Involve the SALT Ops team in Sutherland more deeply in this next stage of design. We worked closely with team in February 2020 to produce many of the features of the current design. But in particular, issues of MT installation, de-installation, access, and maintenance, and testing will be essential to solve with this team jointly, as they have the critical hands-on knowledge about the tracker operation and maintenance.
2) Optimize the mounting base assembly for structural stiffness, using member sections, structural geometry, and materials. Iterate with finite element analysis (FEA) until satisfactory first mode frequencies and deflections are obtained. Look for and fix high stress areas, possible excitation modes from wind, and (unlikely) servos.
3) Optimize the interface between the mounting base assembly and the swing arm to ensure easy installation and removal of the swing arm assembly from the mounting base. This interface should be effectively kinematic and repeatable.
4) Modify the swing arm web geometry to minimize deflection and weight, and maximize stiffness. A two-beam solution may also be feasible.
5) Develop a better pivot drive design. Suggest trying a sector ring and friction drive concept. The cable drive for the trolley motion is probably sufficiently stiff, if 8 to 10 small cables are used as in the rho drive. A linear encoder should be added to the design.
6) Trial design modification: Push the swing arm pivot locations further outboard radially, allowing for shorter swing arms and more pivot rotation. Goal is to maintain or even increase the patrol area while shortening the swing arms to improve overall stiffness.
7) Consider the following design concept: Installing a large diameter driven ring at this outer pivot location would allow the MTs to be mounted on the ring, and not need to be driven individually to de-rotate the sky. Shorter pivot arms could be mounted on the ring, and the number of MTs would not necessarily be limited to four.
8) Mass/moment calculations for the tracker. Determine what, if any, modifications may be made to the tracker to carry additional MT mass, and analyze the effect of varying moments on the pointing vector of the main SAC.
9) Consider/explore the "desk lamp" concept further – there may be a configuration that is simpler and stiffer than the swing arm design with the correct pivot point geometry and kinematics.

8 Optical Design

8.1 The Mini-Spherical Aberration Corrector (MSAC)

Along with the mechanical deployment mechanism, the other essential component for an MT is its spherical aberration corrector. We were fortunate that SAAO optical engineer Melanie Saayman was available part-time to do much of the optical design and analysis work that was required.

We pursued MSAC designs using only two mirrors for cost and size reasons. An affordable, two-mirror design in glass with sufficient aperture, field size, and image quality would be (and still is) the ultimate goal for the MSAC. A two-mirror MSAC is much lighter, much shorter, and much simpler to align (read "much less expensive") than, for instance, a smaller version of the four-mirror SALT SAC.

Our initial aim was to produce a family of two-mirror designs of varying apertures, to develop a basic understanding of what was possible, and to answer the following questions:

1. How does MSAC diameter and length vary with aperture size?
2. How does MSAC mass vary with aperture size?
3. How large a field could each design produce?
4. What level of image quality could be delivered using only two mirrors?

Over the course of the study Melanie was able to produce four MSAC designs of apertures 10, 9, 8, and 4-m (the latter is not discussed in this report). She also quickly did a four-mirror design based on the SALT SAC when questions about manufacturing problems arose with the 9-m design very late in the study.

Please note that due to limitations on Melanie's time owing to the press of work on other projects, none of the below designs were optimized.

8.1.1 The 9-m Design

Melanie first designed a 9-m aperture f/1.8 output MSAC based on the design of the HET Surrogate SAC from 1995. The Surrogate SAC was designed and built for HET's First Light and initial shakedown and testing, when it became apparent that the SAC itself would be delivered about two years behind schedule. The 9-m MSAC became our point design until late in the study, when a manufacturability issue arose. This issue is discussed in Section 8.1.4.

The raytraced layout of the 9-m MSAC is shown in the top left panel in Fig. 8. Light from the SALT primary mirror enters from the left through the perforation in M3, is collected by M2, reflected back to M3 and focused through the M2 perforation behind M2.

The top right panel in Fig. 8 shows the spot diagrams produced by this design in one arcsec boxes at three different field positions, on-axis, 1 arcmin, and 2 arcmin (edge of field) off axis.

The lower left panel in Fig. 8 shows the encircled energy for each field position. Encircled energy is a more detailed way to quantify the light distribution in a spot diagram. Note that all of the encircled energy is under 0.5 arcsec on axis and at the 1 arcmin field positions, but only about 80% is within 0.5 arcsec for the outer field position. The vignetting curve is shown in the lower right panel in Fig. 8.

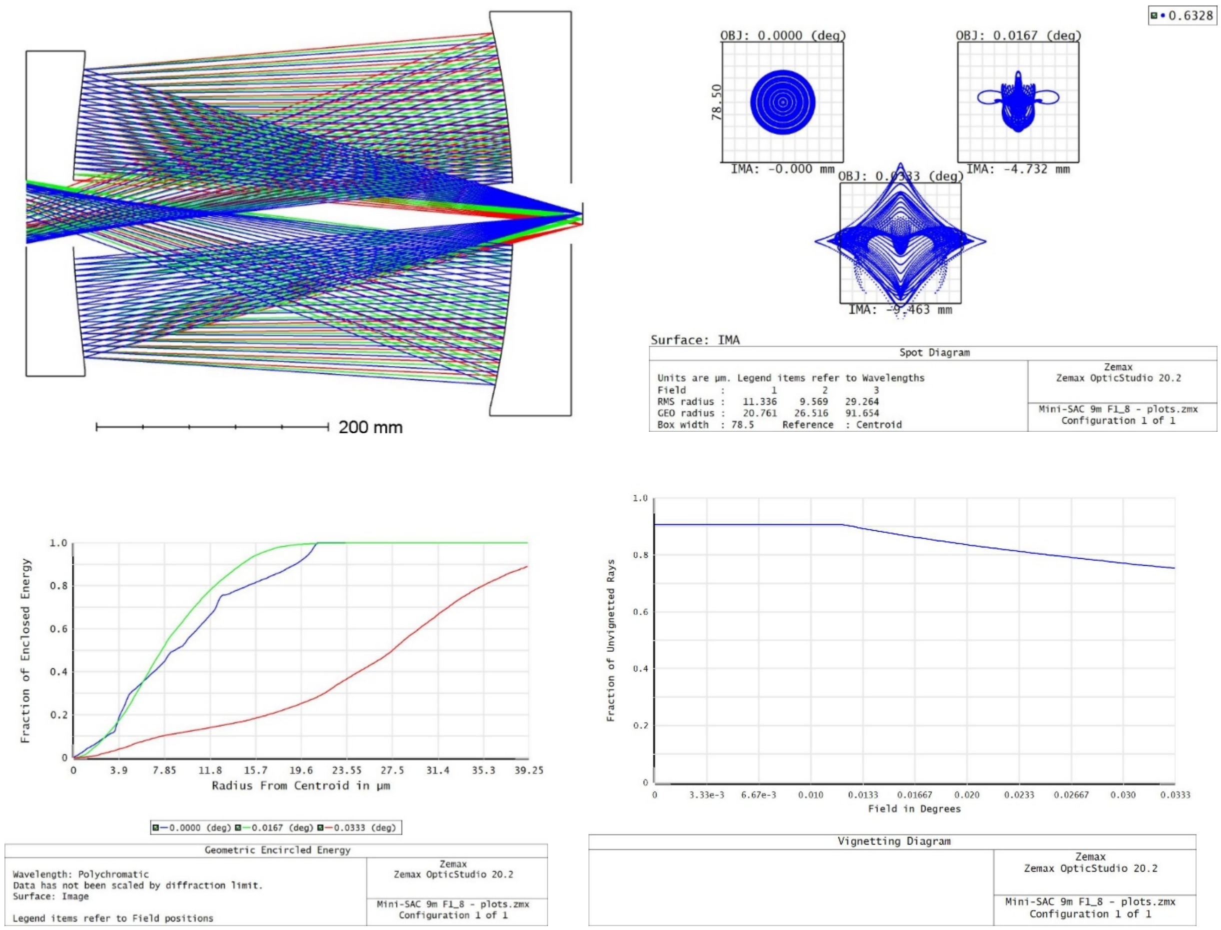


Fig. 8: The optical layout, spot diagrams, encircled energy and vignetting curves for the 9-m MSAC.

Based on the mirror sizes (the clear aperture of M2 is 314 mm in diameter, and M3 is 252 mm in diameter), and using standard rules of thumb, this corrector is estimated to weigh around 15 kg, using 50% light-weighted mirrors. There is no real corrector housing design, but Fig. 9 shows what it might look like in a sectional view. This view is looking towards the central tracker payload from the end of the swing arm, which can be seen to the right of the corrector. The "post-MSAC optics" would reside in the rectangular housing above the MSAC.

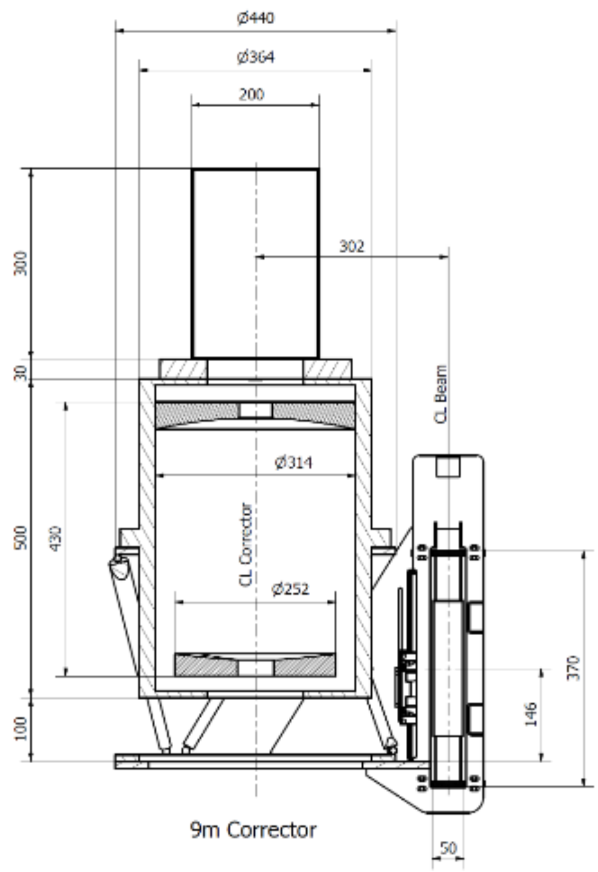


Fig. 9: Sectional view of the MSAC, swing arm, and trolley.

8.1.2 The 10-m Design

The same description of the 9-m diagrams applies to the 10-m and 8-m sets shown in Figs 10 and 11, respectively.

