

PROCEEDINGS OF SPIE

SPIDigitalLibrary.org/conference-proceedings-of-spie

Multi-object spectroscopic operations with the Sloan Digital Sky Survey V

Sánchez-Gallego, José, Sayres, Conor, Donor, John, Almeida Toro, Andrés, Araujo, Ricardo, et al.

José R. Sánchez-Gallego, Conor Sayres, John Donor, Andrés Almeida Toro, Ricardo Araujo, Luzius Kronig, Loïc Grossen, Richard Pogge, Stefanie Wachter, Solange Ramírez, Joel Brownstein, "Multi-object spectroscopic operations with the Sloan Digital Sky Survey V," Proc. SPIE 11449, Observatory Operations: Strategies, Processes, and Systems VIII, 114490O (13 December 2020); doi: 10.1117/12.2561810

SPIE.

Event: SPIE Astronomical Telescopes + Instrumentation, 2020, Online Only

Multi-object spectroscopic operations with the Sloan Digital Sky Survey V

José R. Sánchez-Gallego^a, Conor Sayres^a, John Donor^b, Andrés Almeida Toro^c, Ricardo Araujo^d, Luzius Kronig^d, Loïc Grossen^d, Richard Pogge^e, Stefanie Wachter^f, Solange Ramírez^f, and Joel Brownstein^g

^aUniversity of Washington, Dept. of Astronomy, Seattle, WA USA 98195-0002

^bTexas Christian University, Dept. of Astronomy, Fort Worth, TX USA 76129

^cUniversity of La Serena, Dept. of Astronomy, La Serena, Chile

^dEcole Polytechnique Fédérale de Lausanne, Laboratoire d'Astrophysique (LASTRO), CH-1015, Lausanne, Switzerland

^eThe Ohio State University, Dept. Of Astronomy, Columbus, OH, USA 43210-1173

^fCarnegie Institution for Science, 813 Santa Barbara Street, Pasadena, CA 91101, USA

^gUniversity of Utah, Dept. of Physics and Astronomy, Salt Lake City, UT USA 84112

ABSTRACT

The Sloan Digital Sky Survey V (SDSS-V) is an all-sky spectroscopic survey of more than 6 million objects, designed to decode the history of the Milky Way, reveal the inner workings of stars, investigate the origin of solar systems, and track the growth of supermassive black holes across the Universe. SDSS-V presents significant innovations in both hardware and software, chiefly due to the introduction of a robotic Focal Plane System (FPS) that replaces plug-plate operations. This new mode of operations introduces new challenges with respect to target scheduling, fibre robot positioner reconfiguration optimisation, telescope guiding, observer interfaces, and observatory operations. During normal operations SDSS-V will observe a new field every 15 minutes. For each field requiring a new telescope pointing the FPS will reconfigure 500 robotic fibre positioners with feedback from an external Field Viewing Camera (FVC) in less than two minutes. Six CCD cameras mounted on the FPS will be used to automatically acquire the field and maintain the necessary guiding accuracy. These strict requirements highlight the need for streamlined operations software and procedures to minimise the time spent during FPS reconfigurations. We describe the overall design and implementation of the SDSS-V survey operations, with special emphasis on software development, conventions, and observing procedures. While specific to SDSS-V, the solutions we describe can be readily applied to other astronomical surveys and are of special interest given the rapid increase in projects employing robotic fibre positioners.

Keywords: SPIE Proceedings operations SDSS software scheduling robotic fiber positioner

1. INTRODUCTION

The Fifth iteration of the Sloan Digital Sky Survey (SDSS-V, Kollmeier et al.¹) will provide all-sky, multi-epoch spectroscopy of over 6 million objects ranging from stars in our Solar neighbourhood to black holes in other galaxies. Its two main scientific programs, the Black Hole Mapper (BHM) and the Milky Way Mapper (MWM) will shine new light on our understanding of the chemical composition of stars, the formation of solar systems, and the growth of supermassive black holes.

SDSS-V will replace the plug-plate system that has been used with extreme success for the last 25 years with a new Focal Plane System (FPS). The FPS will deploy 500 state-of-the-art robotic fibre positioners that enable a full reconfiguration of the focal plane in fewer than two minutes, thus enabling a whole new series of time-domain explorations.

Further author information: (Send correspondence to José Sánchez-Gallego)
José Sánchez-Gallego: E-mail: gallegoj@uw.edu

In addition to the BHM and MWM, SDSS-V will also obtain wide-field integral field spectroscopy of large regions in the Milky Way, the Magellanic Clouds, and the Local Group as part of the Local Volume Mapper program. The LVM instrumentation and procedures are not described as part of this paper (instead, see Konidaris et al.² in these proceedings).

2. INSTRUMENTATION

2.1 Telescopes

All the multi-object spectroscopic observations carried out by SDSS-V will make simultaneous use of the Sloan 2.5-metre Telescope (Ref. 3) at Apache Point Observatory (APO) in New Mexico, and the 100-in du Pont Telescope at Las Campanas Observatory (LCO) in Chile (Ref. 4). Both telescopes share a Ritchey-Chrétien design. The Sloan 2.5m telescope has an effective focal ratio $f/5$ which results in a field of view of approximately 3 degrees. The DuPont telescope is an $f/7.5$ with a Gascoigne corrector lenses, resulting in a slightly smaller 2.1 degree field of view.

As part of the enhancements planned for SDSS-V, the existing non-telecentric Gascoigne corrector lenses in the Sloan telescope will be replaced with a telecentric 3-element corrector. The new corrector also optimises image performance and coatings for the H-band, which were suboptimal with current corrector.

Images and diagrams of the Sloan and DuPont telescopes, and of the new corrector are shown in Figure 1.

