Optical Design & Engineering

Building the world's largest digital camera

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A flat, mechanically and thermally stable focal plane will help the Large Synoptic Survey Telescope generate unprecedented measurements of dark matter and insights into the nature of dark energy.

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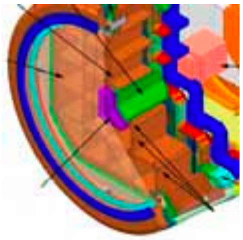

Dark matter and dark energy are now believed to constitute about 95% of the mass in the universe, and yet we know little about the nature of either. The Large Synoptic Survey Telescope (LSST) is a ground-based instrument designed with the sensitivity to map the evolution of dark matter and energy back to about half the current age of the universe. The telescope and digital camera will generate a large and precise data set, enabling physicists to apply many complementary analysis techniques. One of these, 'gravitational weak lensing,' is a primary driver of the LSST design. The subtle gravitational distortion of light from the expected three billion newly detected galaxies can be used to map otherwise invisible dark matter. The system is expected to dramatically improve measurements of Type Ia supernovae, used to track the expansion rate of the universe, which is believed to be driven by dark energy.

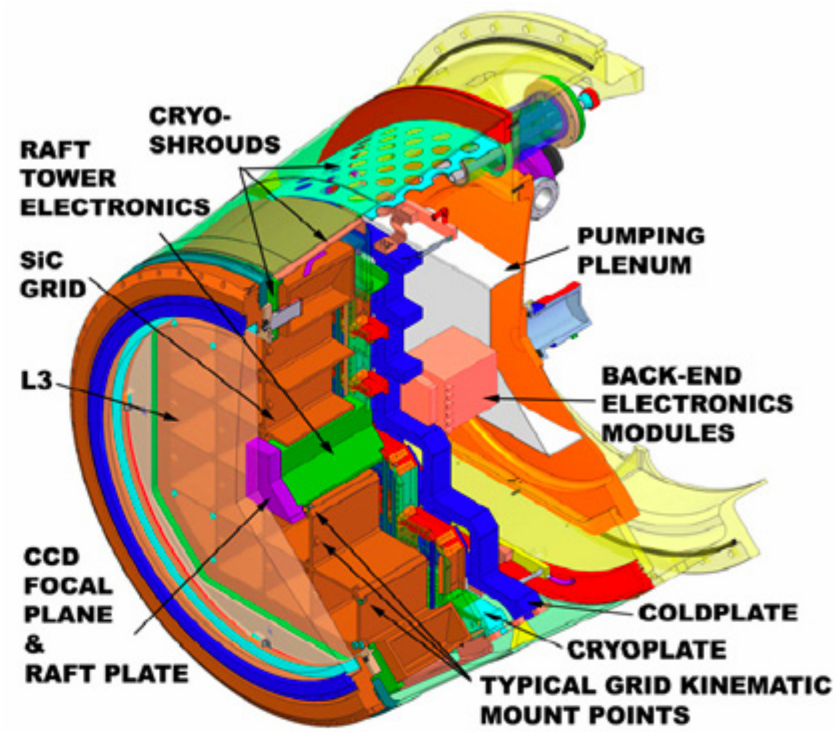

Figure 1. *Cross section of the cryostat. SiC: Silicon carbide. L3: Third lens in the optical train.*

Scientists have long deployed smaller, multi-CCD imagers for use with optical telescopes, but rarely designed them from the start as a single 'system' to maximize both the survey field and light-collection capability, while minimizing exposure, readout, and recovery time. The LSST, a three-mirror, 8.4m (diameter)-class telescope and its imager are designed as a single wide-field survey system with very fast (focal ratio, *f*/1.23) optics coupled to a 3.2 gigapixel camera. Its 63.4cm diameter focal plane (FP) samples the 3.5°field of view at 0.2 arcseconds/pixel. Short (15s, <2s readout time) exposures will allow us to map the sky every few nights, producing a 20,000 deg^2, six-color (350–1070nm) survey to a depth of r_{AB}~27.5mag (AB magnitude) in 10yr. The temporal picture will enable us to rapidly detect faint and transient phenomena.

To achieve quality images, LSST's narrow depth of field relies on tight control of the FP's flatness and stability (10μm peak to valley, PV). Its high quantum efficiency in the near-IR and low noise requires thermally uniform and stable

~100μm-thick back-illuminated CCDs. The camera's short exposures and fast recovery spurred development of a custom 4k×4k, 16-port CCD on a four-sided buttable package. This package will have a 95% active area and readout with fast, massively parallel low-noise electronics within the cryostat. We must also prevent contamination of the FP from circuit boards and cables.