The 10-m design was done in order to see "how big is too big", and a 10-m corrector is very likely "too big". It is estimated to weigh between 25 kg and 30 kg. This load, along with the weights of the hexapod, trolley and drives, and the post-MSAC assembly, will probably exceed a reasonable weight limit for the MT, and drive its first frequency below an acceptable threshold. Only structural analysis in the next phase of design can determine this definitively.

It should be noted that the mirror diameter of M2 was arbitrarily limited to 400 mm, which results in the additional on-axis vignetting shown in Fig. 10. A 10-m design "wants" bigger mirrors, both to reduce vignetting and improve image quality. Consider that the 11-m SALT SAC has mirrors of order 600 mm in diameter (M2 and M3) to accomplish this.

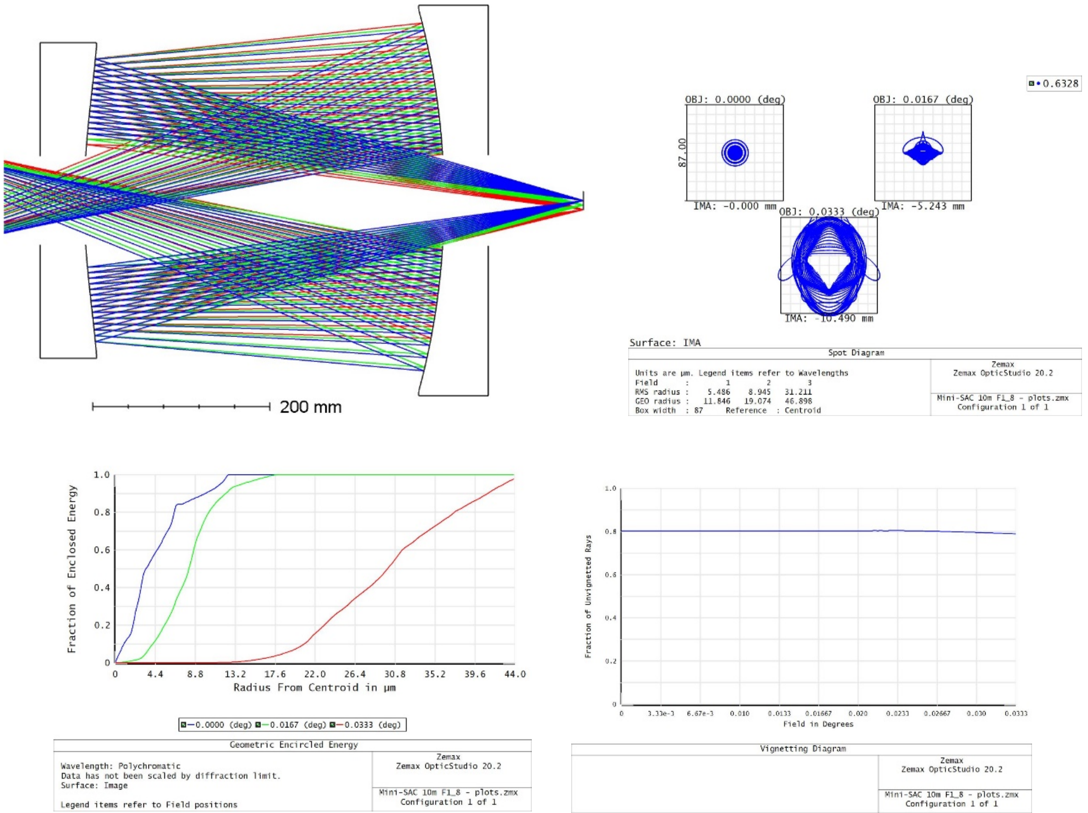
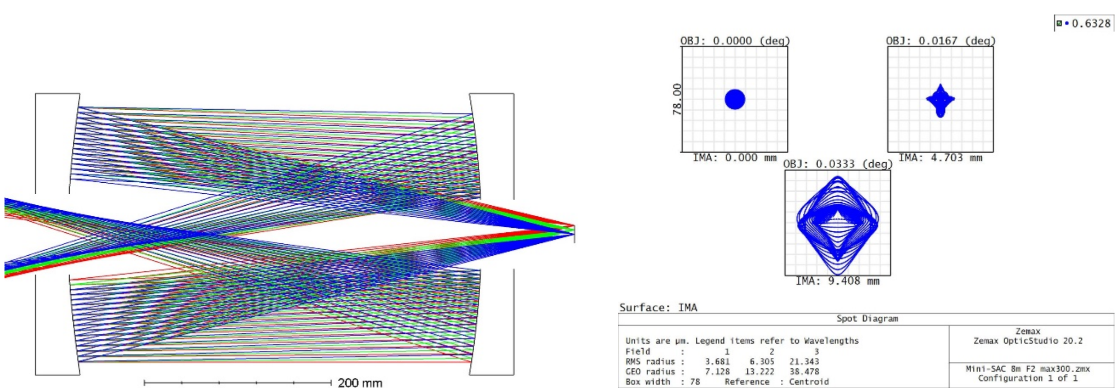


Fig. 10: The optical layout, spot diagrams, encircled energy and vignetting curves for the 10-m MSAC.

8.1.3 The 8-m Design

MSAC design space was further explored with the below 8-m design. Note that, not surprisingly, the image quality has improved vs. the larger aperture designs. The higher vignetting is simply due to the fact that Melanie did not have time to optimize this design.



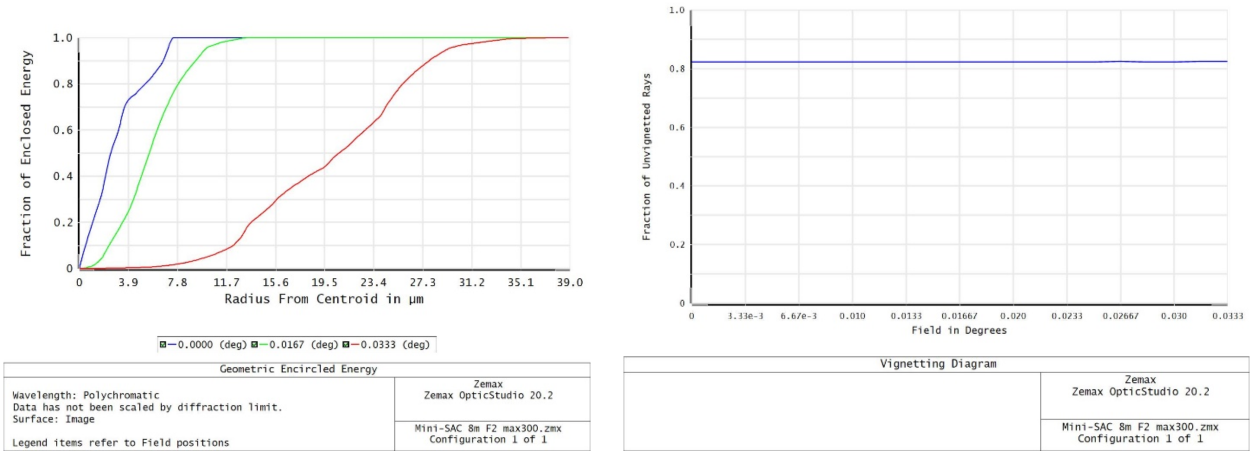


Fig. 11: The optical layout, spot diagrams, encircled energy and vignetting curves for the 8-m MSAC.

8.1.4 Manufacturing Issues

Near the end of the study, and with the above preliminary optical designs in hand, we approached three optical vendors to discuss manufacturing issues and a ROM budgetary cost for the 9-m version of the MSAC. Arizona Optical Systems (AOS) in Tucson, Arizona, Asphericon, which is based in Germany with a satellite office in Florida, and SAFRAN/REOSC (SAGEM) were contacted. AOS and Asphericon responded quickly and engaged with us at a very helpful level in both cases.

Asphericon delivered budgetary quotes in both glass (Zerodur) and diamond-turned aluminum, without mentioning manufacturing difficulties. After reviewing our design, AOS responded in late May that M2 manufacture would be difficult, and M3 would be "impossible" due to the large second derivative of this particular curve. This is not terribly surprising, as it is not uncommon to be able to design an asphere that works within an optical design, but is difficult or impossible to manufacture.

Quickly responding to this difficulty, Melanie designed a smaller version of the SALT 4-mirror SAC and forwarded it to AOS. Equally quickly, AOS responded just before the Board meeting with a very rough and very high quote ($2.5 – 3.6M!). Additionally, it is not even clear that an MT could support a 4-mirror corrector.

All of this simply means that there is more work to be done here, both on the optical design side, and on the vendor side, to converge on a practical design that serves our needs, and that is manufacturable and affordable. There are many other vendors now that can produce aspheric optics in this size range.

8.1.5 Glass vs. Single Point Diamond-turned (SPDT or DT) Mirrors and Coatings

Procuring the MSACs with glass mirrors, rather than diamond-turned aluminum mirrors, is our ultimate goal. While virtually any aspheric shape can be generated on a diamond-turning machine in highly annealed aluminum alloys, the problem with this approach has always been the development of a suitable highly reflective, durable, and replaceable overcoat. Without such a coating, the bare aluminum surface tends to oxidize just as the typical aluminized mirror does in a conventional telescope, and within a few years has degraded significantly. However, advances have been made in recent years with coating DT surfaces, and this option should be explored further. If the form accuracy and surface quality of DT mirrors are sufficient, and a suitable broadband durable coating can be successfully applied, this combination could result in a relatively low cost MSAC. Another important question is whether the coating can be stripped and recoated after a few years, when it inevitably degrades. This is on the list of "Next Steps", below.

It would certainly be possible to produce an affordable diamond-turned SAC for a prototype MT without an additional coating, as the response from Asphericon shows (M2 + M3 at the best surface quality, $88,000 total). But again, the problem for the "suite" of multiple MTs would be longer-term reflectivity, so a solution for this would need to be found independently of the prototype development.

8.1.6 Next Steps

1) Optimize the 8-m and 9-m two-mirror MSAC designs, with an eye towards reducing the second derivative problem to enable manufacture.
2) Continue to develop the family of two-mirror designs of smaller aperture (7 m, 6 m?) with perhaps slightly larger fields (>4 arcmin) to find the sweet spot among size, manufacturing difficulty, cost, image quality, and mass. This will give us more options to choose from in making this eventual trade.
3) Contact additional vendors (KiwiStar, Officina Stellare, Optimax, others) for discussion and insight about mirror manufacturability, alignment procedures, and cost for these designs.
4) Research the current diamond-turned mirror coating state-of-the-art, and contact vendors with experience in this area.
5) If DT mirror coatings are acceptable, consider MSAC designs that are less sensitive to small surface figure errors inherent to DT mirrors.
6) Add front and rear optical windows to the MSAC designs for dust prevention and maintenance of inert gas atmosphere inside the corrector. Such windows could also be used to improve the delivered image quality of the MSAC.

