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The SDSS-V Local Volume Mapper telescope system

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ABSTRACT

The Sloan Digital Sky Survey V (SDSS-V) is an all-sky spectroscopic survey of >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. The Local Volume Mapper (LVM) is one of three surveys that form SDSS-V. LVM will employ a coordinated system of four telescopes feeding three fiber spectrographs at Las Campanas Observatory in Chile. The goal is to map approximately 2500 square degrees of the Galactic plane over the wavelength range 360-980 nm with R~4000 spectral resolution. These observations will reveal for the first time how distinct gaseous environments within the Galaxy interact with each other and with the stellar population, producing the large-scale interstellar medium that we observe.

Accurately mapping and calibrating a substantial portion of the sky at this spatial resolution requires a unique type of telescope system. Each of the four LVM telescopes has a diameter of 16 cm, making them considerably smaller and lighter than the instruments they feed. One telescope will host the science IFU containing ~1800 fibers arranged in a close-packed hexagon. Two additional Calibration telescopes will observe fields adjacent to the science IFU, in order to calibrate out terrestrial airglow and other geo-coronal emission. The fourth, Spectrophotometric telescope will make rapid observations of bright stars (typically 12 during a single IFU / Calibration exposure) to correct for telluric absorption lines and overall extinction. The fibers from all three types of telescope will be interspersed in the entrance slits of the spectrographs, allowing for simultaneous science and calibration exposures.

Although considerably smaller than the next generation of giants, the LVM telescopes must also operate close to the limits of physical optics, and the geometry and scope of the LVM survey present unique challenges. For example, with this type of telescope at the Las Campanas site, the effects of optical aberrations, diffraction, seeing, and (uncorrected) atmospheric dispersion are all of comparable scale. This, coupled with the need for repeated and reliable measurements over years, leads to some unconventional design choices. This paper presents the preliminary design of the LVM telescope system and discusses the requirements and tradeoffs that led to the baseline choices.

Keywords: LVM telescopes, telescope array, survey, Local Volume Mapper, SDSS-V

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1 THE LOCAL VOLUME MAPPER

The Local Volume Mapper (LVM) is one of three surveys that form the Sloan Digital Sky Survey V project (SDSS-V). Las Campanas Observatory in Chile will host the initial phase of LVM. When funded, a second northern-hemisphere facility will be installed at Apache Point Observatory in New Mexico. As its name suggests, LVM has the goal of mapping the local volume around the Sun within the Galaxy, and the local volume of galaxies around our Milky Way. LVM is primarily a spectral line survey, targeting emission features from the near UV to the near infrared that are diagnostics of the interaction of star formation with the interstellar medium (ISM). With the 3D information provided by LVM's Integral Field Units (IFU's), we plan to spatially resolve the spatial scales on which star formation and energy injection into the Galactic ISM occur. And, by observing the entirety of the Milky way and nearby systems, such as the Magellanic clouds, LVM will span local to global scales to teach us how feedback, in the form of radiation, momentum flow, and shocks, shapes the evolution of galaxies. As a large, dedicated survey, LVM has by necessity a very close connection between the primary science of the survey and the design of the hardware to carry it out.

1.1 The LVM Survey

The LVM Survey initially comprises two observational targets, the Galactic disk and the Magellanic Clouds. With the expansion to the northern hemisphere, the survey will eventually include M31 and other nearby galaxies, as well as the remainder of the Milky Way disk.

The **LVM Milky Way Survey** will map the metallicity and ionization structure of the entire southern portion of the Galaxy, some 2500 square degrees. By spanning physical scales from sub-parsec to kilo-parsecs, LVM will let us connect the local injection of radiation, momentum flow, and shocks to galaxy-wide phenomena, such as inflows and outflows, galactic fountains, and disk dynamics. This survey exceeds the breadth and scale of previous studies by 3-4 orders of magnitude.

The **LVM Magellanic System Survey** will target the Large and Small Magellanic clouds, which, at a typical distance of 50 kpc, will require sub-spaxel sampling for LVM to achieve its goal of 10 pc spatial resolution. These satellite galaxies have qualitatively lower metallicity than the Milky Way, allowing us to distinguish shocked versus photoionized emission, identify large scale ionization gradients in star forming regions, and sample both individual stellar nurseries and the large scale diffuse gas in a metal-poor stellar population.

1.2 The LVM Instrument (LVMi)

Surveying such vast regions of sky within a finite amount of time requires some unique technology solutions, and nowhere is this more true than with the design of the telescopes. LVMi employs an array of four small telescopes (16 cm diameter) configured as siderostat – optical table pairs (Figure 1). These telescopes feed microlens-based fiber Integral Field Units in their focal planes. The fibers form an integrated slit at the input focal planes of three spectrographs located in an isolated, environmentally controlled chamber. To maximize throughput, particularly at the shortest wavelengths, the total fiber runs are less than 10m.

The spectrographs themselves are three-channel instruments (Red, Blue, and Near-Infrared), based on the DESI design produced by Winlight System in southern France. They operate at a spectral resolution of ~4000 over the wavelength range 360-980 nm. This range encompasses dozens of diagnostic lines, from OII at 372 nm to SIII at 953 nm. Attached to each spectrograph are three separate cryostats hosting CCDs from Imaging Technology Laboratories at the University of Arizona. The CCD controllers are from Semiconductor Technology Associates in southern California.

A custom-built enclosure with a roll-off roof houses the telescopes, fibers, and spectrographs, as well as the necessary support infrastructure, including calibration lamps, network and power, and a small observing room.

The LVM Instrument is truly an international project, with contributions from North America, South America, Europe, Asia, and Australia. Note that, at this conference, Konidaris *et al.* (contribution 11447-237) describe the overall LVM instrument, while Feger *et al.* (contribution 11447-204) discuss the IFU's, fiber bundles, and spectrograph slits.