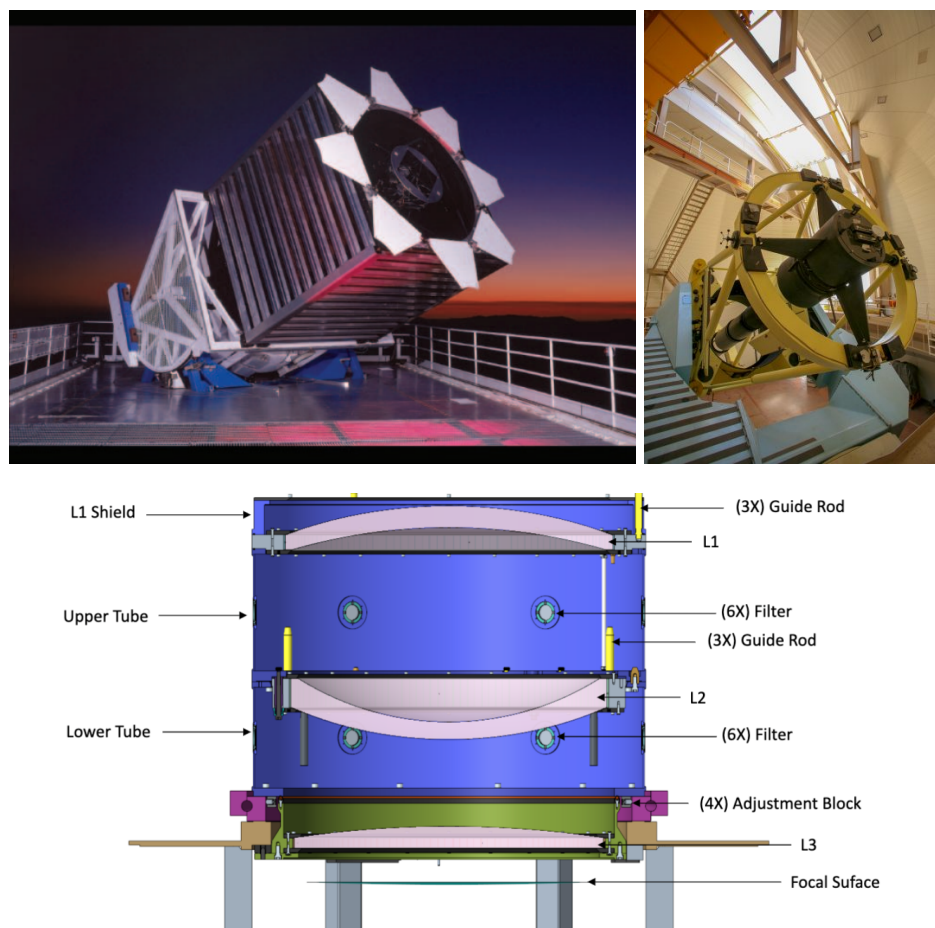


Figure 1. The Sloan 2.5m Telescope (upper left), the DuPont Telescope (upper right), and the diagram for the new corrector for the APO telescope (bottom).

2.2 Spectrographs

Each one of the SDSS-V telescopes will make use of two identical BOSS and APOGEE spectrographs.

The two BOSS spectrographs (Smee et al.⁵) provide coverage for $360\ \mu\text{m} < \lambda < 1000\ \mu\text{m}$ with resolving power $R \sim 2000$ for a total of 1000 $120\ \mu\text{m}$ optical fibres. Currently both BOSS spectrographs are in use at the Sloan 2.5m telescope. As part of the SDSS-V preparations, one of the spectrographs will be relocated to the du Pont telescope in Chile. The spectrographs are mounted at the rotator on each telescope, thus minimising throughput losses due to fibre length. We will take advantage of the need to ship the spectrograph to replace the mechanical and CCD controllers and to develop new control software. The same upgrades will be performed on the spectrograph that will remain at APO at a later time.

Two APOGEE spectrographs (Wilson et al.⁶) provide near-infrared coverage in the range $1.51 - 1.70\ \mu\text{m}$ with $R \sim 22,500$, each one accepting up to 300 fibres. The spectrographs are bench-mounted and housed on a different room. The fibre link from the spectrograph is routed to the telescope and groups of 30 fibres each are assembled in an MTP connector. The resulting 10 MTP connectors are housed in a “gang connector” that is then plugged to the telescope-side fibres.

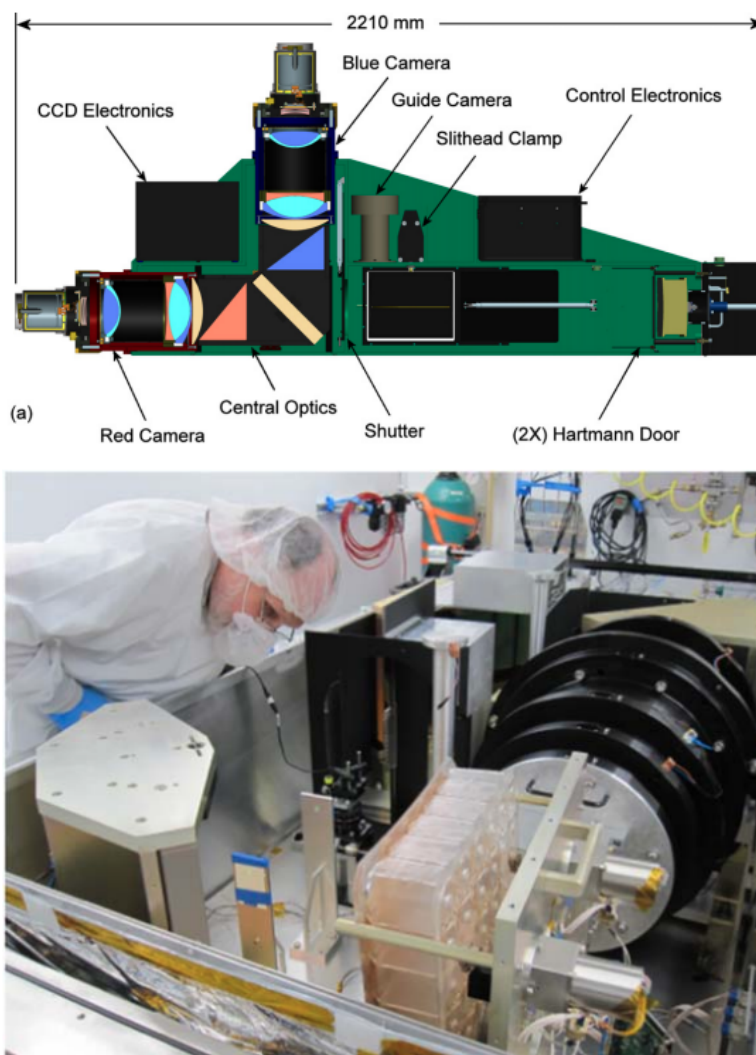


Figure 2. Section view of one of the BOSS spectrograph showing the optical and mechanical components (top) and a view of the APOGEE spectrograph during laser alignment of the fore-optics (bottom).

2.3 Robotic fibre positioners

The robotic fibre positioners used for the SDSS-V Focal Plane System are described in detail in Araujo et al.⁷ in these proceedings and in Kronig et al.⁸ We use a “theta-phi” design with two serial arms of 7.4 and 15 mm, respectively, which provides full coverage of an annular region from 7.4 to 22.4 mm (see Figure 3). While a given positioner cannot reach its own centre, the positioners are packed together in a way that neighbouring positioners can reach the centres of other positioners.

Approximately 1200 positioners will be produced for use in SDSS-V, 1000 of which will be used to populate the two Focal Plane Systems at APO and LCO, while the remaining 200 will be used as spares. The positioners are individually calibrated and characterised to determine the exact arm lengths, centres of rotation, tilt, and the non-linearity parameters of the gear boxes. The calibration strategy and results are detailed in Grossen et al.⁹ (these proceedings).