8.2 Post-MSAC Optical Path

The downstream optical path from the MSAC will be similar to a conventional optical telescope. The MSAC will produce a field about 4 arcminutes in diameter at ~f/1.8 – f/2. We envision a conventional optomechanical arrangement here in which the central part of the field is reserved for an IFU, which will route the light to a low-resolution spectrograph mounted on the main tracker carriage. The beam will need to be reduced in speed to about f/3 by a small focal expander. The surrounding field will be used for acquisition, guiding, and wavefront sensing to maintain focus and tip/tilt alignment.

Wisconsin has world-class capability in designing and building astronomical grade high efficiency IFUs, and they would be our obvious first choice in procuring this critical element.

A more detailed description of this area was included in the 2018 SPIE paper, and there is little new to add here.

8.3 Spectrograph

A spectrograph was not included within the scope of this study, as we focused on subsystems that were much less understood. But in general, a small, low-resolution (R=1000) spectrograph, optimized for identification spectroscopy, is envisioned for each MT. (A more ambitious spectrograph located here or elsewhere is of course also possible.) The spectrographs would be located in an enclosure on the tracker carriage to minimize fiber length and losses in the blue. Tracker performance is relatively insensitive to additional mass on the carriage.

However, we wanted some sort of strawman cost, size, and weight for the instrument, and so we contacted Kathryn Rosie at SAAO, who is working with Liverpool John Moores University (LJMU) to produce a new low-resolution spectrograph for Lesedi called Mookodi. In the course of this interaction, it became clear that an MT spectrograph design should be done in parallel with the MT design, to optimize its performance.

The Mookodi design is adapted from that of the SPRAT spectrograph on the 2-m Liverpool Telescope and so it would not be suitable for MT purposes. But for the sake of providing a rough indication of cost and scale for a relatively simple spectrograph, Mookodi costs about $250,000, and weighs about 27 kg.

9 Software

Among the various subprojects which we had hoped to address but simply did not get to, the software subproject is perhaps the most important and challenging. A short email exchange with Anthony Koeslag at SALT resulted in the following list from him regarding the software development that would be required for fully robotic operation of the MTs:

- Brokering incoming survey data
- Filtering/selecting targets
- Acquisition, pointing, tracking, and guiding
- Reporting/QC of observations/MT performance monitoring

Clearly this area will need to be tackled in the concept design phase, in order to better understand the overall effort required here. We have likely underestimated the effort at 5 person-years for the project.

10 Trajectory Analysis and Illumination Calculator

The mini-trackers will select targets and operate entirely dependent upon the trajectories run by the main SALT tracker. The instantaneous effective aperture for each MT, the patrol field from which an MT may select suitable targets, and the maximum length of an MT trajectory and hence its overall effective aperture – all of these critical parameters are functions of the chosen SALT trajectory. It therefore seemed logical to explore what SALT actually observes, and the trajectories it actually runs over the course of a normal year.

Retha and Freya undertook a study to assess the observations that could have been performed with 4 MTs, during all the science trajectories that SALT ran during 2019. They developed a tool which calculates the effective apertures of the 4 MTs at different positions relative to the main tracker for each target SALT observed. The square of that aperture multiplied by the track length is proportional to the signal from a target. The distribution of this quantity, for a given MT at different distances out from the center of the main tracker, shows the fraction of SALT tracks in which targets of a given brightness can be usefully observed, in different parts of the patrol field. The tool is still a work in progress, but when it is vetted and the results are better understood, they will be distributed for wider discussion.

An illumination calculator is also under development. It calculates the effective aperture of a given MT for a given track, i.e. the equivalent aperture of a non-moving pupil telescope that would have the same number of photons incident on its primary mirror for the same track.

11 Cost Estimate

A rough order of magnitude (ROM) cost estimate is included below, divided into “Personnel”, “Equipment and Parts”, and “Summary Total” sections. These are the same (corrected) estimates that were distributed to the SALT Board in early June.

Please note that because of various problems created by the pandemic, many of these numbers are necessarily quite rough, and the next order of business in any future phase of this project is to reduce their uncertainty. This can only be done by refining the optical and mechanical designs, working with knowledgeable vendors to cost the designs, and working with the various SALT groups, particularly the software group, to lend better reality to these numbers.

An exchange rate of 18 ZAR/USD is employed in the calculations that follow and an approximate salary of ZAR 1M/year is assumed for most personnel in section 11.1.

11.1 Personnel

	Year 1 Prototype	Year 2 Prototype		Year 3 Suite (+3)
Personnel				
Principle Investigator	0.5	0.5		0.5
Project Manager	0.75	0.5		0.5
Optical Engineer	0.5	0.5		0.5
Project Engineer	1	1		1
Mechanical Designer	1	1		1
Structural Engineer	0.5			
Mechatronics Engineer	1	1		0.5
Software Engineer	2	2		1
Mechanical Technician	1	1		1
Consulting as required	0.5	0.5		0.5
Travel & misc.	0.5	0.5		0.5
Total Personnel	9.25	8.5	Total, Prototype	7
ZAR	10,120,000	9,080,000	**19,200,000**	**7,580,000**
USD	562,222	504,444	**1,066,667**	**421,111**

11.2 Equipment and Parts

	Prototype		Year 3 Suite (+3)	
Equipment and parts	USD	ZAR	USD	ZAR
Base frame	20,000	360,000	45,000	810,000
Swing arm	40,000	720,000	105,000	1,890,000
Test stand, lifting jig	30,000	540,000		0
Drives and controls (2 per)	10,000	180,000	30,000	540,000
Corrector	300,000	5,400,000	750,000	13,500,000
Hexapod	130,000	2,340,000	330,000	5,940,000
Small optics and IFU	50,000	900,000	150,000	2,700,000
Spectrograph (e.g. LJMU)	300,000	5,400,000	750,000	13,500,000
Misc. parts	20,000	360,000	20,000	360,000
Total equip/parts	900,000	16,200,000	2,180,000	39,240,000
Contingency (20%)	180,000	3,240,000	436,000	7,848,000
Total equip/parts + contingency	**1,080,000**	**19,440,000**	**2,616,000**	**47,088,000**

11.3 Summary Total

Summary (ZAR)	Prototype	Suite (+3)	Total
Personnel & travel	19,200,000	7,580,000	26,780,000
Equipment and parts	19,440,000	47,088,000	66,528,000
Total	**38,640,000**	**54,668,000**	**93,308,000**

Summary (USD)			
Personnel & travel	$ 1,066,667	$ 421,111	$ 1,487,778
Equipment and parts	$ 1,080,000	$ 2,616,000	$ 3,696,000
Total	**$ 2,146,667**	**$ 3,037,111**	**$ 5,183,778**

12 Draft Schedule

The draft schedule, below, was presented during the May Board meeting. It is necessarily notional, as we don't know at this point what resources will be available, at what level, and when. Absent any of these realities, the timeline below assumes the full complement of capable scientists, engineers, software people, technicians, etc. are available when needed. How realistic this is is of course open to question, but we have little else to go on at this point, particularly given the current realities of the pandemic and its effect on the workplace.

Phase	Duration (months)	Dates
Concept design	2	1 Jan - 28 Feb 2021
Preliminary design	3	1 Mar - 31 May 2021
Critical design	3	1 Jun - 31 Aug 2021
Initial build phase (2 mo. overlap)	2	1 July - 31 Aug 2021
Fabrication and assembly	8	1 Sep - 30 Apr 2022
Ground shakedown/test	2	1 May - 30 Jun 2022
(install mounting base on SALT)		May 2022
On-telescope installation/test	2	1 July - 31 Aug 2022
Commissioning	1	Sep 2022
Prototype operational		1 Oct 2022
Full suite of 3 more MTs	12	1 Oct 2023
(build, test, install, commission, if start correctors early)		

13 Final Recommendations

Throughout this document, we have suggested a series of specific "next steps" in order to reach the concept design level and in many cases, beyond this level. The following are general recommendations which, together with these next steps, constitute a path forward for the straightforward engineering design development of the mini-tracker project.

1. Work the trade between the “interesting” science, the MSAC aperture and patrol area (instrument “grasp”) to better understand the scientific viability of the project. If we have gone from “a few interesting targets per square degree” previously to a few per hundred square degrees as stated in Section 5 above, we need to consider the impact of this change.
2. Engage a lead engineer who can serve as a local project manager for the MTs. This position is critical to moving the project forward. They must have a demonstrated ability to work well with scientists in an R&D environment, successful experience developing and fielding astronomical or similar instrumentation, and the ability to manage an unusual project with the normal mix of disparate personalities involved. They must be creative, able to foster a team environment that is open to innovative ideas and solutions, but with the ability to synthesize these solutions and converge to a practical product.
3. Focus design efforts on development of a Prototype MT design. A demonstrator prototype could be relatively inexpensive depending on its capabilities. Keep in mind that a DT corrector for the prototype may not be suitable for the final version, so parallel efforts on the MSAC may need to be made.
4. Complete and refine the cost estimate. As work on the MSAC converges to a manufacturable device, and initial structural and modal analysis and design iterations are completed for the mechanical assembly, work with vendors to better cost these critical elements.

14 Conclusion

The feasibility study was conceived of and performed with the purpose of determining whether the mini-tracker concept was viable and practical as a means to do the proposed transient follow up science. Although the effects of the global pandemic, including the stringent lockdown in South Africa and elsewhere, hindered our efforts midway through the study period, we were able to complete the most critical portions of the study and reach the following conclusions:

1. A viable mechanical deployment mechanism for the device appears to be achievable.
2. The mass of an 8- or 9-meter aperture MSAC looks like it can be supported by the device, and a 10-m MSAC is very likely too heavy. Preliminary structural analysis work will need to be done to determine this definitively.
3. Problems were identified with the manufacturability of the MSAC mirrors, so more optical design work needs to be completed to solve this issue.
4. The budget and schedule should be reworked once additional critical design work (above) has been performed, and more consultation with relevant vendors is completed.
5. The design and analysis of a prototype device should be pursued next, with an eye toward solutions that will be useable by the entire suite of MTs.
6. The science case indicates that there will be 1-2 “interesting” targets per 100 sq. deg., which is two orders of magnitude fewer than our “going in” understanding. Hence more work needs to be done to ensure that the science goals envisioned for the project are still congruent with the capabilities of the MTs.