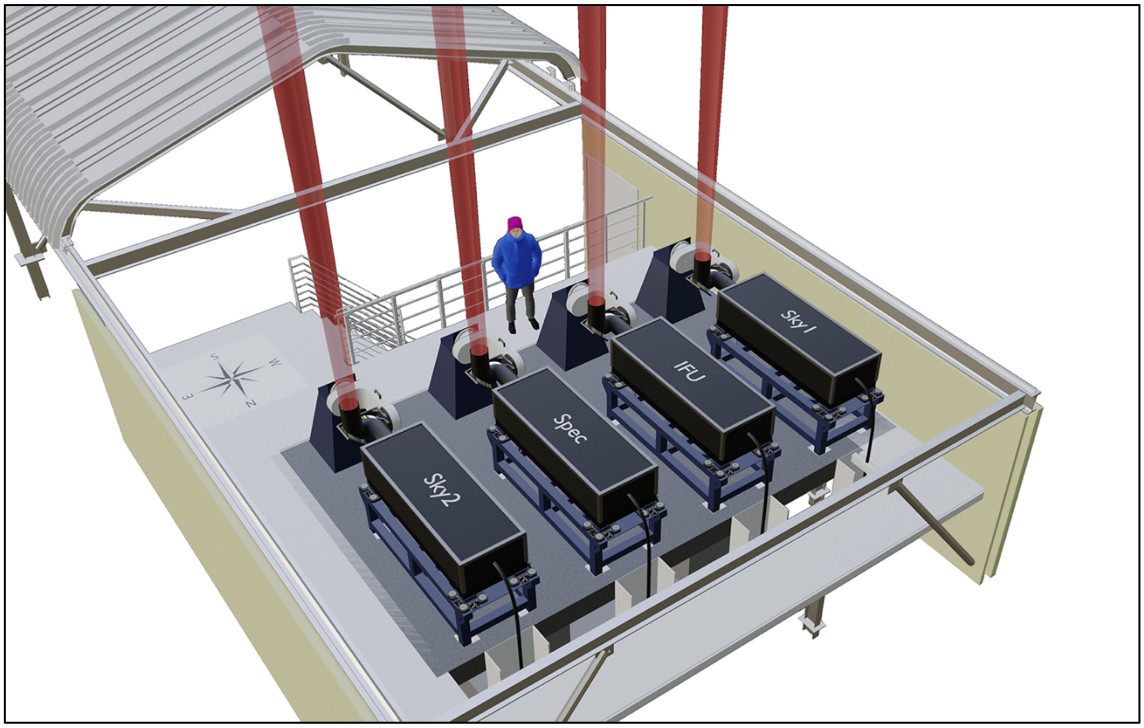

Figure 1: The four telescopes of the LVM survey. Note the roll-off roof and the human figure for scale.

2 OPERATING PRINCIPLE

The four LVM survey telescopes fall into three categories, as shown in Table 1. The Science IFU telescope hosts the primary science channel, while the two Sky telescopes and the Spectrophotometric telescope acquire simultaneous observations critical for proper survey calibration.

Table 1: The number and type of the LVM telescopes

Category	Units	Description
Science IFU	1	The science channel
Sky	2	For subtraction of geocoronal emission
Spectrophotometric	1	Telluric line and photometry calibration

Light from the sky enters the **Science IFU telescope** and is conveyed to the fixed, IFU fiber bundle in the focal plane. This bundle contains 1801 individual fibers in a hexagonal array of 25 concentric rings. Micro-lens arrays accomplish the coupling between the telescope focal plane and the bundle, and at the other end of the fibers, a slit mechanism re-formats the focal plane on the entrance slits of the spectrographs. See Feger *et al.* (contribution 11447-204 at this conference) for more. A typical science exposure takes 15 minutes (Figure 2).

At the same time, two **Sky Calibration telescopes** make measurements of the telluric geocoronal emission near the Science IFU field. This light is coupled in the same way into 119 fibers, 60 from one Sky telescope and 59 from the other. These IFU's are also microlens-based, with the fibers emerging from 5-ring hexagonal arrays. To reduce systematic errors and improve calibration, the spectrograph entrance slits intersperse the science and sky calibration fibers, resulting in about 40 sky measurements per spectrograph.

Finally, a single **Spectrophotometric telescope** points at 12 different bright calibration stars for approximately 1 minute each during the 15-minute science exposure. The focal plane of this telescope hosts 12 fibers that are coupled and fed to the spectrographs in the same way. An internal shutter (see Section 3.3.4) ensures that only one of the 12 fibers is exposed at each star, and as with the sky calibration, the spectrophotometric measurements are interspersed with the IFU fibers, leading to 4 spectrophotometric observations per spectrograph.

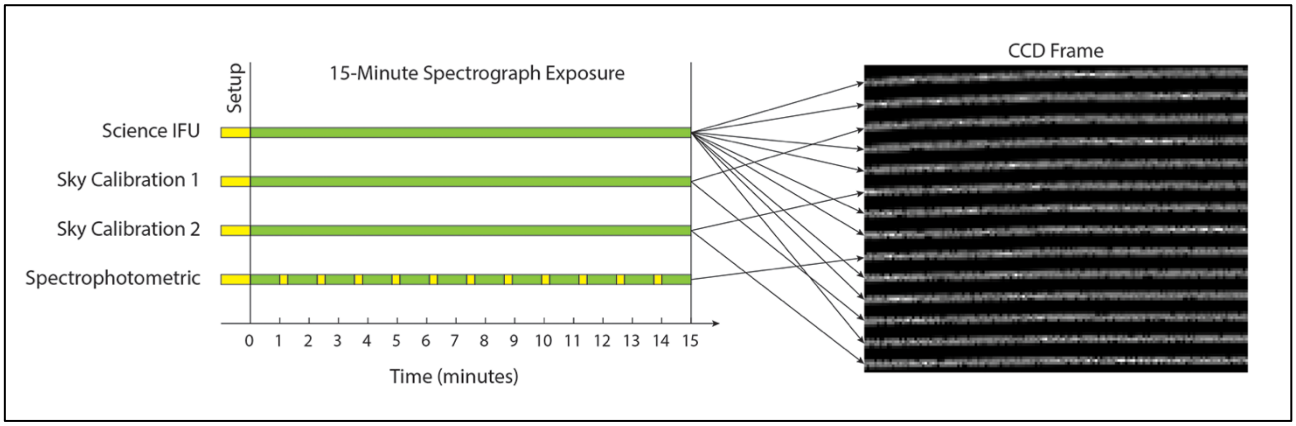

Figure 2: Timeline and portion of a notional science exposure illustrating the LVM telescope operating principle of interspersing science, sky, and spectrophotometric observations.