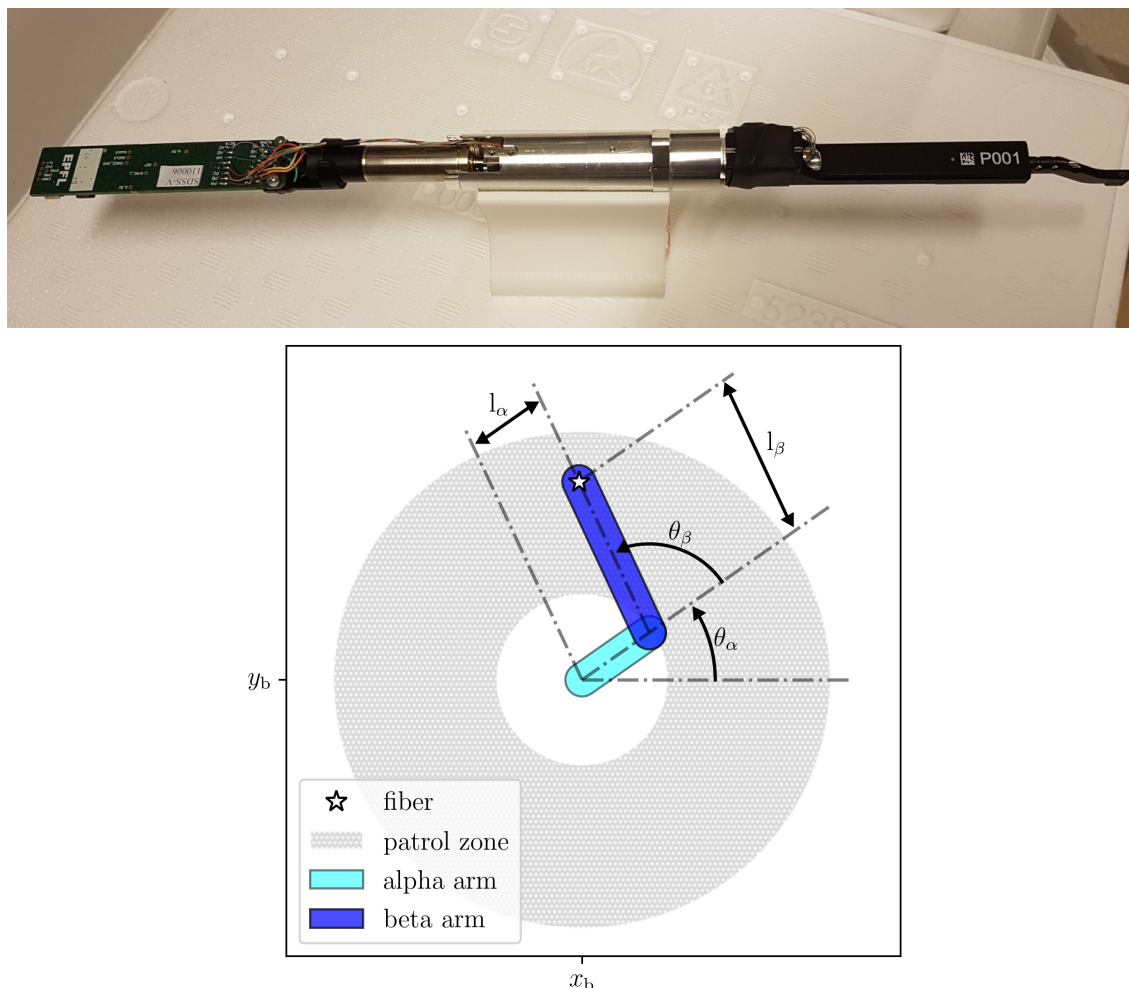


Figure 3. Top: one of the first production-series positioners. Bottom: patrol area of the SDSS-V positioners, reproduced from Sayres et al.¹⁰

Each positioner carries three fibres, one attached to the BOSS spectrograph, one to the APOGEE spectrograph, and a back-illuminated calibration fibre. The three fibres are assembled in a fibre-in-glass capillary ferrule and their positions with respect to the calibration fibre, as well as the vertical position of the ferrule with respect to the positioner arm, are carefully measured.

The positioners are connect to a dedicated Controlled Area Network (CAN) that is used to send commands and receive replies and statuses. Groups of 20 or 21 positioners are connected together to a single CAN bus. The CAN network is accessed via an ethernet-to-CAN device, which connects it to the larger observatory network.

While the majority of today’s fibre positioner arrays are designed such that a target in the focal plane is generally accessible to only a single positioner, SDSS-V has selected a densely packed fibre positioner layout with heavily overlapping workspaces. Astronomical targets in SDSS-V will be generally accessible to multiple overlapping positioners, thus optimising the options for target assignment. However, this approach suffers from a higher risk of entanglement and collisions between positioners during motion.

The KAIJU package* provides collision avoidance routines that allow for safe FPS configuration transitions. The algorithm is described in Sayres et. al¹⁰ (submitted to AJ). Figure 4 provides a high-level picture of the algorithmic strategy. The array is initialized to the desired configuration. Small perturbations are applied to each positioner in turn such that the collective array is driven to a final “folded” lattice-like state. The forward path is then found by a simple reversal of the solved trajectory. As all paths are built between a desired configuration and common folded state, valid transitions between any two configurations are trivially achieved. The routines compute paths in a matter of seconds, equipping the FPS with the capability of real-time path generation. The duration of robot motion during reconfiguration is on the order of 30 seconds. The efficiency of the routine is not perfect, but it is very high. We expect an average loss of less than one target per configuration due to collision avoidance constraints. While developed for SDSS-V, the algorithm is generally applicable to any set of overlapping positioners that use a phi-theta configuration.

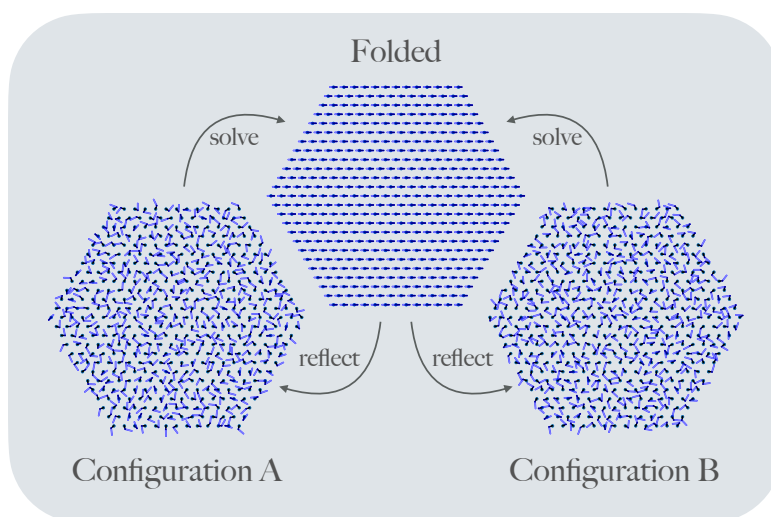


Figure 4. A schematic view of how KAIJU determines a save transition between configurations A and B via an intermediate “folded” state.

2.4 Focal Plane System

At each telescope, the FPS provides the housing for the robotic fibre positioners and replaces the current plug-plane cartridge system. The FPS is reviewed in detail in these proceedings in Pogge et al.¹¹

Figure 5 shows a model of the FPS with its main components. 500 positioners are uniformly spaced on a slightly bent metal surface that approximates the shape of the focal plane at each telescope. The BOSS fibre assemblies are routed to a slithead mounted on the FPS which feed the BOSS spectrograph while the APOGEE fibres are grouped into MTP blocks that are connectorised to the APOGEE spectrograph via the gang connector. While all the positioners carry an APOGEE fibre, only 300 of them are actually connected to the APOGEE fibre link. The FPS electronics boxes provide the power supply, relays, logic and CAN controllers, and environmental sensors.