In our opinion, the project looks to be sufficiently technically and scientifically viable to pursue through the concept design phase. Detailed recommendations for logical next steps were made in each appropriate section of the report, so that when work is restarted on this project, it can be picked up where we left off.

The team appreciates the opportunity to work on this exciting new capability for SALT, and is hopeful that this summary report will be helpful to the SALT Board in their deliberations about how to proceed.

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Appendix A

Science case for mini-trackers on SALT

Retha Pretorius

With input from Tony Bird, David Buckley, Malcolm Coe, Paul Groot, Christian Knigge, Moses Mogotsi, Patricia Whitelock

June 11, 2020

Deploying 4 mini-trackers (MTs) on SALT, each with a ≃100 sq.deg. patrol field inside which a small field can be corrected for spherical aberration, will add the capability to simultaneously observe 4 targets in addition to the observation being done with the main tracker and SAC. If these mini-trackers feed low-resolution spectrographs, this allows for spectroscopic surveys of objects with sky densities of a few per 100 sq.deg. In particular, it will greatly enhance SALT's capability to do identification spectroscopy of transients.

1 The expanding field of time-domain astrophysics

Violent, extremely energetic astrophysical events are commonly detected as transient sources by the all-sky monitors of X-ray and g-ray observatories, and now by a rapidly growing range of wide-field optical time-domain surveys. These extreme events – e.g. nova eruptions, supernova explosions, magnetar outbursts, neutron star mergers, and relativistic jets ejected from accreting black holes – provide outstanding opportunities to study the laws of physics operating in conditions of density, temperature, pressure, and gravity well beyond anything achievable in a laboratory. The study of transients is therefore becoming one of the dominant astrophysical fields of the 21st century. The recent discovery of gravitational wave events resulting from compact object mergers, as well as the electromagnetic radiation that accompanies them (e.g. Abbott et al. 2017) has already opened up a new window on astrophysics. A revolutionary new generation of radio telescopes have just started operating (e.g. Fender et al. 2017; Hobbs et al. 2016). These SKA pathfinders have driven improvement in survey capabilities that now make efficient detection of transients possible for the first time in the radio band. Upcoming facilities such as the LSST and SKA will again open up new parameter space, and likely also transform time-domain astronomy, in the coming years. The major missing component in this field is the capacity in large telescope rapid spectroscopic follow-up, which is critical to a full understanding of the physical processes taking place.

1.1 Transients from LSST

The SALT community has wide interests, and will observe sources discovered by surveys observing across the electromagnetic spectrum. Discovery observations will come from X-ray and g-ray observatories, Gaia, MASTER, ASAS-SN and several other optical transient surveys, upcoming infrared facilities including Euclid, and MeerKAT/MeerLICHT. In addition, there is of course great interest in LIGO/Virgo sources. However, by far the largest number of transients will be discovered in the optical, where core collapse supernovae, dwarf novae, and flare stars dominate the population. Amongst optical surveys, LSST (The Rubin Observatory; e.g. Ivezic et al. 2019) stands out as the largest.

LSST is expected to start its ten-year survey towards the end of 2022. The Wide-Fast-Deep main survey will use the majority of telescope time, covering most of the visible sky at a cadence of about 3 nights (with the exact observing strategy still to be decided; e.g. Marshall et al 2017). This will likely transform our understanding of the transient Universe, and, besides transients, the survey will discover vast numbers of variable stars.

1.2 The need for identification spectroscopy

Transient astronomy (and time-domain astronomy in general) has a huge need for identification spectroscopy (e.g. Abell et al. 2009; Frail, et al. 2012; Kulkarni 2020), and this step will be the main bottleneck in exploiting transient surveys. Initial (ideally automated) classification based on variability time-scales, optical colours, and data from existing catalogues will become increasingly important (e.g. du Buisson et al. 2015; Pietka et al. 2017). Nevertheless, in most cases, an optical spectrum will be a crucial step in determining the physical origin of the transient. This is particularly relevant to prompt identification of LSST sources, because of its low cadence. Light curve classifiers may eventually correctly identify the nature of many LSST transients, but only after days or weeks of data are in hand.

2 Optical follow-up capacity for transient science

LSST will discover large numbers of transients near its flux limit. However, spectroscopic follow-up of objects beyond 22nd or 23rd magnitude is prohibitively expensive even with large telescopes, and observations of the majority of these faint sources will not be attempted. The sky density of bright transients (up to roughly 21st magnitude) will be low, even in the LSST era. This means that optical follow-up will be performed with single-object spectrographs. Massively multiplexed facilities such as LAMOST and 4MOST (e.g. de Jong et al. 2012; Zhao et al. 2012), which take thousands of simultaneous spectra over a few square degrees, are therefore not relevant in the area of transient follow up.

2.1 Southern hemisphere 4- and 8-m class telescopes

Telescopes in the northern hemisphere will be able to reach a large fraction of the sky covered by LSST, but southern hemisphere facilities are obviously in the best position to exploit the discoveries made by LSST.

Beyond about 18th magnitude, 4-m class and larger telescopes are needed for spectroscopy. Only 4 southern hemisphere 4-m class telescopes are not engaged in specific surveys or programs that use all available time. These are the NTT, AAT, SOAR, and the Blanco telescope. The NTT will dedicate most of its observing time to transient follow-up, using the new instrument SOXS (e.g. Schipani et al. 2018). The 6-m Magellan telescopes will also do important work, and indeed obtained the first spectra of the optical counterpart of a gravitational wave event (Shappee et al. 2017). Two UTs of the VLT have suitable instruments for transient ID spectroscopy, but the large telescope expected to do the most in this area is Gemini South, with its upcoming instrument SCORPIO (e.g. de Ugarte Postigo et al. 2016).

SALT is therefore one of only a small number of 4m+ telescopes able to dedicate a large amount of time to transient follow-up.

2.2 SALT and mini-trackers

The SALT user community has easy access to a large telescope at a longitude where there are no comparable facilities in the southern hemisphere. Furthermore, SALT is well suited to ToO observations, since it is fully queue scheduled. With 4 mini-trackers, each feeding a low-resolution spectrograph, in addition to RSS-Dual on the main tracker, our transient follow-up capability is a large fraction of the world's total. We should therefore be able to make an important impact in this field.

We also anticipate spending significant telescope time on more detailed follow-up and monitoring of individually interesting transients, after identifying their physical nature; this additional follow-up is another key ingredient in making good use of transient surveys. Given their constrained pointing, the role of MTs will be only to take ID spectra, saving SALT from doing an expensive aspect of the work, and leaving it free to do the higher-value detailed follow-up, or to target especially interesting events.

3 Using mini-trackers on SALT for transient follow-up

Identification spectroscopy of transients is the type of science program that is suited to MTs. For additional time-constrained monitoring of the evolution of a particular source, we will still have to rely on SALT itself. MTs make it possible to obtain ID spectra of a number of transients that would be too expensive to schedule on SALT, and their discoveries will feed back into the main SALT queue.

There is a large range of projects that require spectra of ∼1,000 objects, spread across the sky (very expensive to obtain one by one on a large telescope, but too low sky density to use MOS). Below are only 3 obvious examples.

3.1 Main limitations

MTs are constrained to point within about 15 deg of SALT, and the patrol field that each MT can access is expected to be roughly 100 sq.deg. Furthermore, a MT observation must fit into the SALT track during which it is taken (this will for the most part imply that MTs are idle during short SALT tracks). With an effective aperture of roughly 4 m and up, and a typical exposure limited to around 30 minutes, a reasonable conservative flux limit for low-resolution spectroscopy with MTs is about 21^{st} magnitude.

3.2 Sky density of bright LSST transients

Results from the 4 years of survey data by PTF (Rau et al. 2009) can be used to estimate transient rates for LSST. This survey discovered 50,000 transients and nominally went down to 21^{st} magnitude, but the transient recovery efficiency dropped steeply from ≃19th magnitude (Frohmaier et al. 2017). Another useful indicator comes from the PTF Sky2Night program, which found 34 transients, split roughly evenly between Galactic and extra-galactic sources, at $R < 19.7$ over 407 sq.deg. in 8 nights (van Roestel et al. 2019). Scaling the survey volume to the deeper flux limit, both programs indicate that at magnitudes < 21, LSST will find roughly 2 transients per 100 sq.deg. per night. It is not possible to obtain ID spectra of all of the ∼200 new transients every night and many will still benefit from a spectrum after a few nights, implying that each patrol field will contain several potential targets to observe during a given SALT track, including those that were not observed on the first night after being discovered.

A sky density of a few targets per 100 sq.deg. means that bright transient follow-up is a science program that cannot be sensibly addressed with e.g. 4MOST. It is however sufficiently high for MTs, despite their pointing constraints. This sky density also implies that demanding AI light curve classifiers are not needed to prepare MT queues[1]. On the other hand, assuming each MT can observe 10 targets per night, ∼40 out of a total ∼200 implies that we will be able to construct statistically complete samples of transients with spectroscopic IDs. Such samples, gathered over the first few years of LSST operations or from brighter existing surveys, will be very important in providing training sets to improve the performance of machine learning classifiers, enabling more selective follow-up later in the survey (see e.g. the Kavli-IAU report on International Coordination of Multi-Messenger Transient Observations in the 2020s and beyond).

[1]Such tools may be valuable in scheduling more selective observations with the main tracker, as well as for operations of the "Intelligent Observatory". Development work is being done by a group of our colleagues at AIMS.

4 Other potential science programs to pursue with MTs

Each MT is effectively just a (relatively large) telescope, and many science programs can be make use of this facility. What limits the type of program sensibly tackled with MTs are the pointing constraints (implying target sky density on the order of a few objects per 100 sq.deg.), and the instruments that will be fed by MTs (presumably low-resolution spectrographs). Programs that do not involve transients or other time-critical observations will in fact be easier to do, and can be planned to be executed over a period that allows for the required sample size to be obtained.

4.1 Follow-up of MeerKAT sources

The MeerKAT radio telescope is discovering huge numbers of previously unknown radio sources. These sources appear in every field observed as part of the various different Large Survey Projects (about 100 different fields, each of 2.7 sq.deg. using the majority of telescope time) and open time proposals. MeerKAT also observed a large part of the Galactic plane (where the LSST cadence will be lower), as an observatory project, and a point source catalogue based on these data will soon be available.

The majority of radio point sources are background quasi-stellar objects (QSOs), but the Galactic plane survey will also have detected many sources in our Galaxy, including accreting compact binaries, young stellar objects, and flare stars. This rich dataset can be used to understand the contributions that different binary and stellar objects make to the Galactic radio source population. An obvious first step in understanding the new radio sources will involve cross matching the radio data to existing catalogues at other frequencies. The addition of time-resolved MeerLICHT data will also be of great value. These data will allow rough classifications, however, it is likely that optical spectroscopic follow-up of a large number of new MeerKAT sources will be needed to guide classifications based on imaging data.