3 TELESCOPE ARCHITECTURE AND COMPONENTS

As mentioned above, the LVM telescopes adopt a siderostat – optical table paradigm. Figure 3 shows this architecture and labels the major components. Formally, the LVM telescope system consists of all opto-mechanical elements between the sky and the micro-lenses on the fiber bundle. These elements include:

Subsystem	Components
Siderostat	Alt-Alt mount
	Flat mirrors with mounts and sky baffles
	Pier with telescope platform interface
Optical Table	Optical breadboard
	Rigid support with adjustment
Opto-Mechanics	Objective lens with focus drive
	K-mirror de-rotator
	Acquisition and Guide Hardware
	Fiber selector hardware
	IFU / fiber bundle interface

Note that the IFU and Sky calibration telescopes contain K-mirror de-rotators as shown in Figure 3, while the fourth, Spectrophotometric telescope does not. It hosts a fiber selector mechanism in its focal plane for isolating the flux of individual bright stars. See Section 3.3.4 for details.

3.1 Siderostats

Physical motion of the focal plane IFU's and, in particular, the fiber bundles, can induce variations in focal ratio degradation and throughput that would affect the global calibration of the LVM survey. Early on in the project, concerns about these effects led to the requirement that the focal planes be fixed in XYZ space and rotation. Of course, conveying the light from a moving telescope, particularly one that is 16cm in diameter, to a firm, fixed focal plane hosting a large, heavy, and delicate fiber bundle is far from straightforward.

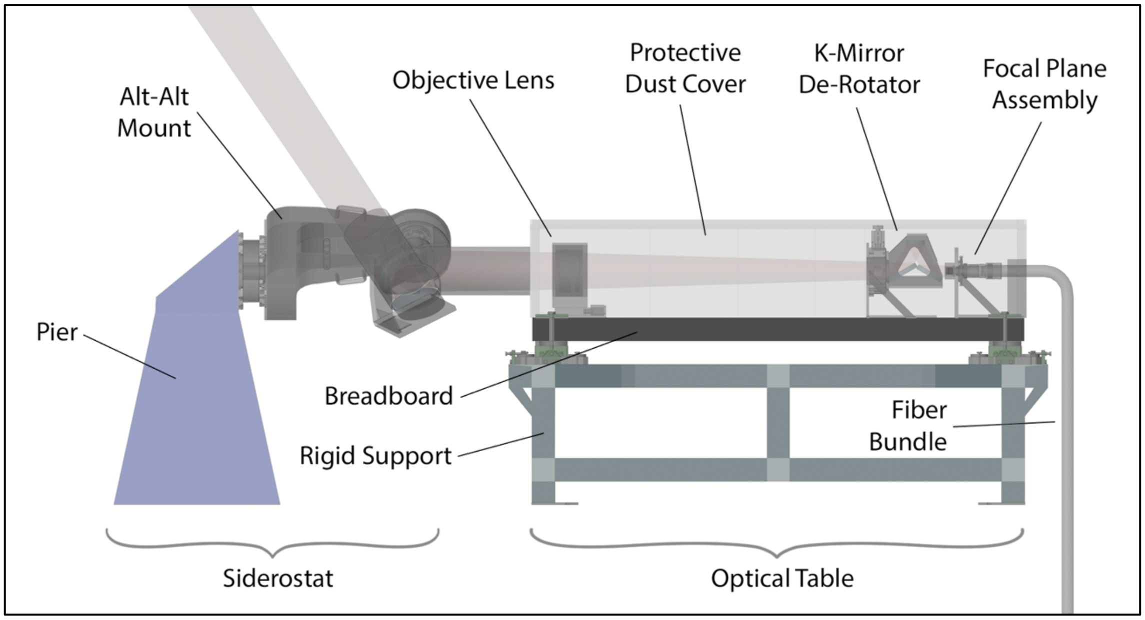

Figure 3: Side view of one telescope showing major components. Note that only 3 of the 4 telescopes have a K-mirror de-rotator. The Spectrophotometric telescope has a direct path to the focal plane, which is therefore closer to the edge of the optical breadboard.

Early telescope solutions included a relatively standard alt-azimuth Ritchey-Chrétien configuration with the fiber bundle looking upward through a hole in the center of the azimuth axis. A compact K-mirror de-rotator could then remove sky rotation. An advantage of this approach is the opportunity to use commercial, off-the-shelf hardware for both the optics and mechanics: the amateur telescope market offers a wide variety of high-quality telescopes and mounts with suitable dimensions and properties. The team struggled to make this type of system work, but eventually recognized that it was unfeasible. For example, the IFU fiber flanges are *ca.* 100mm in diameter, 60% of the size of the entrance pupil, and no standard commercial offering would work.

In December 2019, the LVM team selected the siderostat / optical table configuration shown in Figure 3 for the LVM telescopes. The key element in such a scheme is, of course, the siderostats themselves, which must point and track across the full survey region of the sky and redirect the light to a fixed location on the optical table. The LVM siderostats employ a commercial L-350 mount from Planewave Instruments operating in altitude-altitude configuration. These devices can operate in all orientations from vertical (i.e. standard altitude-azimuth) to horizontal (altitude-altitude, as used by LVM). Note that these orientations correspond directly to operation of the L-350 as an equatorial mount at the Earth's pole or equator, respectively.

