Science case for mini-trackers on SALT

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Deploying 4 mini-trackers (MTs) on SALT, each with a $\simeq$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 γ-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 γ-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 $\sim$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 21st 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 21st magnitude, but the transient recovery efficiency dropped steeply from $\simeq$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 $\sim$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, $\sim$40 out of a total $\sim$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).

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[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 $\sim$1000 sq.deg.; e.g. Abbott et al. 2020) needs to imaged and searched for transients. In the case of optical follow-up 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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