4.2 Follow-up of eROSITA sources

eROSITA has started observations for an all-sky survey that will be roughly 20 times deeper than the *ROSAT* all-sky survey (e.g. Cappelluti et al. 2011). ART-XC (e.g. Pavlinsky et al. 2011), flying on the same satellite, is also doing an all-sky survey, in a harder band.

Spectroscopic follow-up of X-ray sources with sufficiently bright optical counterparts will be valuable both for understanding the Galactic and extra-galactic X-ray source population better, and for identifying new, uniform samples of e.g. X-ray binaries and accreting white dwarfs. Candidate samples can be constructed using X-ray spectral properties and optical to X-ray flux ratios. Optical ID spectra will again be the key to confirming source classifications.

The *eROSITA* all-sky survey data should be public in about 5 years, but astronomers based at SAAO also have existing collaborations with both Russian and German partners.

Although *eROSITA* and ART-XC are the main new X-ray surveys, there are of course many X-ray and γ-ray sources that have not been identified and followed up at other wavelengths (from e.g. Swift/BAT, INTEGRAL, MAXI, Astrosat). There are no doubt interesting discoveries to be made from mining these existing datasets as well.

4.3 Variable stars from LSST and other optical time-domain surveys

Existing optical time-domain surveys are already discovering vast numbers of variable stars, and LSST will add to this. Several types of e.g. pulsating variables can be reliably classified based on their light curves, but in other cases more information is needed.

The sky density of all variables is too high for a blind spectroscopic follow-up survey to the best choice, and a facility such as LAMOST would be better suited for that than MTs are. However, samples of candidates for rarer classes of variables, such as accreting binaries, can be constructed using e.g. optical/IR colours, variability properties, and possibly emission at X-ray energies. Higher cadence data, from e.g. MeerLICHT and LCO, will be of more use than those from most transient surveys for identifying compact binary candidates based on optical variability (see e.g. Macfarlane et al. 2015). Also, with the addition of data from Gaia, large volume-limited samples of different classes of variables can be constructed for the first time. A spectroscopic follow-up survey will be needed in the case of many types of variables to confirm their classification, and for rare classes such as interacting binaries, the sky density of targets will be in the range where MTs are best suited for that follow-up.

4.4 Identifying the electromagnetic counterparts of gravitational wave events

The uncertain localization of gravitational wave sources detected by LIGO/Virgo implies that in order to find an electromagnetic counterpart, a large area of the sky (several 100 or even ~1000 sq.deg.; e.g. Abbott et al. 2020) needs to imaged and searched for transients. In the case of optical followup imaging, such searchers leads to many candidate counterparts, which require ID spectroscopy (e.g. Coughlin et al. 2019). The ability to take spectra of 5 objects, separated by 10s of degrees on the sky, simultaneously with SALT and 4 mini-trackers would be of great value in this important work.

4.5 Extra galactic science

Wide-field extra galactic surveys are moving into a new era with the advent of DESI (Aghamousa et al. 2016) and Taipan (da Cunha et al. 2018), which will provide the deepest wide area (> 14,000 sq.deg.) spectroscopic optical extragalactic surveys to date. Taipan will cover the southern hemisphere but will be limited to galaxies with $i < 17$. Despite SALT mini-trackers not being optimized for extragalactic surveys, they will be able to probe deeper (in redshift and sensitivity) than Taipan, and even the DESI Bright Galaxy Survey in the north, which will be limited to $r < 19.6$. DESI BGS predict a source density of ~ 900 sources per sq.deg., at their magnitude limit, and TAIPAN ~ 100 sources per sq.deg. at their magnitude limit. Therefore there will be many available sources for mini-trackers to target based on photometric surveys (or following up spectroscopically observed galaxies which require deeper observations). In addition to infrared 2MASS and WISE all-sky surveys, wide-field radio surveys such as EMU, WALLABY and GLEAM on the ASKAP and MWA radio arrays respectively, will provide unprecedented detections of extragalactic radio sources all across the southern sky that require optical follow up to measure redshifts and galaxy/AGN properties. Having such wide field of view and depth will allow enable studies of galaxy evolution that will complement dedicated ongoing and planned deeper (but small area), wider area and targeted optical spectroscopic surveys.

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Appendix B

Mini-Tracker concepts for the SALT transient follow-up program

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ABSTRACT

The MeerKAT radio telescope array, the Large Synoptic Survey Telescope (LSST), and eventually the Square Kilometer Array (SKA) will usher in a remarkable new era in astronomy, with thousands of transients being discovered and transmitted to the astronomical community in near-real-time each night. Immediate spectroscopic follow-up will be critical to understanding their early-time physics – a task to which the Southern African Large Telescope (SALT) is uniquely suited, given its southerly latitude and the 14-degree-diameter uncorrected field (patrol area) of its 10-m spherical primary mirror. A new telescope configuration is envisioned, incorporating multiple "mini-trackers" that range around a much larger patrol area of 35 degrees in diameter. Each mini-tracker is equipped with a small spherical aberration corrector feeding an efficient, low resolution spectrograph to perform contemporaneous follow-up observations.

Keywords: Southern African Large Telescope, SALT, Hobby-Eberly Telescope, field partitioning, Schmidt telescope, spherical aberration corrector, mini-trackers, spectroscopic follow-up

1. INTRODUCTION

Cosmic Discovery[1] offers an excellent perspective on uncovering unique new astrophysical phenomena. Each such object differs in at least one of its physical characteristics (e.g. central density, mass, luminosity) from its nearest neighbor in multi-dimensional, physical parameter-space by at least a factor of 1000. For example; red giants, main sequence stars and white dwarfs are fundamentally different phenomena, while F and G dwarfs are not. The book also makes the point that the discovery of most new classes of astrophysical phenomena demands novel instrumentation that can probe previously unexplored regions of sensitivity, time- or spectral-resolution, or wavelength space. In addition, most such instruments make their most important discoveries within just a few months or years of going online.

Surveys from the Zwicky Transient Facility[2] and GAIA[3] are already detecting an unprecedented number of transients and in South Africa, the MeerKAT[4] radio array and its optical slave, MeerLICHT[5], will soon become fully operational. These two facilities will offer the unprecedented combination of simultaneous radio and multi-band optical coverage of the southern sky, at superb sensitivity levels and spatial resolution. Having a corresponding optical image to accompany every night-time radio observation will open up the regime of simultaneous, short time-scale radio-optical correlations in astrophysical transients: dwarf novae, novae, X-ray binaries, pulsars, fast radio bursts, supernovae, gamma-ray bursts, active galactic nuclei, gravitational wave events and sources yet unknown.

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The next generation of astronomical facilities will provide even larger scale monitoring of extensive regions of the sky to extremely faint limits, over a range of wavelengths and timescales. These future projects include, among others, the Large Synoptic Survey Telescope (LSST)[6], the Wide Field Infrared Survey Telescope (WFIRST)[7], the Cherenkov Telescope Array (CTA), and the Square Kilometer Array (SKA). The resulting surveys will discover vast numbers of transient objects, a small fraction of which may be representative of new phenomena. Low-resolution identification spectroscopy is necessary to classify the sources before more comprehensive follow-up can be done on the most interesting objects.

A key challenge for the next decade is that the astronomical community is facing an overwhelming "impedance mismatch"; these transient surveys will produce a far greater number of transient sources than can be spectroscopically followed up by existing telescopes. Even after the number of sources has been whittled down by smart algorithms that identify the most interesting targets requiring immediate follow-up, the sheer number of remaining objects will still be significantly greater than the current planet-wide spectroscopic follow-up capability. Furthermore, the limited fields-of view of modern 10-m-class telescopes are not well suited to following up a large number of these sources, due in part to the relatively low space density of transient objects.

Telescopes with spherical primary mirrors, however, can deliver an extremely large field-of-view. This has historically been the province of Schmidt telescopes. For example, the 1.2-m UK Schmidt telescope has a field-of-view of 43.6 deg^2 and will next be used for the Taipan survey, a wide field extragalactic spectroscopic survey[8]. For telescopes with a larger primary mirror, the Schmidt design with a single, large optic for correcting spherical aberration at the primary mirror center-of curvature is impractical. The largest field-of-view for a current instrument on a 10-m-class telescope is 1.77 deg^2 for the Subaru Hyper Suprime-Cam[9]. However, spherical primary mirrors have also been used to build cost effective 10-m-class telescopes such as the Hobby-Eberly Telescope (HET)[10] and SALT[11-13], through the use of "field partitioning"[14,15]. In the current design configuration of SALT, all of its instruments are fed by a single spherical aberration corrector mounted on a large prime-focus tracker. The corrector has an instantaneous field-of-view (partitioned field) of about 50 arcmin^2, but the telescope can patrol an area of about 154 deg^2 (14 degrees in diameter) by moving the tracker and corrector to a different location within this area while maintaining the same telescope azimuth.

We propose to increase this patrol area by a factor of six (35 degrees in diameter), and to populate it with four to six positionable mini-trackers. In this paper, we present design concepts for such a system that could potentially return spectra of 10,000-to-15,000 unique transients per year (four to six mini-trackers, each observing ten objects/night, for 250 clear nights/year), without significantly disrupting the telescope's present mode of operation.

1.1 One Example: LSST Transient Alerts

As an example, LSST is expected to produce ~10,000 alerts per minute from a 9.6 deg^2 area of sky. The telescope will typically have about 1000 pointings per night, and these alerts will occur for any object that varies with respect to a previous pointing of the telescope. This will result in tens of millions of alerts per night[4]. The vast majority of these alerts will not need immediate follow-up since many will be known variable stars, previously-discovered solar system objects, etc. However, if even 1% of these objects appear to be interesting, this will still result in perhaps 100,000 objects per night that will benefit from spectroscopic follow-up. These sources will have a space density of approximately 10.5 sources per deg^2.

2. BACKGROUND

Figure 1. SALT, the Milky Way, and the Magellanic Clouds (along with considerable airglow). The distance between the Large and Small Magellanic Clouds, the fuzzy patches in the lower right corner of the image, is about 20 degrees, or approximately 1.5 times the current patrol area of SALT.