Figure 4 shows the opto-mechanics of the siderostats and identifies the relevant rotation axes. Light from the sky strikes the SEl ("Siderostat Elevation") mirror, which is mounted to the motorized elevation axis of the L-350. The SEl mirror redirects the incoming radiation to the SAz ("Siderostat Azimuth") mirror whose center is located on the azimuth axis of the mount. Rotation of this axis points the siderostat East-West as shown in the figure, while rotation of the L-350 elevation axis allows the SEl mirror to explore North-South. Together, these two motions give access to the full sky while feeding the light to a fixed location.

The SEl and SAz mirrors are relatively large components (28 x 20cm) mounted on stiff, lightweight supports. To prevent veiling glare, that is stray light from scattering off surface dust on the mirrors, the siderostats include lightweight carbon fiber baffles on both axes. These interlocking baffles block all sightlines more than 30° from the target, and as shown, the SEl baffle will consist of rings rather than a solid tube to reduce wind loading. Note also that the SAz baffle will likely be mounted to the optical table, not the siderostat itself, to reduce the total payload on the L-350 mounts.

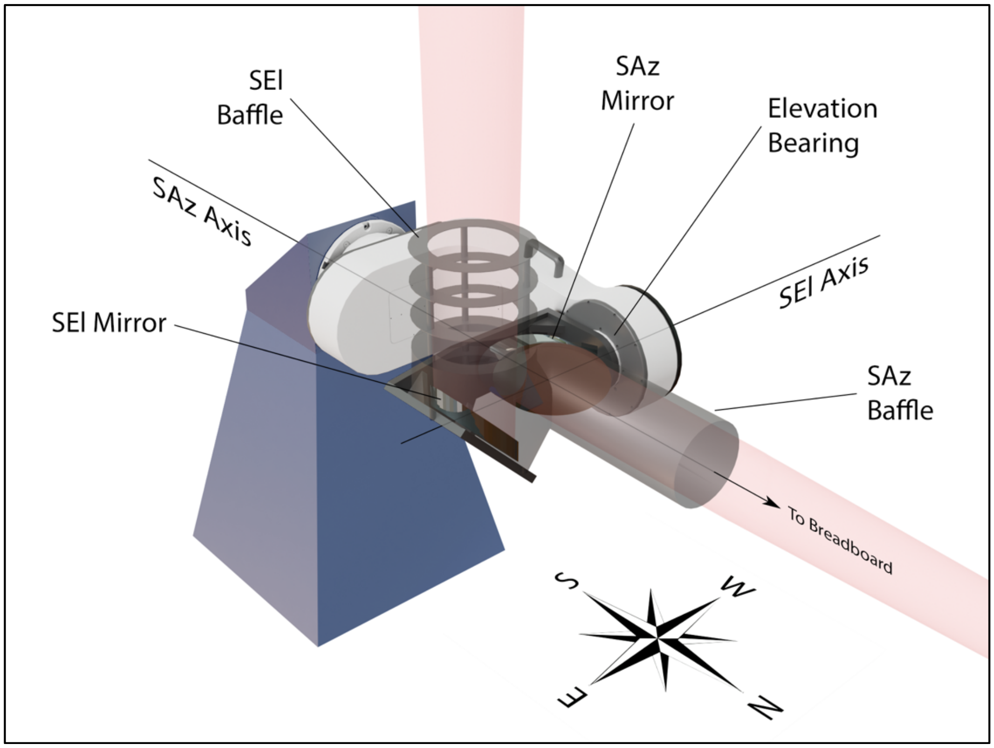

Figure 4: Siderostat opto-mechanics. The SAz mirror is attached to the azimuth L-arm of the Planewave L-350 mount, while the SEl mirror rotates with the L-350 elevation bearing.

Of course, this configuration conveys the field of view from a moving telescope to a fixed location, and hence, image rotation will occur. A K-mirror de-rotator on the optical table accounts for this (see Section 3.3.2). A very significant benefit of this alt-alt arrangement compared to a standard alt-az solution is that the field rotation rates do not diverge at zenith, and hence, the K-mirror tracking rates are always manageable.

The L-350 mounts attach to individual piers, which are simple steel weldments bolted to the telescope platform. Although fine positioning via shimming is possible, these piers should not require adjustment, since the optical tables provide ample degrees of freedom for alignment (see next section).

3.2 Optical Tables

Four identical optical table systems provide the stable platform for the fixed fiber bundles and the opto-mechanical components that establish and maintain a stable focal plane. The initial baseline plan called for a commercial optical table solution, but concerns about seismic safety led the team to adopt an established optical table concept with heritage from the VLT Gravity instrument (Figure 5). A custom rigid support built by D.H. Frank (Germany) using commercial Airloc (MA, USA) adjustment mechanisms mates to a 210x75 cm commercial breadboard from Ametek (Germany) with standard M6 optical bench threaded holes on a 25mm raster. These tables not only provide substantial adjustment in XYZ location and tip/tilt for alignment, but also they have demonstrated performance in a seismically active observatory situation.

Note that, unlike a typical laboratory setup, we do not want to be strongly decoupled from the ambient environment, using pneumatic legs, for example. This could lead to misalignments between the tables and siderostats. While the system will be fairly robust to small displacements, we will firmly attach both the optical tables and siderostats to the concrete telescope platform using M16 anchor bolts.

To protect the internal opto-mechanics, the optical tables will be equipped with simple protective covers assembled from aluminum extrusion and flat panel modular components from Item24 (Germany). We are still investigating the option of having motorized hatches to minimize daytime dust contamination, as well as the possibility of mounting the SAz baffles (Figure 4) to the tables instead of the siderostats.