*<https://github.com/sdss/kaiju>

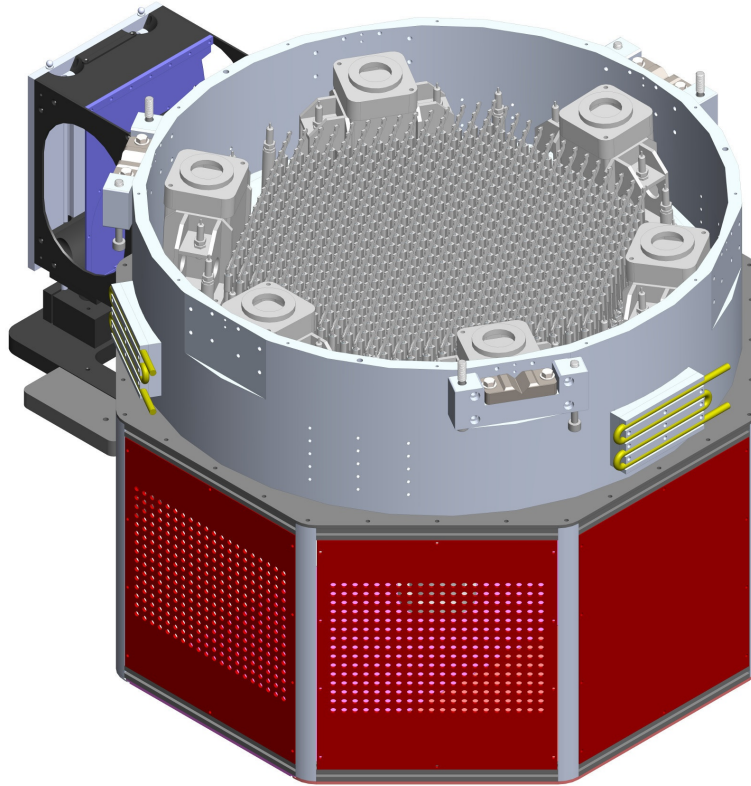


Figure 5. Model of the FPS including the 500 robotic fibre positioners, fiducials, guide cameras, as well as the cooling and latching systems and the BOSS slithead.

Along with the positioners there is a set of 72 back-illuminated fiducial fibres (FIF), distributed across the focal plane and on its periphery. During positioner reconfiguration, a Field Viewing Camera (FVC) looks “down” to the FPS through the telescope optical system and images the back-illuminated metrology fibre on each robot as well as the FIFs. This feedback system allows to solve for the real position of the science fibres and, if needed, command positioner offsets until the desired positioning accuracy has been reached.

Six Guide, Focus, and Acquisition (GFA) MK4340 cameras are distributed at the edge of the focal plane. Each one carries an e2v CCD42-40 $2K \times 2K$ pixel sensor with a $13.5 \mu m$ pixel and a field of view of ~ 7.5 arcmin at the Sloan telescope and 5 arcmin at the du Pont. All the cameras are equipped SDSS r-band filters, and two of the cameras have filters of different thicknesses to produce intra- and extra-focal images that are used for focusing. Each camera is connected over USB-2 to a dedicated small-form computer that runs the software for image acquisition and readout and that is connected to the observatory network.

3. TARGET SELECTION

The wide ranging scientific goals of the MWM and BHM programs translate into a variety of subprograms, each one with specific target selection needs. In addition different subprograms (and even different targets selected from the same subprogram) may have independent and sometimes conflicting requirements for the number of observations and the cadence between observations (we define an observation as a valid 15-minute exposure).

Our approach to target selection is based on the following requirements:

1. All targets must be selected from parent catalogues that have been published in a peer-reviewed journal.
2. The list of all potential targets must be cross-matched to produce a list of unique targets.

3. The targets for each subprogram, or “carton”, must be selected using an algorithm that relies only on the available parent catalogues.
4. The process must be versioned in a way that any target selection run can be reproduced in the future.

3.1 Parent catalogues and cross-matching

The process of parent catalogue processing and cross-matching is conceptually defined in the flowchart in Figure 6. The data is first loaded as new tables into a PostgreSQL database named. A table `catalog` in that database is populated with a list of the unique targets, which receive an internal unique identifier `catalogdb` (a 64-bit unsigned integer). If provided by the parent catalogue, we use proper motions to propagate the target coordinates to ICRS epoch 2015.5 (selected to match Gaia DR2).

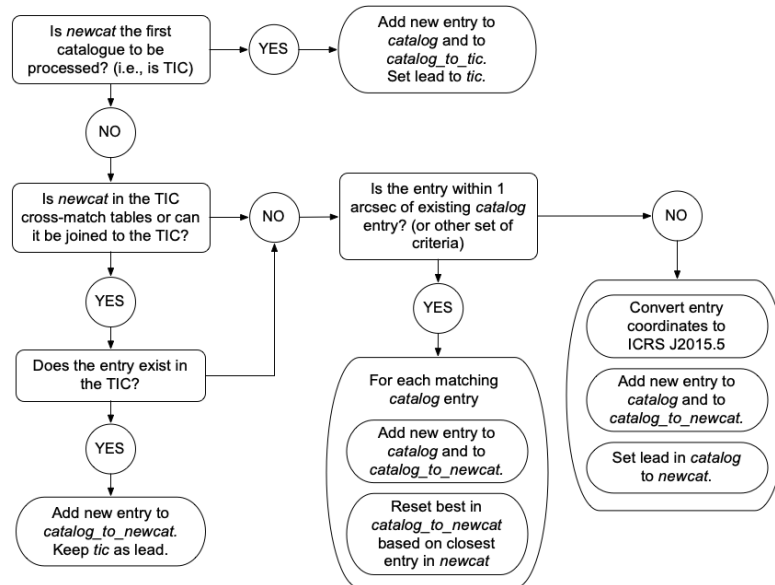


Figure 6. Flowchart for the process of catalogue ingestion into catalogdb and cross-matching.

Each parent catalogue is processed in order, starting with the TESS Input Catalog (TIC; Keivan et al.¹²) that we adopt as our base catalogue. The TIC is fully ingested into `catalog` and we consider that all their targets are unique. TIC coordinates are already in 2015.5 epoch. `catalogid` unique identifiers are assigned sequentially.

For each additional catalogue we first identify already existing joins with the TIC or other catalogues, i.e., cross-matches from the literature that we trust. The targets that can be joined to entries already in `catalog` are added to a `catalog_to_<parent>` table that relates each unique target with the associated record(s) in the parent table.

For targets that cannot be matched this way we do a spatial cross-match between the parent catalogue and `catalog`. Targets that are within a radius of X arcsec (where X can be adjusting depending on the resolution of the parent catalogue) are considered to be the same and are associated in the relational table. If multiple targets are associated with an existing entry in `catalog`, all of them are added to the relational table and the closest one is marked as the best match.