2.1 SALT description and operation

SALT is a 10-m telescope located near Sutherland, South Africa, at 32.4°S latitude, 20.8°E longitude. In an economical design adopted from the HET, it has a segmented, spherical primary mirror with 91 hexagonal 1-m segments mounted at a fixed 37 degree zenith angle. The tracker is supported by the telescope structure at a distance of 13 meters above the primary mirror. The tracker holds the spherical aberration corrector (SAC)[16] that delivers an 8-arcmin diameter field-of-view to feed a suite of instruments. The tracker follows an object across the sky during an observation (see Fig. 2), but due to its fixed elevation, there is a limited amount of time that SALT can observe any object. This track time can range from 45 minutes to about four hours, depending on the object's declination. The current instrument suite includes SALTICAM (an acquisition and imaging camera[17]), the Robert Stobie Spectrograph (RSS, a multi-purpose medium resolution spectrograph)[18], the High Resolution Spectrograph (HRS)[19,20] and BVIT (a high time resolution imager)[21].

SALT saw first light in 2005, but severe image quality problems[22,23] and RSS throughput issues led to an extended trouble-shooting, repair and commissioning phase. The telescope began full science operations in 2011 and its scientific productivity has increased steadily since then (with ~200 refereed papers in total as of mid-2018, 49 of which were published during 2017). These outputs, combined with the telescope's extremely low operating costs make SALT the most cost-effective 10-m class telescope[24]. As an entirely queue-scheduled observatory with its full complement of instruments available at all times, and with the option of breaking into the scheduled observing queue at any time with a high-priority target of opportunity, SALT is extremely well suited to observations of transients[17,25-29].

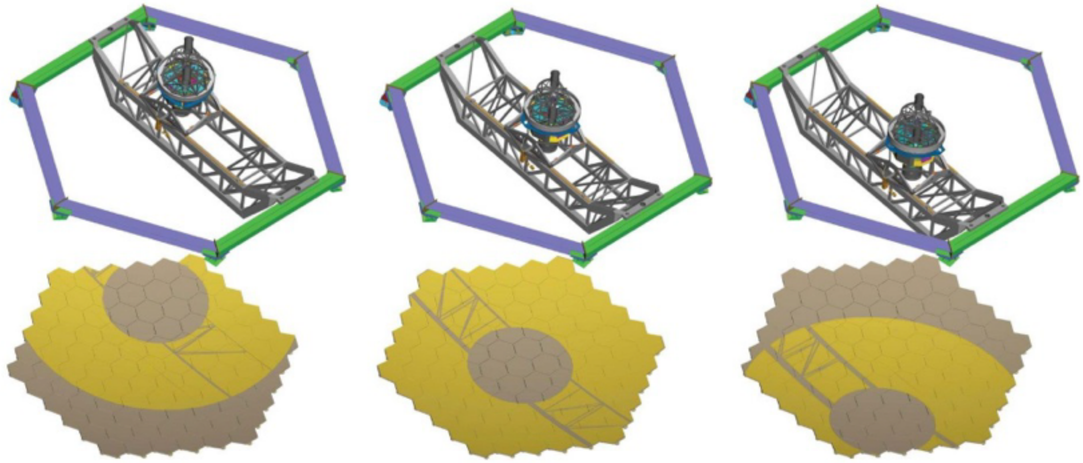

Figure 2. Tracking and effective mirror illumination for a typical SALT observation.

3. SALT AND MINI-TRACKERS

This paper describes a means by which SALT could be augmented and used to provide spectroscopic follow-up of thousands of targets per year, even while executing its normal observing queue.

Observing large numbers of objects simultaneously with a SALT-style telescope will require the following three problems to be addressed:

1) Moving targets, since the SALT primary mirror is stationary during observations
2) Massive spherical aberration, since its primary mirror is spherical
3) Having far more targets in the primary mirror field than the existing SALT corrector, or any practical single corrector and detector system, can possibly acquire and track

SALT, and its predecessor in the Northern Hemisphere, the HET, have solved the first two problems; using a tracking secondary system to follow the target image as it moves along the focal sphere[30,31], and having a SAC to address the second problem. The SALT SAC has an 8 arcmin field-of-view, and HET has recently upgraded its original corrector to a 22 arcmin version for the HETDEX project[32].
We propose to solve the third problem, that of large numbers of interesting targets in the field-of-view of the primary mirror, by attaching a number of small mini-trackers to the main tracker and using all or most of the main tracker's precision motion axes (depending on the concept) to track various objects simultaneously.

4. MINI-TRACKER CONCEPT

4.1 Field partitioning

The idea of correcting small portions of the large uncorrected field-of-view of a spherical primary mirror is not new. Meinel[14] and Burge[15] have described methods of "field partitioning" in cases where the fabrication and mounting of a Schmidt-type corrector plate is impractical (typically, in the cases of large telescopes.)

Both of the above concepts are predicated upon more traditional, fully-steerable telescope designs. In the case of a fixed elevation telescope like SALT, which can only rotate in azimuth between observations, one must trade aperture for field-of- view and for track length. Still, at the edge of SALT's mini-tracker-extended 35 degree diameter field-of-view, the mini-SACs see the equivalent of a 3.5-m telescope aperture.

4.2 What is a “mini-tracker”?

In SALT’s case, the SAC partitions and corrects a relatively small (8 arcmin) field-of-view and can track this field over a range of about 14 degrees of sky. The notion behind the mini-trackers (MT) is that if one could deploy small SACs from the tracker around an expanded field (up to 35 degrees), each with its own “patrol area”, one could potentially then acquire and observe several objects within 10-to-12 degrees of the main SAC boresight of the telescope. In effect, the small SACs could be observing these extra objects “for free”; that is, these observations could be achieved without materially affecting the original observation being performed by the main SAC.

In order to accomplish these observations, each MT would require the following elements:

1) A mini-spherical aberration corrector (MSAC) to bring the highly aberrated image in the prime focus “focal sphere” to a well-corrected, focused image. The MSAC design could be a four-mirror axial design (perhaps a small version of the existing corrector), or an off-axis, two-mirror design[19]. The field-of-view for the MSAC would need to be large enough to normally include a guide star.
2) An acquisition and guiding (AGM) module to acquire and center objects onto an optical fiber bundle, and then maintain focus and tip/tilt alignment.
3) An integral field unit (IFU), consisting of an optical fiber bundle with end treatments appropriate to the final design. This might include a lenslet array or field lens at the input end of the bundle, and a transitioning optical element at the spectrograph end.
4) A low-resolution spectrograph, or part of a spectrograph, suitable for the science objectives of the program.
5) A mechanical deployment mechanism.

Items 1) through 4) above will be largely identical for each MT. Item 5) is the main subject of this study and is treated in section 5, below.

4.3 Mini-spherical aberration corrector (MSAC)

A much smaller version of the current SALT SAC is envisioned as the baseline corrector for the MT heads. This corrector would be approximately 300 mm in diameter and 600 mm long, with an output beam of approximately F/3.5 and a field of approximately 1 arcmin in diameter. Depending on the results of a primary mirror field vs. vignetting study, it could have an effective aperture when fully filled of between 7-and 10-m. The four reflective elements would be fabricated from either diamond-turned aluminum and overcoated for lowest cost, or else figured from low-expansion optical glass blanks.

As an example, a small two-mirror, diamond-turned aluminum SAC called the “Surrogate SAC” was designed[33] and built in the mid-1990s and successfully used in early shakedown and testing of the HET. The Surrogate SAC is 355 mm in diameter, 472 mm long, and weighs 25 kg. It has an entrance aperture of 9.2-meters and an output focal ratio of F/1.8 (see Fig. 3).

Figure 3. The “Surrogate SAC” used on the HET in the late 1990s.

4.4 Acquisition and guiding module (AGM)

The AGM is comprised of an optical and a mechanical subsystem. The optical subsystem will consist of a simple imaging camera, wavefront sensor, and associated optics that can acquire and center target objects on the IFU bundle. The wavefront sensor will sense focus and local tip/tilt errors of the MT. The mechanical alignment subsystem will consist of a small precision rotation stage to which the SAC is mounted, and a small commercial hexapod assembly on which the rotation stage is mounted.

The rotation stage will de-rotate the sky, and the hexapod will receive processed commands from the optical subsystem and maintain focus and tip/tilt alignment. The hexapod will also receive very small Right Ascension (RA) and declination (dec) guiding commands from the optical subsystem to maintain the object's position on the IFU. Since the hexapod can be programmed to rotate about virtually any point in space, the rotation point will most likely be about prime focus, which will eliminate "crosstalk" between tip/tilt and guiding commands.

4.5 IFU bundle

An IFU consisting of optical fibers will transmit the target object's light from the MT "head", along the deployment mechanism, and back to a small spectrograph mounted on the tracker payload within the central obscuration of the main corrector. The HETDEX project at McDonald Observatory now has a great deal of experience producing and safely deploying armored fiber bundles from a moving corrector to fixed spectrographs on the HET, and it is anticipated that this experience can be used to good advantage for the MTs.

4.6 Spectrograph

A small, low-resolution (R=1000) spectrograph, such as the one under development by SALT called MaxE[34], would be ideal to produce spectra of target objects from each MT. A small number of such spectrographs rack-mounted in an enclosure on the SALT payload assembly would minimize fiber length and maximize the amount of light reaching each instrument.

5. DEPLOYMENT MECHANISM CONCEPTS

5.1 General

There are a number of methods that can be used to deploy the MT heads described in the previous section, each having advantages and disadvantages. We have considered more than a dozen different approaches, and have narrowed the field down to what we believe are the five most practical concepts. Of the five concepts described in this paper, the first two concepts (PMRA, or Payload-mounted Robot Arm, and PMXY, or Payload-mounted X-Y Stage) are nearly identical to the second two concepts (CMRA, or Carriage-mounted Robot Arm, and CMXY, or Carriage-mounted X-Y Stage), differing only in their mounting points.
The fifth concept deploys from two to four additional "Y" rails off the main tracker beam, and the MT heads are supported and positioned by a substage on these rails.

Note: For the purposes of this concept study, "tracking" refers to movement in tracker X, Y, tip, and tilt. Sky de-rotation is accomplished open-loop using individual rotation stages in each MT head, and focus is sensed and maintained locally by the MT head.

Each variant has a slightly different "patrol area", or section of the entire SALT field that is accessible at any given time, given the main tracker position.