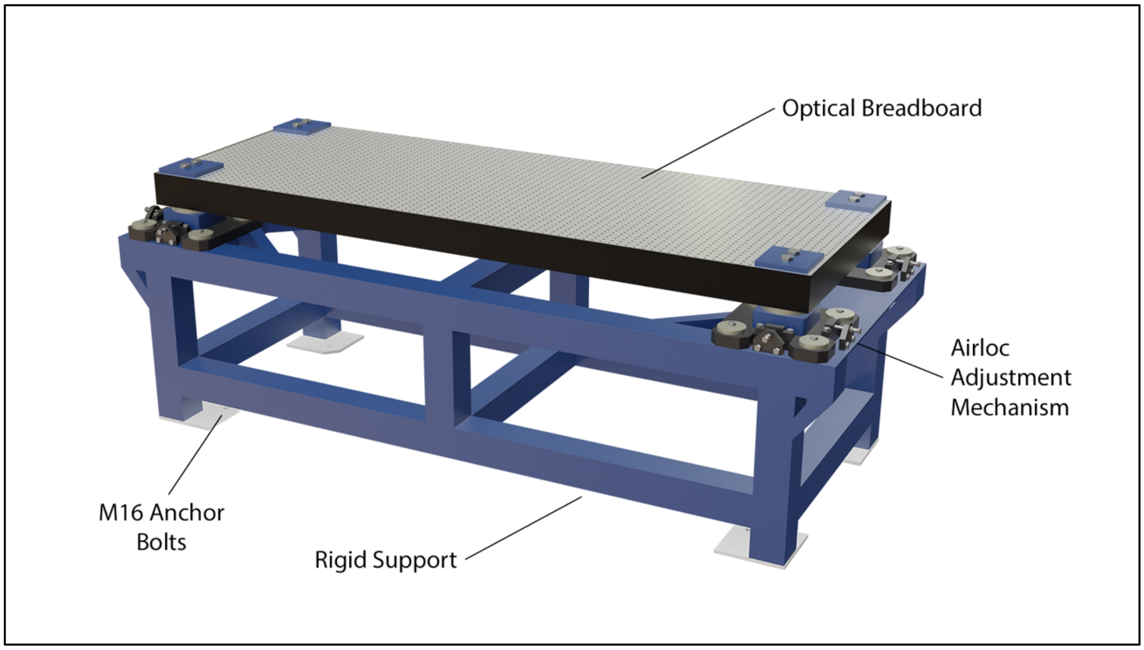

Figure 5: The LVM optical tables consist of a custom rigid support and a commercial optical breadboard connected by Airloc adjustment mechanisms.

3.3 Opto-Mechanics

3.3.1 Objective Lenses and Baffling

The powered optics of the LVM instrument have some very demanding requirements: excellent image quality, extraordinarily broad wavelength coverage, and insensitivity to temperature change. This led to a challenging design exercise. The LVM objectives are bonded triplets of N-BAK2 glass (Schott) and monocrystalline CaF_2 elements. The bonding agent is SYLGARD 184 by Dow Corning, a material which retains mechanical flexibility and with which the consortium has extensive experience. Optimax (NY, USA) will fabricate and anti-reflection coat the individual lenses. Thereafter, Carnegie Observatories (CA, USA) will bond the lenses to BAK2 – CaF_2 – BAK2 triplets and mount them in a precision aluminum barrel with machined reference points for attaching alignment targets.

A series of blackened baffle plates, which divide the interior volume of the optical table into compartments, will prevent stray light from reaching the focal plane. These baffles will be spaced along the breadboard so that, from a point of view anywhere in the focal plane looking toward the objective lens, one can only see the back side of a baffle plate. This ensures that any stray light must undergo at least two bounces off a blackened surface before striking the focal plane.

The requirement of a fixed IFU means that we must use an upstream actuated element to focus. By far the most straightforward means is to move the objective lens along the optical axis. LVM will use a commercial, off-the-shelf linear motorized stage (model M-413.12s from Physik Instrumente, Germany) for this purpose. The lens interface will be a V-shaped block with kinematic mounts that permit repeatable and accurate placement of the lens barrel.

3.3.2 K-Mirror De-Rotators

As mentioned above, the fixed "off-telescope" focal plane configuration introduces image rotation, and we have the requirement to properly align and tile the hexagonal footprints of the science IFU (see Figure 6). As a result, the LVM telescopes employ relatively standard K-mirror de-rotators mounted to the optical breadboard. Of course, adding three reflections to the optical path can significantly impact throughput, particularly at the shortest wavelengths. To address this, the de-rotator mirrors will have high performance dielectric coatings that should deliver 99%-plus reflectivity across the full range of operating wavelengths.

To minimize the size of the required reflecting optics, we locate the K-mirror as close as possible to the focal plane in the converging beam. This arrangement has the added virtue that the beam footprints from different sky locations are correspondingly reduced, since the mirrors are close to focus. This relaxes somewhat the demand on surface quality, which can be important with thick, multi-layer coatings.

Section 3.1 emphasized the benefits of the alt-alt siderostat configuration in terms of maximum tracking rates near zenith. This, combined with the relatively modest demands on rotational positioning and tracking accuracy, leads to requirements that can be satisfied with commercial, off-the-shelf rotation stages (see Table 2). We have identified suitable hardware from both Newport and Physik Instrumente.