Finally, targets that cannot be linked or cross-matched are assumed to be new unique targets and added to `catalog`, propagating their coordinates to epoch 2015.5 if needed.

This approach has two main limitations. Firstly, the order in which the parent catalogues are processed can have a significant effect on the resulting cross-match. This caveat can be addressed by ingesting catalogues with high spatial resolution (optical) before those with lower resolution (infra-red, UV, radio). Secondly, only spatial information is used in the cross-match. In future revisions of the target selection procedure we aim to implement

a more sophisticated approach based on Bayesian distributions that incorporate priors such as the magnitude or colour distributions.

3.2 Carton implementation

Each science subprogram is implemented as a SQL query that uses the tables in `catalogdb` to produce a list of targets (defined by their `catalogid`) and associated observing information (astrometry, number of observations, cadence, preferred spectrograph). This information is stored in a new database `targetdb`, whose schema is shown in Figure 7.

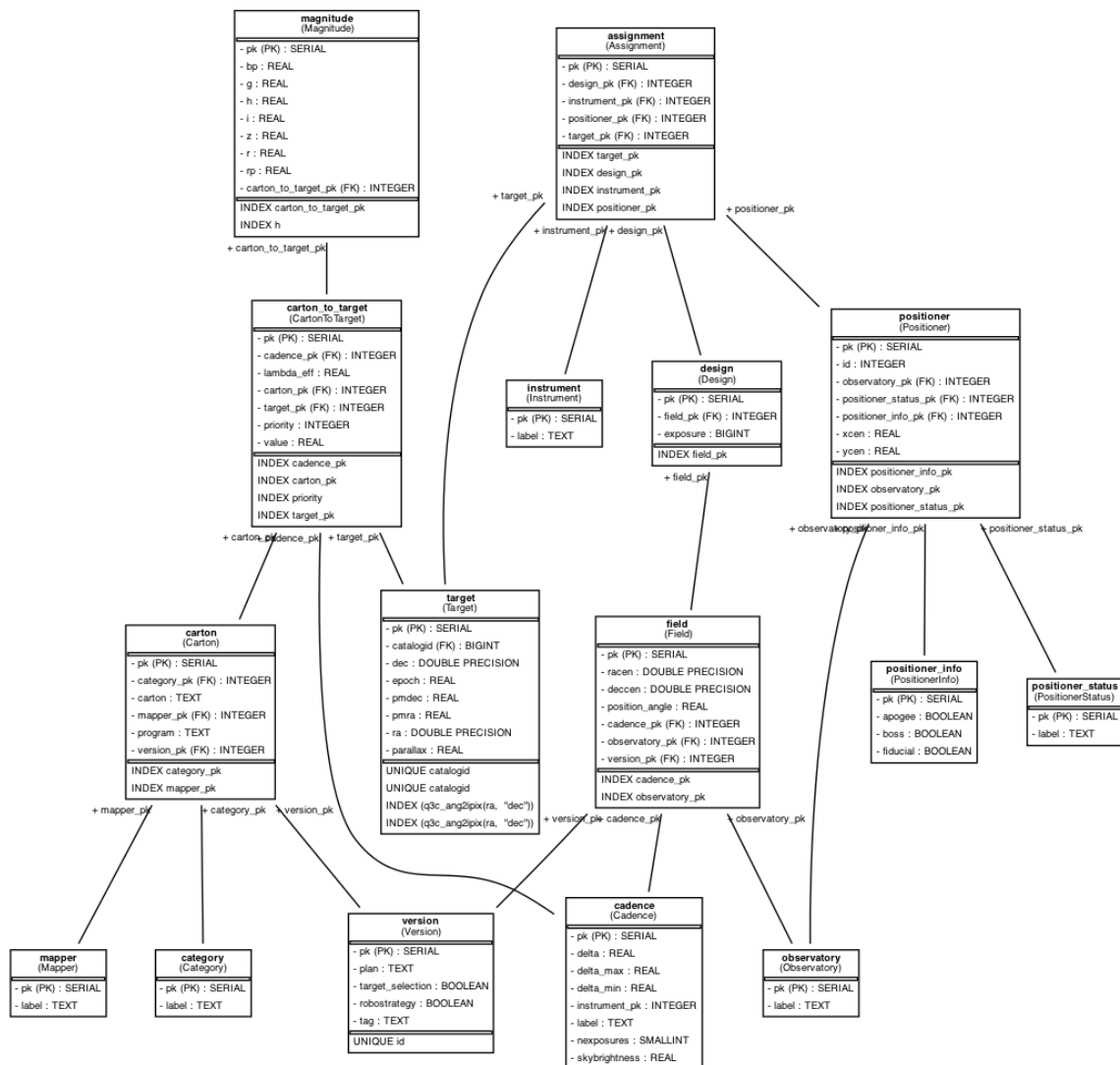


Figure 7. Database schema for targetdb.

The main table, `target`, contains all the targets selected from `catalogdb` along with their astrometric information and provides the link to `catalogdb.catalog` via `catalogid`. Photometric information is stored in the magnitude table for each target.

The program table contains the target selection cartons associated with their leading survey (MWM or BHM) and a category (science, standards, etc). Programs are version controlled and as in the case of cross-matching we refer to a run of target selection as a plan with an associated code tag.

The allocation of targets to programs is done in the `program_to_target` table, which also assigns the cadence (frequency, number of observations, lunation conditions) for a given target and program. Note that a given target may be associated to multiple cartons, each one with different observing requirements.

3.3 Tiling and scheduling

Once that targets have been selected for each carton we need to determine how they will be observed, which is made especially complicated by the variety of cadence requirements. A dedicated piece of code, codenamed ROBOSTRATEGY performs the following optimisation tasks:

1. Tiles the sky in a series of overlapping fields that minimise the number of observations required to observe all available targets.
2. For each field, groups the available targets according to their cadence requirements.
3. Determines what targets should be observed at each exposure, accounting for overall time as a function of LST and lunation.
4. Determines what fibre and positioner should be assigned to each target, accounting for the real geometry of the positioners and whether it is possible to generate a path that does not results in collisions.

The result of a ROBOSTRATEGY run is a series of field centres and “designs” that associated specific fibres to targets. This output is also stored in `targetdb` and versioned.

A nightly scheduler determines what is the best succession of designs to be observed to meet their cadence requirements while achieving the necessary signal-to-noise. Actual observations are then stored in an operational database, `opsdb`, that is used in successive runs of ROBOSTRATEGY to determine what fields and targets have been completed and re-optimize the observing strategy.

4. COMPUTING AND SOFTWARE ARCHITECTURE

The main computing hardware for observations consists of two Dell R7515 computer servers along with a Dell ME4012 storage array. Operational software runs in virtual machines (VM) managed using VMWare vSphere hypervisor. Of the utmost importance is to ensure that observations can continue during the night, with minimal downtime, even if a server or disk fails. This is achieved with a combination of disk RAID that guarantees data availability, and VM load balancing between the two main servers, so that if one of the server fails completely the remaining server can manage all the running VMs.