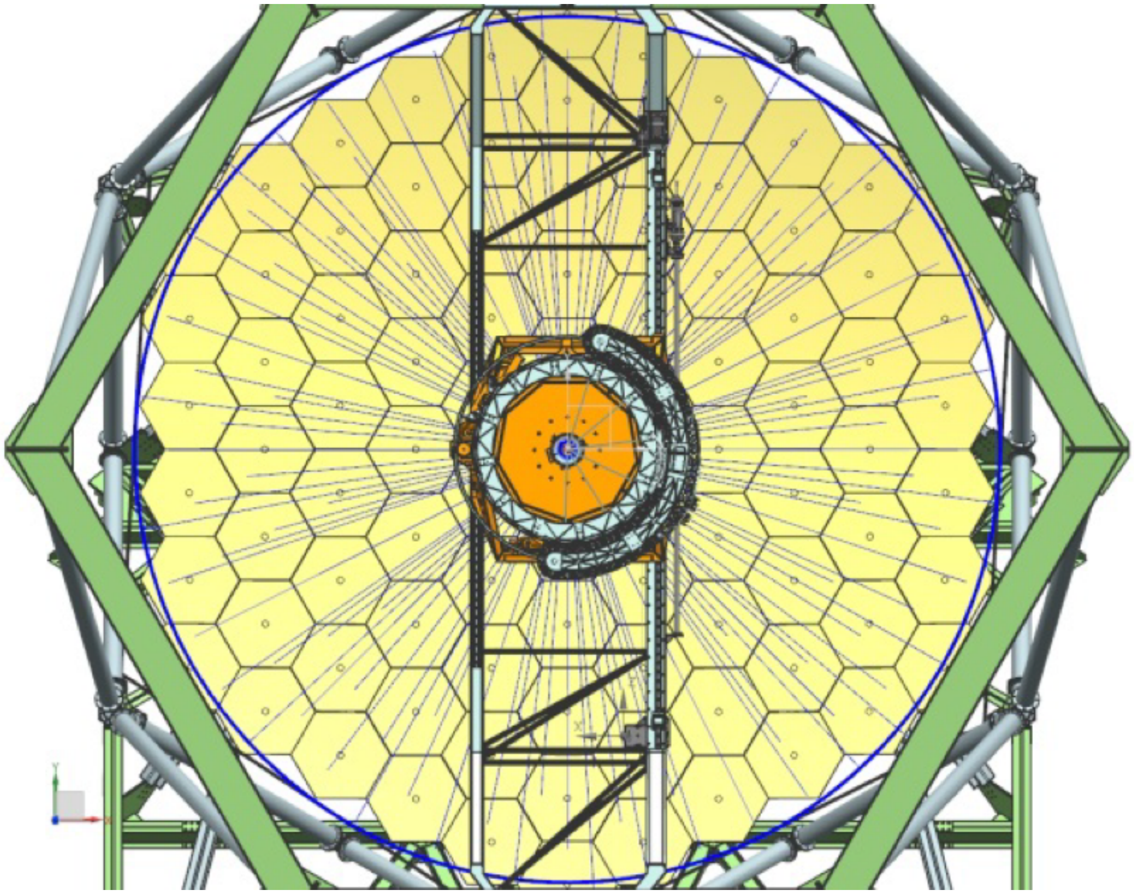

Figure 4. View “down the barrel” of SALT, showing the 91-hexagonal segment primary mirror array and the existing tracker structure and payload at center (spanning the upper structural hexagon from top to bottom in the figure). Light rays are shown as lines radiating inward from the primary mirror to the payload.

5.2 Concept PMRA – Payload-mounted Robot Arm

Robotic swing arms mount to the Non-Rotating Structure (NRS) of the Tracker Payload, and position the MT heads on the focal sphere, on desired targets. No additional tracking is required since the MT is effectively mounted to the upper end of the tracker hexapod. Only small guiding and tip/tilt/focus corrections are necessary, accomplished autonomously by the MT control system.

An important advantage of this concept is simplicity of operation. The MT head can be moved to a target on the focal sphere and the positioner fixed in place for the duration of an exposure. The MT head will acquire and center the target, and using its imager, wavefront sensor, and small hexapod, will guide in RA and declination, and maintain focus.

Shown below in Figs 5 and 6 are schematic diagrams of a “R-Theta” type mechanism, in which the arm is pivoted from a rotating base mounted to the payload (Theta motion), and a single axis stage (R or radial motion) is translated to position the MT head to the target. The patrol area for each arm is about 16 deg^2.

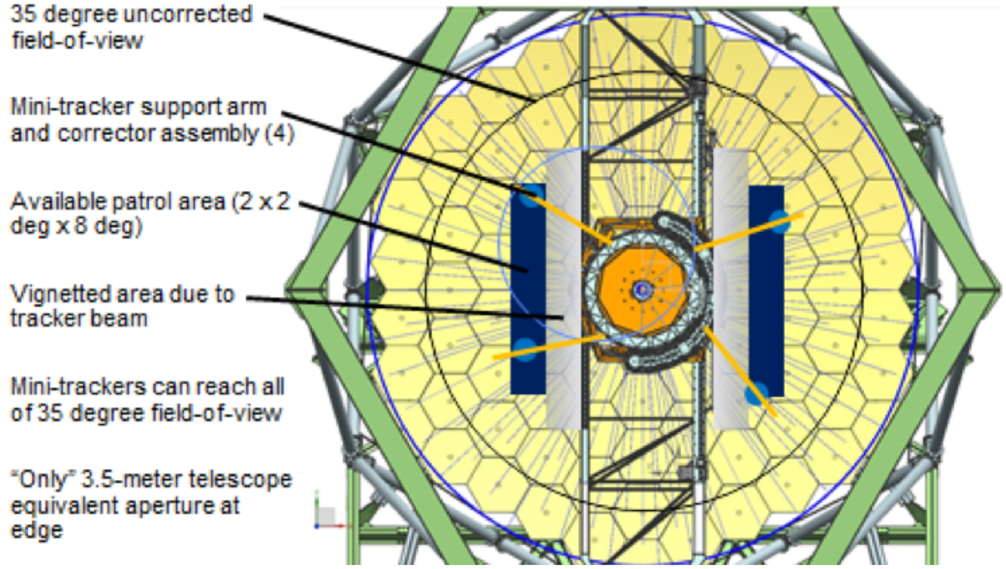

Figure 5. Concept PMRA - Payload-mounted Robot Arm, Top View. Note that the robot arms extending radially from the Payload center can swing through about 270 degrees of rotation.

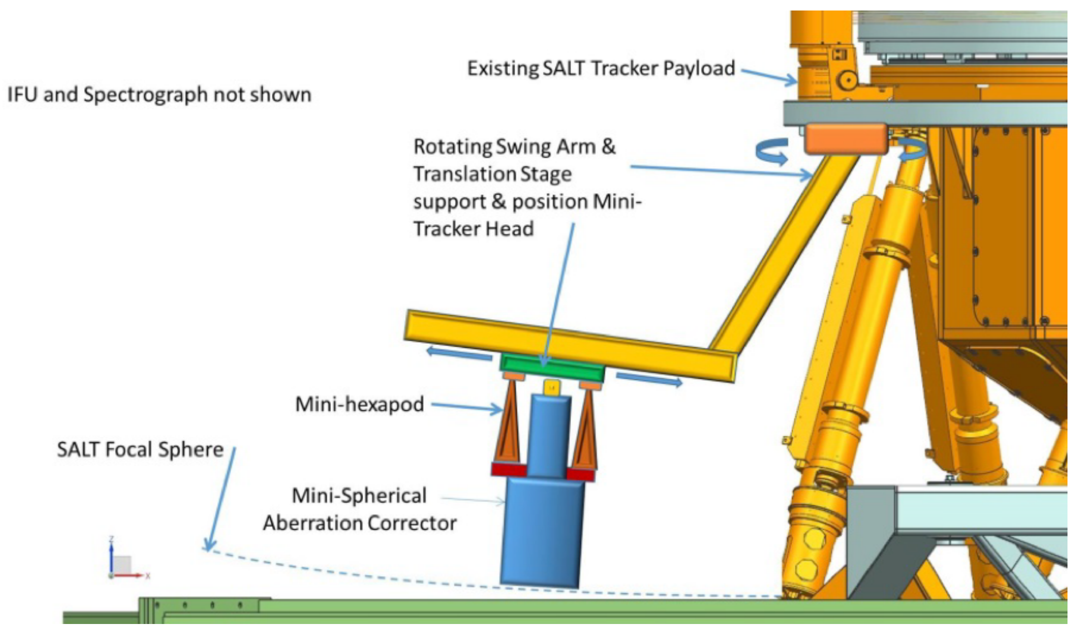

Figure 6. Concept PMRA - Payload-mounted Robot Arm, Side View.

5.3 Concept PMXY – Payload-mounted X-Y Stage

A large, "thin" rectangular X-Y gantry stage mounts to the NRS on fixed struts above the level of the focal sphere (see Figs 7 and 8). MT heads are positioned around the patrol areas using the gantry stages and fixed in place on each target. As in Concept PMRA above, no additional tracking is required, only small guiding and tip/tilt/focus corrections are necessary, accomplished autonomously by the MT control system.

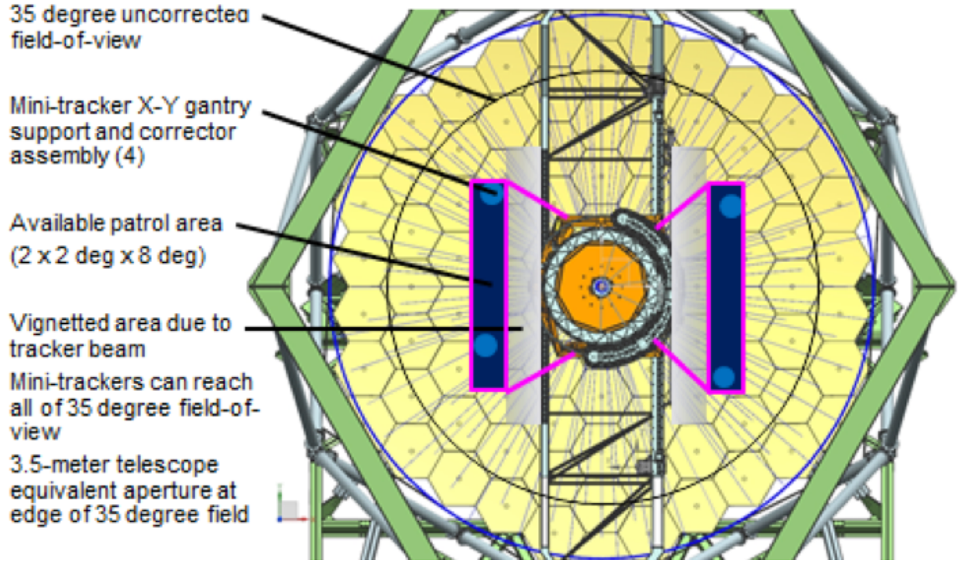

Figure 7. Concept PMXY Payload-mounted X-Y stage. Mini-correctors can roam about the available patrol areas on small gantry stages. (The side view of this concept is nearly identical to Fig. 6, where the swing arms become support struts for the X-Y gantry stage.)