Table 2: Positioning and tracking requirements for the K-mirror de-rotators

Item	Requirement
Rotation range	±135° from straight up, or 540° on-sky
Positioning accuracy	<0.234 mrad or 0.8 arcmin
RMS rotation tracking error	< 0.23 mrad or 0.8 arcmin over 15 minutes
Maximum rotation rate	0.01° / second while maintaining accuracy

Note that, in principle, only the Science IFU telescope requires a de-rotator for proper IFU tiling. In the case of the two sky telescopes, however, unwanted sky rotation could cause bright stars to drift in and out of the field of view during an exposure, complicating enormously the job of calibration. As a result, both of the Sky calibration telescopes have K-mirrors that are identical to that in the science channel. As mentioned in Section 2, the Spectrophotometric telescope will make a series of 1-minute pointings at very bright stars during the 15-minute spectrograph exposure. The light of these stars will dominate any additional sources in the field, and hence no de-rotation is necessary for this telescope.

3.3.3 Acquisition and Guide Hardware

Figure 6 below shows the focal plane layout for each of the three types of telescope. This is the view looking toward the fiber bundle, in other words, in the direction that light travels. The Science Telescope hosts a large, 16.5 mm diameter IFU with 1801 fibers and two CMOS Acquisition and Guiding (AG) sensors. To avoid partial vignetting of the beam converging to focus, the minimum gap between the large IFU and the 45° mirrors feeding the AG sensors is 4 mm, leading to the requirement of a 44.5 mm or 1.4° overall delivered field of view. Note that for compactness and precision mounting, the fold mirrors are actually prisms with the hypotenuse aluminized (Thorlabs model MRA25-P01or similar).

The two Sky Calibration Telescopes have smaller, 3.3mm diameter IFUs, one with 60 and the other with 59 fibers, in addition to two AG sensors. Although the guide fields could in principle be much closer to the IFU in this case, we have prioritized standardization in the LVM project. Thus, all of the objective lenses, K-mirrors, and (where possible) focal plane hardware are the same, leading to the 9.7mm gap between the IFU and the AG cameras shown in Figure 6.

Finally, the Spectrophotometric Telescope has an IFU identical to that in the Science IFU telescope, but with only 24 populated fiber locations. A hole mask sequentially selects bright reference stars on individual fibers during an exposure (see next section). These individual pointings are short (1-minute), and hence open-loop tracking suffices. As a result, the Spectrophotometric telescope hosts a single AG sensor which performs acquisition only.

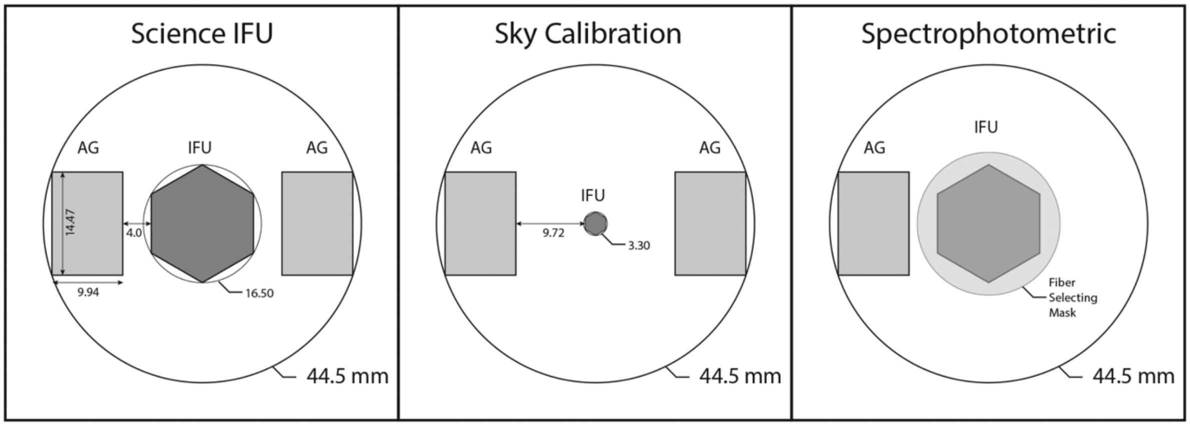

Figure 6: The focal plane layout for the Science (left), Sky Calibration (center), and Spectrophotometric (right) telescopes.

LVM will use seven Acquisition and Guiding sensors: two for the Science IFU telescope, two each for the two Sky Calibration telescopes, and one for the Spectrophotometric telescope. We initially examined CCD detectors, but devices with the appropriate size, noise properties, and sensitivity are quite costly. Although largely unnoticed by the astronomy community, there has been a revolution in CMOS technology in recent years, and inexpensive, commercial off-the-shelf offerings provide more than enough performance.

The LVM team has selected the FLIR Blackfly S GigE CMOS camera equipped with the Sony IMX432 sensor as the baseline AG camera. This device has (relatively) large, 9µm pixels and excellent performance for acquisition and guiding. As a further benefit in this application, the FLIR packaging is compact (29 x 29 x 39mm) and requires only a single Power over Ethernet connection to the device. Finally, the FLIR cameras have entirely internal readout and amplification infrastructure. The output is a digital data stream in a standard (SLVS) format that is compatible with existing SDDS-V software.