All the telescope, FPS, and spectrograph hardware is connected to the servers over fibre EtherNET via dual linking to two 10 Gbps managed switches. The system is designed so that a single switch can provide all the networking services needed, in case of failure. The APOGEE spectrograph has its own dedicated control computer and hardware that run on a dedicated subnet.

All the VMs and physical devices are isolated in a private subnet, separate from the rest of the observatory network, thus preventing unwanted access and network noise. Access to the private subnet from the wider observatory network or the outside world can only be achieved via a gateway VM, which also provides any service that needs to be accessed from outside the observatory (e.g., status webapps, weather, etc). The system and software infrastructure is designed so that an Internet outage would not preclude night observations.

Operations software, or “actors”, follows the principle that each individual piece of code must serve a well defined purpose, and that a issue or bug with the code should not affect other subsystems. Each actor is a TCP/IP server which allows it to receive commands and output replies to a client using a custom message protocol. A central message passing service, named TRON, allows actors to communicate and command other actors without having to establish a dedicated connection.

Observers typically interact with the operations software using a graphical user interface (GUI), STUI, which connects as a client to TRON and allows to command and receive replies from any actor in the network. While convenient, the GUI is not required to carry out successful observations.

Actors and operations software are written primarily in Python 3 and C/C++. The code is version controlled using Git and stored in the SDSS GitHub organisation[†]. We use unit testing and continuous integration (CI) to prevent regression issues. The majority of the SDSS operations code is open source under a BSD-3-clause license.

5. NIGHT OPERATIONS

Night operations usually begin a couple hours before sunset when the observers perform a series of afternoon checks, which includes inspecting the hardware and software performance, confirming the levels of liquid nitrogen for the instruments, and preparing the night plan. A long series of calibrations (bias, darks, and dome flats) are taken for both instruments.

At any point during the night the scheduling software provides an optimal queue of designs that should be observed. This queue can be modified in real time by the observers to account for atmospheric effects that are too complicated to take into account during scheduling (cloud cover, transparency, S/N trends from previous exposures). Figure 8 shows a schematic view of the observing process.

The top design in the observing queue is executed, which in turn triggers the “go to field” sequence. The telescope automatically slews to the design field centre. At the same time, the on-sky coordinates for each target are converted into focal coordinates taken into account the effects of atmospheric refraction and the telescope optical model. KAIJU is used to determine the optimal path for each positioner to the desired focal coordinates. The trajectories are then sent to the positioners over the CAN network and the positioners start to transition to the new configuration. When the slew and the initial FPS reconfiguration are complete, the FVC is used to determine the exact position of the metrology fibre and, by using the lab metrology, the science fibres. If the fibre positioners are not at the desired location, an offset is commanded and the process is repeated until $> 99\%$ of the positioners have converged. The slewing and reconfiguration process, including FVC feedback, is required to take fewer than 2 minutes.

Depending on the magnitude of the slew and the time passed since the last calibrations, a new set of flats, darks, and focus frames may be taken. Overall we want to minimise the overheads introduced by taking calibrations, while still maintaining excellent cross-calibration. The exact sequence of calibrations will be determined during survey commissioning but we expect to take new calibration at least once every hour during observations or if the telescope has moved significantly, altering the gravity vectors that affect the spectrograph throughput and LSF.

We use the GFA cameras to perform field acquisition. While both the Sloan and du Pont telescopes have good pointing accuracies, we cannot guarantee that position of the telescope after each slew will be good enough. For each field a series of guide and acquisition stars are preselected from the Gaia DR2 catalogue (thus providing excellent astrometry) to fall within the field of view of each one of the six GFAs. We use astrometry.net (Lang et al.¹³) to solve for the exact position and scale of the telescope and offset to the desired position. Our simulations indicate that selecting stars with G-band magnitude in the range (13, 19) will provide enough stars to determine the position of the telescope in $> 95\%$ of the fields, and we rely on human intervention from the night observers for the remaining cases.

We use the precomputed stars to guide during the 15-minute science exposure. The coordinate conversions between on-sky, positioner, and GFA coordinates have been calculated using ZEMAX models of the optical system and lab metrology of the FPS, positioners, and ferrules, and will be further improved with on-sky calibration during instrument commissioning. The goal is to be able to achieve a guide precision of 0.1 arcsec RMS when working under ideal seeing conditions. Better precision has been deemed not possible due to the mechanical characteristics of the telescopes. We used the intra- and extra-focal GFA CCDs to estimate the focus of the telescope from the differential PSF of the guide stars, and correct the position of the secondary mirror to optimise focus. We will not actively guide on plate scale but scale will be corrected between exposures. At LCO it's not possible to adjust scale by altering the position of the primary mirror, so we will perturb the desired position of the fibre positioners on the focal plane to account for scale corrections.