5.4 Concept CMRA – Carriage-mounted Robot Arm

Since they are mounted on the carriage rather than the payload, both this concept and Concept CMXY – Carriage-mounted X-Y Stage below require tip/tilt tracking to keep the MT head normal to the focal sphere. They also require tracking in focus, and the depth of the focal sphere at the corner of the proposed patrol area, 12 degrees from the tracker center of travel, is about 290 mm. This is beyond the range of a typical commercially-available hexapod, and a custom-built hexapod or separate Z stage may be required.

Mounting the device on the tracker carriage appears to be simpler and more straight-forward mechanically than mounting it on the tilting part of the Payload, and a more detailed mechanical study is required to make this trade.

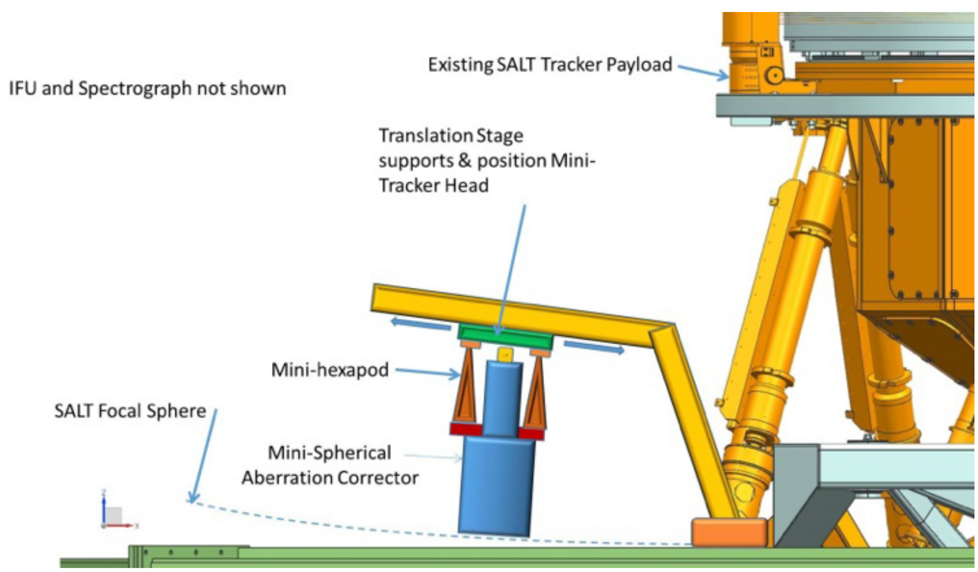

Figure 8. Concept CMRA – Carriage-mounted Robot Arm. The robot arm is mounted to the carriage as shown, and swings through similar arcs to those shown in Fig. 5.

5.5 Concept CMXY – Carriage-mounted X-Y Stage

Similar to Concept PMXY but mounted to the tracker carriage rather than the payload, this concept provides a large gantry stage to position the MT head, but the head must include tip/tilt tracking motion and a large tracking focus range as with Concept CMRA, above. Again, either a longer travel hexapod (300 mm plus tip/tilt simultaneously) or a separate Z stage is required. Schematic diagrams of this concept are essentially identical to Fig. 5, the top view of the payload-mounted X-Y stage, and Fig. 8, the Carriage-mounted robot arm side view, where the robot arm shown in Fig. 8 just becomes a set of static support struts for the X-Y stage.

5.6 Concept TBXY – Tracker Beam-mounted X-Y Stage

Concept TBXY (not illustrated) mounts a smaller Y-beam on a parallelogram mechanism on either side of the main Y tracker beam. An MT head is mounted on a small Y-carriage which travels up and down the smaller Y-beam. Positioning in the X direction is accomplished with the parallelogram deployment mechanism, and this is fixed relative to the tracker beam once the MT head is positioned on a target. This would allow similar coverage to the two 2 x 8 degree dark rectangles shown in Figs 5 and 7, but would require a driven Y-stage for each MT, along with the tip-tilt and large focus requirements of the carriage-mounted concepts.

This concept would only be considered if insurmountable difficulties were encountered with each of the first four concepts described above.

6. DISCUSSION OF DEPLOYMENT CONCEPTS

6.1 Field coverage vs. mirror illumination for an MT

It is important to note that all of the above MT deployment concepts must work around the existing tracker, which is of course optimized to take advantage of the "fattest" part of the primary mirror during a typical observing track, as shown in Fig. 2. Assuming for the moment a 10-m aperture MT SAC, the closest an MT can be positioned to the existing SAC is about 8.5 degrees without vignetting from the lower structural members of the main tracker beam (see Fig. 9).

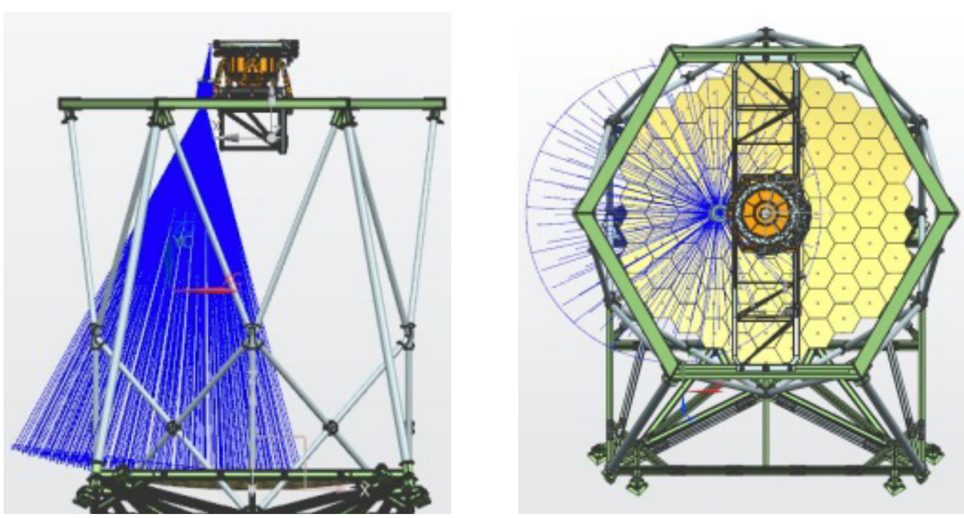

Figure 9. Nearest position of an MT SAC to the tracker beam, front and top views.

Let us look at a typical example: If the tracker starts a full track from the extreme left position, for instance (7 degrees from the above centered position), the MT starts the track at 15.5 degrees, and sees only about 18 primary mirror segments initially. This is the equivalent of a 4.7-m aperture Ritchey-Chrétien telescope, and things do not get better very fast for the MT, owing to the presumed ~4-m diameter central obscuration of the MSAC. This obscuration, mapped to the primary mirror, begins to appear on the primary soon after the beginning of the track. For more outboard patrol positions of the MT, the illumination becomes even worse, diminishing down to virtually no light at the extreme corners at the beginning or end of certain tracks (these positions become useful as the tracker approaches the center.) Hence, target selection, based on brightness, and taking the total effective aperture into account, will be critical to the successful operation of the MTs.

6.2 Optimal Deployment Concept

Concept PMRA, the Payload-mounted Robot Arm, appears to be the optimal concept considered in this study, from the standpoint of simplicity of design and operation. The payload performs all of the tracking operations except sky de-rotation, which is easily accomplished by mounting the MT SAC on a commercially-available rotation stage. Once developed, the design can be prototyped and thoroughly tested off-telescope, then mounted on the telescope payload with minimal interference to operations for additional testing.

At this very early concept stage it appears possible to mount four such MTs to the payload, and perhaps as many as six. There are several possible configurations for the robot arm design itself (note that the concept shown only rotates from its mounting point on the payload, and has no other articulation).

Concept PMXY, the Payload-mounted X-Y stage, has similar advantages to the above concept, but is a larger assembly that may be more difficult to prototype and mount on the payload. It would likely obscure slightly more of the primary mirror that the robot arm concept, and the outer corners of the stage will be less useful from an effective aperture standpoint.

Concepts CMRA and CMXY, similar to Concepts PMRA and PMXY but mounted to the carriage, and Concept TBXY, the tracker beam-mounted concept, would only be pursued if one of the first two concepts were for some reason impractical to implement, owing to the additional complexity in tracking with these last three concepts.

7. NEXT STEPS

This small study of possible MT configurations and deployment concepts for SALT has been extremely limited in scope. We have attempted to lay out the most promising MT deployment concepts that could be adapted to SALT in a practical way. Clearly there is much work to be done for this capability to become a reality. An initial feasibility study that would address, at a minimum, the following issues in more detail seems to be the logical next step:

1) Transient science trade study to include trades of number of MTs, field, range of motion, and patrol field and track length vs. effective telescope aperture
2) MT SAC design and trade study:
   - Diamond-turned vs. glass mirrors, optical coatings, cost
   - Field size vs. SAC size, effective aperture, and mass
   - Need for internal moving baffle or telescope structure baffling
3) Optical and mechanical design development of acquisition and guiding module and IFU bundle and routing
4) Deployment mechanism design development options, trade study:
   - Mechanical stability, flexure analysis, windshake analysis
   - Maximum feasible and affordable number of MTs
   - Field coverage vs. primary mirror illumination, cost
5) Preliminary project plan, project cost, and schedule

8. CONCLUSION

Upcoming large-scale surveys associated with MeerKAT/MeerLICHT, LSST and SKA will soon begin identifying enormous numbers of transients. A substantial fraction of these will require rapid spectroscopic follow-up observations to identify the most interesting objects for more detailed study. A subset of these targets will undoubtedly represent entirely new astrophysical objects/phenomena, while others will contribute statistics to fill in gaps in our current understanding of particular types of sources and events.

Present and planned future facilities will not be able to keep pace with the alert streams predicted to accompany these surveys and so the development of new optical spectroscopic follow-up capabilities is essential. Given SALT's location in the southern hemisphere, its close proximity to MeerKAT (and the future SKA) and MeerLICHT (which is located at the same observing site as SALT), it is clear that there is a significant niche to be exploited here.

Additional work is necessary to fully develop the SALT mini-tracker concept explored in this paper. However, this initial study indicates that there may be a relatively straightforward way for SALT to take strategic advantage of its unconventional design. A set of deployable mini-trackers would allow us to capitalize on the huge uncorrected field-of-view of the telescope's primary mirror and at least quadruple the number of targets simultaneously observable by Africa's Giant Eye. If we hope to take advantage of the ground-breaking surveys on the horizon, we would need to complete a formal design study and build a working prototype mini-tracker within the next two years.

Figure 10. SALT at sunset.

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