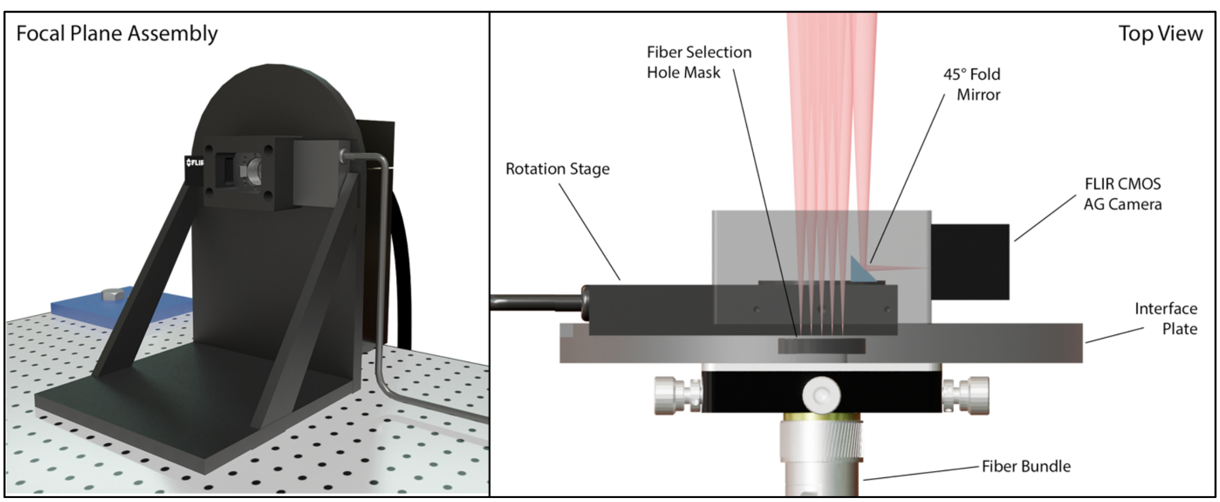

Figure 7: The focal plane assembly of the Spectrophotometric telescope hosts one CMOS Acquisition and Guide camera and hardware for fiber selection. The other three telescopes have two AG cameras, one on each side.

3.3.4 Fiber Selector Hardware

As described in Section 2, the spectrophotometric telescope makes 12 separate observations of bright stars during the 15-minute period of a single science exposure (see also Figure 2). This means that, without additional hardware, each of the 12 active spectrophotometric fibers will receive unwanted light for 14 of the 15 minutes of an individual exposure. In order to prevent this excess background and contamination, there will be a fiber selecting mask in the focal plane. This is a simple, rotating disk with two apertures that exposes the fiber tips to light one at a time. It must also block all fibers during telescope motion between acquisitions (Figure 8). A compact rotary stage (model PRP50PP from Newport) mounted on the fiber interface plate (and taking the place of the second AG camera) drives the selection mask (Figure 7).

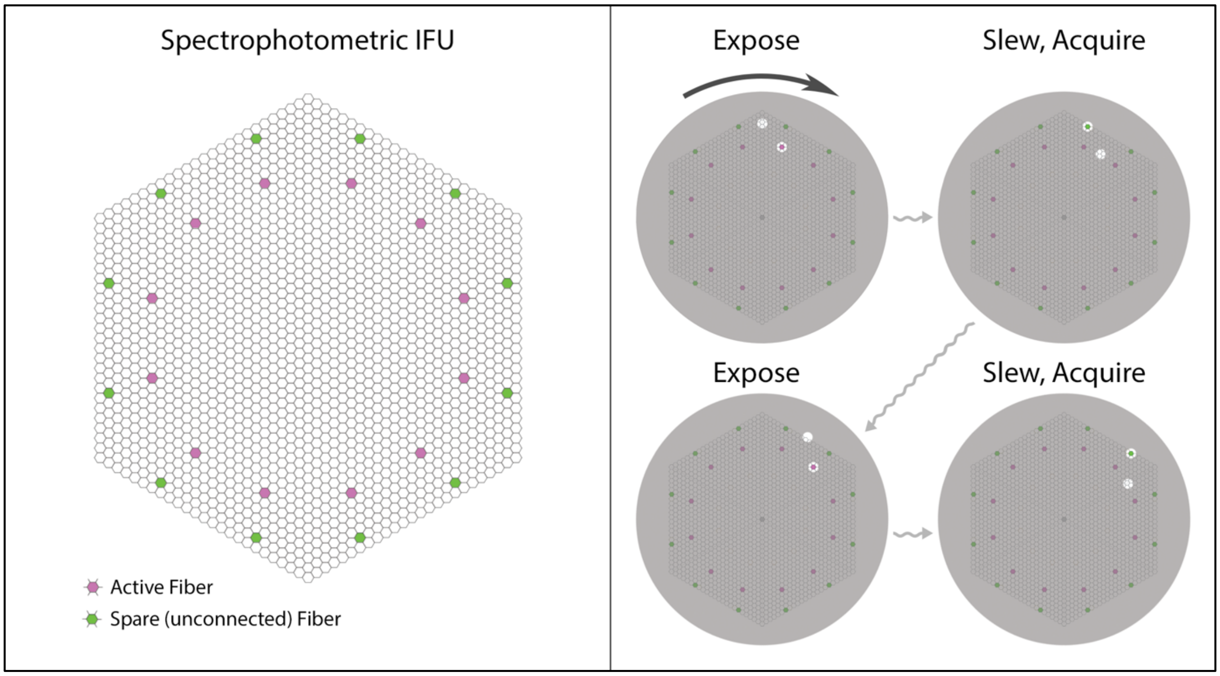

Figure 8: The spectrophotometric fiber bundle (left) contains 25 rings just like the science IFU, but only rings 19 (purple) and 24 (green) are populated with 12 fibers each. This allows for 12 spares (green here). The rotary hole mask (right) exposes the individual fibers in sequence and blocks the active (purple) fibers during slew and acquisition.

3.3.5 IFU / Fiber Bundle Interface

The final component of the LVM telescopes is the IFU interface. This structure (Figure 7) supports the Acquisition and Guiding hardware described in previous sections and provides a stable mounting location for the fiber bundle. Further details appear in Feger et al. (contribution 11447-204 at this conference).

4 MOTOR CONTROL HARDWARE

The LVM telescope system contains eight motorized mechanisms: four objective lens focusers, three K-mirror de-rotators, and one fiber selector. See previous sections for details. We have identified suitable commercial motorized stages for each of these mechanisms. Since all of these stages employ conventional stepper motors, we have elected to use the standard MPIA in-house motor controller units. These have been deployed for several instruments at 2-8 m class telescopes, and the hardware integrates well with the “Twice as Nice” middleware (see next section).

A single MPIA motor unit can host up to three “MoCon” cards, which can each control up to eight motors. This means that a single Motor Unit has more than enough capacity to drive all of the mechanisms of the LVM telescopes. Nevertheless, we are producing two Motor Units to allow for spares and software development.