[†]<https://github.com/sdss>

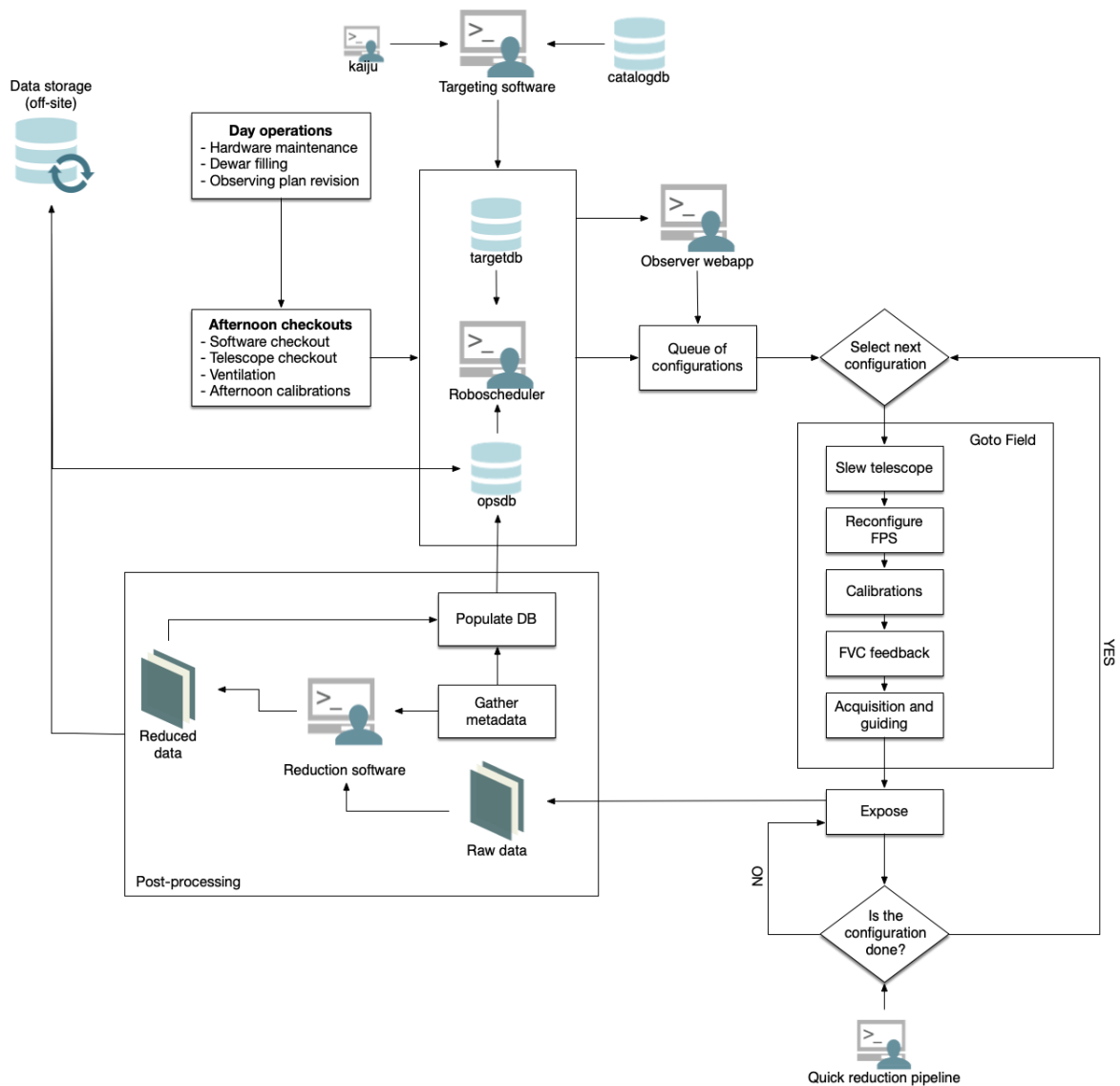


Figure 8. Diagram describing the flow of operations during a normal observing night.

While exposing, we take advantage of the up-the-ramp readout feature of the APOGEE detectors to estimate the cumulated S/N for the APOGEE targets, and extrapolate the corresponding one for the BOSS objects. This information is used by the scheduler to determine, before the current exposure completes, whether additional signal is required to complete the design or to prepare to move to a new one.

The completed APOGEE and BOSS exposures are saved to disk and immediately processed by the quick reduction pipelines. These pipelines produce a better estimate of the cumulated S/N at the cost of taking between 30 seconds and 5 minutes to process a full frame.

The process is repeated by selecting the new top design in the scheduler queue until the end of the night. In practice, many design share the same field centre and will be observed consecutively without requiring a telescope slew and field acquisition. The scheduler balances the efficiency of remaining at a given field with the improved S/N obtained by observing at lower airmass.

At the end of the night, all the raw and processed data, along with the operations database are backed up to the main SDSS data servers at University of Utah, where full reductions and analysis happen in a dedicated

computer cluster. The feedback from these reductions can be used during the day to optimise the observing queue for the next night.

6. SCHEDULE AND COMMISSIONING

The schedule for the deployment of the new FPS and associated hardware at APO and LCO has been severely affected by the COVID-19 pandemic. Our current plan aims to install the new corrector lenses for the Sloan telescope in early Spring 2021, followed by the installation and commissioning of the FPS hardware and software. This instrument commissioning will be followed by a science commissioning to test and optimise the nightly operations plan and evaluate the quality of the initial data. We expect the instrument and science commissioning to last approximately 8 weeks.

Before the deployment of the FPS to APO, one of the BOSS spectrographs will be disassembled, serviced, commissioned, and shipped to LCO where it will be installed in the du Pont telescope. FPS deployment and commissioning at LCO is expected for Summer 2021, followed by science commissioning. We continue to monitor the quickly evolving situation and may modify this plan depending on the on the ground conditions at each observatory and the availability of travel to New Mexico and Chile.

In the meantime, SDSS-V has started observing some of its science targets using plug-plates at the Sloan telescope, and will continue to do so until the FPS is ready for deployment. At LCO, SDSS-IV will continue observing at the du Pont telescope until the end of January 2021.

ACKNOWLEDGMENTS

Funding for the Sloan Digital Sky Survey V has been provided by the Alfred P. Sloan Foundation, the Heising-Simons Foundation, and the Participating Institutions. SDSS acknowledges support and resources from the Center for High-Performance Computing at the University of Utah. The SDSS web site is www.sdss5.org.

SDSS is managed by the Astrophysical Research Consortium for the Participating Institutions of the SDSS Collaboration, including the Carnegie Institution for Science, Chilean National Time Allocation Committee (CNTAC) ratified researchers, the Gotham Participation Group, Harvard University, The Johns Hopkins University, L'Ecole polytechnique fédérale de Lausanne (EPFL), Leibniz-Institut für Astrophysik Potsdam (AIP), Max-Planck-Institut für Astronomie (MPIA Heidelberg), Max-Planck-Institut für Extraterrestrische Physik (MPE), Nanjing University, National Astronomical Observatories of China (NAOC), New Mexico State University, The Ohio State University, Pennsylvania State University, Smithsonian Astrophysical Observatory, Space Telescope Science Institute (STScI), the Stellar Astrophysics Participation Group, Universidad Nacional Autónoma de México, University of Arizona, University of Colorado Boulder, University of Illinois at Urbana-Champaign, University of Toronto, University of Utah, University of Virginia, and Yale University.

REFERENCES

- [1] Kollmeier, J. A., Zasowski, G., Rix, H.-W., Johns, M., Anderson, S. F., Drory, N., Johnson, J. A., Pogge, R. W., Bird, J. C., Blanc, G. A., Brownstein, J. R., Crane, J. D., De Lee, N. M., Klaene, M. A., Kreckel, K., MacDonald, N., Merloni, A., Ness, M. K., O'Brien, T., Sanchez-Gallego, J. R., Sayres, C. C., Shen, Y., Thakar, A. R., Tkachenko, A., Aerts, C., Blanton, M. R., Eisenstein, D. J., Holtzman, J. A., Maoz, D., Nandra, K., Rockosi, C., Weinberg, D. H., Bovy, J., Casey, A. R., Chaname, J., Clerc, N., Conroy, C., Eracleous, M., Gänsicke, B. T., Hekker, S., Horne, K., Kauffmann, J., McQuinn, K. B. W., Pellegrini, E. W., Schinnerer, E., Schlafly, E. F., Schwobe, A. D., Seibert, M., Teske, J. K., and van Saders, J. L., "SDSS-V: Pioneering Panoptic Spectroscopy," *arXiv e-prints*, arXiv:1711.03234 (Nov. 2017).
- [2] et al., N. K., "Sdss-v local volume mapper instrument: Overview and status," in [*SPIE Ground-based and Airborne Instrumentation for Astronomy VIII*], (2020).
- [3] Gunn, J. E., Siegmund, W. A., Mannery, E. J., Owen, R. E., Hull, C. L., Leger, R. F., Carey, L. N., Knapp, G. R., York, D. G., Boroski, W. N., Kent, S. M., Lupton, R. H., Rockosi, C. M., Evans, M. L., Waddell, P., Anderson, J. E., Annis, J., Barentine, J. C., Bartoszek, L. M., Bastian, S., Bracker, S. B., Brewington, H. J., Briegel, C. I., Brinkmann, J., Brown, Y. J., Carr, M. A., Czarapata, P. C., Drennan, C. C., Dombeck,