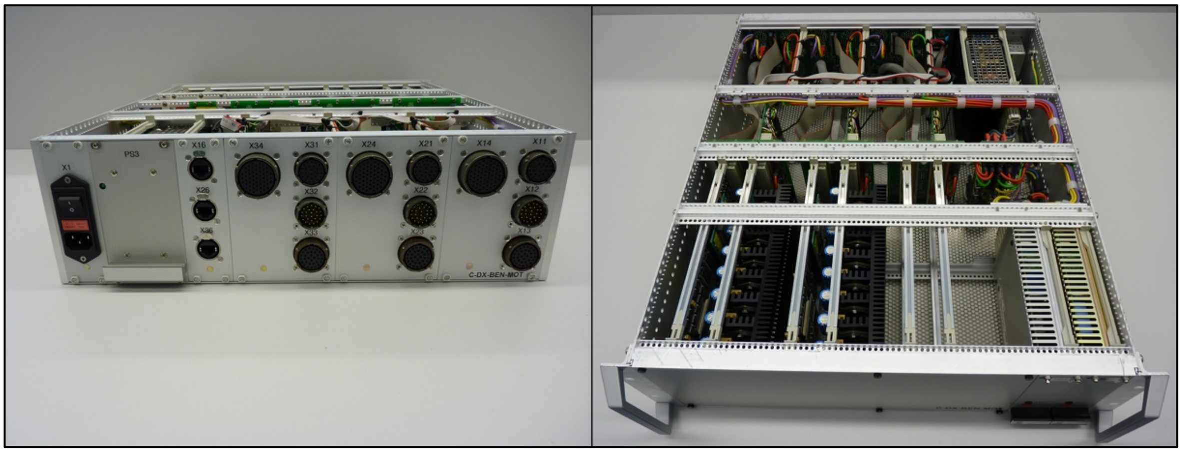

Figure 9: Rear (left) and top (right) view of an MPIA Motor Unit. This particular Motor Unit` handles 16 stepper motors and their associated limit switches and encoders (both absolute and incremental).

5 CONTROL SOFTWARE

For compatibility with the remainder of LVM-i, all components of the telescope system will be controlled via a simple client-server architecture and software development kit. The interfaces are standard and open (ethernet, TCP/IP, etc.) with commands that are easy to transmit using a wide range of operating systems (linux, Mac OSX, etc) and programming languages (python 3, C++, etc..). For these reasons, and because we have extensive experience with it, we will use the MPIA-developed "Twice as Nice" (TaN) middleware and instrument control software. This codebase provides direct python and C++ interfaces to low level functions, as well as engineering GUI's for motors and GigE sensors, such as the AG cameras. It was developed concurrently with the MPIA Motor Units and the two work seamlessly together. Note that the TaN camera interface will be for engineering and development only, as the final system architecture will have a direct link between the high-level software and the AG sensors (Figure 10).

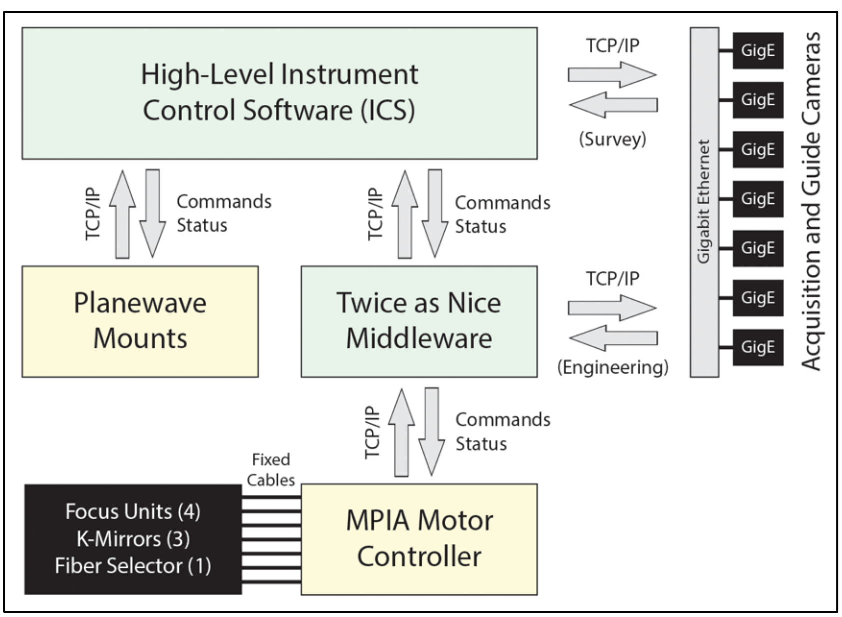

Figure 10: Overall software architecture of the LVM telescope system.

6 IMPLEMENTATION PLAN AND SCHEDULE

With its various elements coming from four different continents (Europe, North America, Australia, and Asia) for eventual AIT and use in a fifth (South America), the logistics of the LVM telescope implementation are complex. All individual sub-systems, such as the objective lenses and K-mirrors, will be tested at unit level before integration. The baseline plan is then to bring together at least one full telescope (i.e. siderostat plus optical table) in one of the large assembly halls at MPIA in Heidelberg. This will allow definition and refinement of the techniques for integration and alignment. This will be followed by on-sky tests either at MPIA or at Carnegie Observatories in Pasadena. If the procedures prove simple and robust, assembly and testing of the remaining three telescopes will take place at Las Campanas.

As with many projects, the current pandemic has had an impact on LVM planning. As of December 2020, much of the work has been focused on concept and design, activities that are well suited to a home office situation. Nevertheless, hardware is beginning to show up, and the need for direct laboratory access is increasing. The current aim is to ship the first telescope in late 2021 with the goal of completing commissioning and beginning the survey early in 2022.

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