- T., Federwitz, G. R., Gillespie, B. A., Gonzales, C., Hansen, S. U., Harvanek, M., Hayes, J., Jordan, W., Kinney, E., Klaene, M., Kleinman, S. J., Kron, R. G., Kresinski, J., Lee, G., Limmongkol, S., Lindenmeyer, C. W., Long, D. C., Loomis, C. L., McGehee, P. M., Mantsch, P. M., Neilsen, Eric H., J., Neswold, R. M., Newman, P. R., Nitta, A., Peoples, John, J., Pier, J. R., Prieto, P. S., Prosapio, A., Rivetta, C., Schneider, D. P., Snedden, S., and Wang, S.-i., "The 2.5 m Telescope of the Sloan Digital Sky Survey," *AJ* **131**(4), 2332–2359 (2006).
- [4] Bowen, I. S. and Vaughan, A. H., "The optical design of the 40-in. telescope and of the irenee dupont telescope at las campanas observatory, chile," *Applied Optics* **12**(7) (1973).
- [5] Smee, S. A., Gunn, J. E., Uomoto, A., Roe, N., Schlegel, D., Rockosi, C. M., Carr, M. A., Leger, F., Dawson, K. S., Olmstead, M. D., Brinkmann, J., Owen, R., Barkhouser, R. H., Honscheid, K., Harding, P., Long, D., Lupton, R. H., Loomis, C., Anderson, L., Annis, J., Bernardi, M., Bhardwaj, V., Bizyaev, D., Bolton, A. S., Brewington, H., Briggs, J. W., Burles, S., Burns, J. G., Castander, F. J., Connolly, A., Davenport, J. R. A., Ebelke, G., Epps, H., Feldman, P. D., Friedman, S. D., Frieman, J., Heckman, T., Hull, C. L., Knapp, G. R., Lawrence, D. M., Loveday, J., Mannery, E. J., Malanushenko, E., Malanushenko, V., Merrelli, A. J., Muna, D., Newman, P. R., Nichol, R. C., Oravetz, D., Pan, K., Pope, A. C., Ricketts, P. G., Shelden, A., Sandford, D., Siegmund, W., Simmons, A., Smith, D. S., Snedden, S., Schneider, D. P., SubbaRao, M., Tremonti, C., Waddell, P., and York, D. G., "The Multi-object, Fiber-fed Spectrographs for the Sloan Digital Sky Survey and the Baryon Oscillation Spectroscopic Survey," *AJ* **146**, 32 (Aug. 2013).
- [6] Wilson, J. C., Hearty, F. R., Skrutskie, M. F., Majewski, S. R., Holtzman, J. A., Eisenstein, D., Gunn, J., Blank, B., Henderson, C., Smee, S., Nelson, M., Nidever, D., Arns, J., Barkhouser, R., Barr, J., Beland, S., Bershad, M. A., Blanton, M. R., Brunner, S., Burton, A., Carey, L., Carr, M., Colque, J. P., Crane, J., Damke, G. J., Davidson, J. W., J., Dean, J., Di Mille, F., Don, K. W., Ebelke, G., Evans, M., Fitzgerald, G., Gillespie, B., Hall, M., Harding, A., Harding, P., Hammond, R., Hancock, D., Harrison, C., Hope, S., Horne, T., Karakla, J., Lam, C., Leger, F., MacDonald, N., Maseman, P., Matsunari, J., Melton, S., Mitcheltree, T., O'Brien, T., O'Connell, R. W., Patten, A., Richardson, W., Rieke, G., Rieke, M., Roman-Lopes, A., Schiavon, R. P., Sobek, J. S., Stolberg, T., Stoll, R., Tembe, M., Trujillo, J. D., Uomoto, A., Vernieri, M., Walker, E., Weinberg, D. H., Young, E., Anthony-Brumfield, B., Bizyaev, D., Breslau, B., De Lee, N., Downey, J., Halverson, S., Huehnerhoff, J., Klaene, M., Leon, E., Long, D., Mahadevan, S., Malanushenko, E., Nguyen, D. C., Owen, R., Sánchez-Gallego, J. R., Sayres, C., Shane, N., Shetrone, S. A., Shetrone, M., Skinner, D., Stauffer, F., and Zhao, B., "The Apache Point Observatory Galactic Evolution Experiment (APOGEE) Spectrographs," *PASP* **131**, 055001 (May 2019).
- [7] Araujo, R., Bouri, M., Brandon, C., Caseiro, S., Gillet, D., Grossen, L., Kronig, L., Macktoobian, M., O'Brien, T., Pogge, R. W., Tuttle, S., and Kneib, J.-P., "Design of a theta/phi fiber positioner robot for the sloan digital sky survey v," in [*SPIE Ground-based and Airborne Instrumentation for Astronomy VIII*], (11447-227) (2020).
- [8] Kronig, L., Horler, P., Caseiro, S., Grossen, L., Araujo, R., Kneib, J. P., and Bouri, M., "Precision control of miniature scara robots for multi-object spectrographs," *Journal of Optomechatronics* (2020).
- [9] L., G., L., K., R., A., S., C., C., S., J., S.-G., M., B., and J.-P., K., "Test results of the sdss-v fiber micro-positioners," in [*SPIE Ground-based and Airborne Instrumentation for Astronomy VIII*], (11447-217) (2020).
- [10] Sayres, C. and Sánchez-Gallego, J. e. a., "Sdss-v algorithms: Fast, collision-free trajectory planning for heavily overlapping robotic fiber positioners," *AJ in press* (2020).
- [11] Pogge, R. W., Derwent, M. A., O'Brien, T. P., Jurgenson, C. A., Pappalardo, D., Engelman, M., Brandon, C., Brady, J., Clawson, N., Shover, J., Mason, J., Kneib, J.-P., Araujo, R., Bouri, M., Kronig, L., Grossen, L., Gillet, D., Macktoobian, M., Tuttle, S. E., Farr, E., Sánchez-Gallego, J., and Sayres, C., "A robotic focal plane system for the sloan digital sky survey v," in [*SPIE Ground-based and Airborne Instrumentation for Astronomy VIII*], (11447-173) (2020).
- [12] Stassun, K. G., Oelkers, R. J., Paegert, M., Torres, G., Pepper, J., De Lee, N., Collins, K., Latham, D. W., Muirhead, P. S., Chittidi, J., Rojas-Ayala, B., Fleming, S. W., Rose, M. E., Tenenbaum, P., Ting, E. B., Kane, S. R., Barclay, T., Bean, J. L., Brassuer, C. E., Charbonneau, D., Ge, J., Lissauer, J. J., Mann, A. W., McLean, B., Mullally, S., Narita, N., Plavchan, P., Ricker, G. R., Sasselov, D., Seager, S., Sharma,

- S., Shiao, B., Sozzetti, A., Stello, D., Vanderspek, R., Wallace, G., and Winn, J. N., “The Revised TESS Input Catalog and Candidate Target List,” *AJ* **158**, 138 (Oct. 2019).
- [13] Lang, D., Hogg, D. W., Mierle, K., Blanton, M., and Roweis, S., “Astrometry.net: Blind Astrometric Calibration of Arbitrary Astronomical Images,” *AJ* **139**, 1782–1800 (May 2010).