Cameras on past telescopes have rarely needed the flatness and thermal stability of LSST's FP, or the short exposure and readout times. With many fewer CCD channels, most of their electronics could be located in close proximity, outside the vessel holding the cold FP. By contrast, the LSST's large physical size requires a unique modular approach to FP construction. The 189 CCDs and ~3000 electronics channels must be housed in a common vacuum-insulating cryostat, necessitating careful control of contaminates (see Figure 1). The plane itself is built using 21 identical subcameras (rafts towers). Each contains a 3×3 array of CCDs on a silicon carbide (SiC) base (raft plate), front-end electronics (FEE), and back-end readout (BEE). Each raft is kinematically mounted (see Figure 2) into a pre-adjusted bay of a larger SiC structure (or 'grid'). The grid's stiffness, small thermal-expansion coefficient, and high thermal conductivity help guarantee a flat, fully aligned CCD mosaic, while the camera operates in all orientations and changing thermal environments. The submicron reproducibility of the kinematic mounts allows us to fabricate and rapidly assemble identical parts. We also developed a noncontact metrology system to verify the flatness of the FP during and after assembly, and in its cold operating state. The vacuum design maximizes FP pumping while minimizing molecular flow. In addition, we built an ultrahigh-vacuum material-test facility to ensure control of potential contaminates from materials introduced into the cryostat.

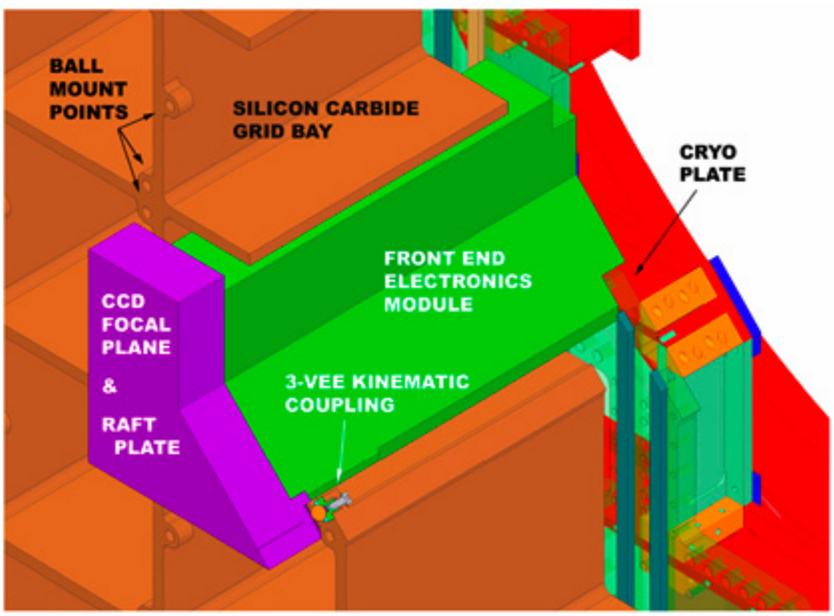

Figure 2. *Detail of the grid and focal plane. 3-VEE coupling: Coupling based on three V-shaped grooves to receive three balls.*

We addressed the unique LSST problems by modularizing and isolating the FP components from external thermal and mechanical influences. In particular, we used SiC for major structural elements, which is critical for achieving a robust and compact design.[1] Our design philosophy was to minimize any significant contributions to FP aplanarity resulting from changes in the gravity vector during operation. Precision assembly and alignment of the FP is based on the submicron reproducibility of kinematic mounts (three-vee couplings). The overall FP aplanarity assumes that CCDs are fabricated planar to ~5μm PV and that a 3×3 CCD array can be assembled onto a SiC raft plate to ~6μm PV aplanarity. Each raft plate contains three-vee blocks for subsequent mounting onto Si-nitride balls fastened onto the grid. The ball height pre-adjusts so the grid's aplanarity contribution is within the 10μm PV allowance. A spring mechanism applies ~5g force to hold all three couplings to the grid. With an 18cm-thick grid, any mechanical distortion of the FP does not exceed 1.2μm.

We also addressed thermally induced effects on FP alignment. We aim to operate the CCDs at −100°C and maintain <0.5°C overnight variation across each. To do so, we isolated the grid from all heat sources. Radiation of ~100W enters the cryostat through the front window, primarily onto the CCDs. Other heat sources include radiation from the FEE in each grid bay and from the cryostat walls (which are fixed at ~20°C), and small conductive leaks where the grid is kinematically mounted to the cryostat. A copper 'cryoplate' located just behind the grid provides all heat extraction. Its pockets align with the bays and embedded channels cross flow refrigerant at ~−120°C. After kinematically mounting each raft in its bay, the FEE housing (containing FEE boards and copper conduction plates) is retracted and tied thermally to the cryoplate to remove ~25W/bay from the FEE and CCDs. We conductively cool each CCD through adjustment studs attached to the raft plate. This, in turn, is tied by thermal straps to the FEE cage and the cryoplate. A thin copper ‘shroud’ tied to the cryoplate surrounds the grid's outer diameter. Where possible, it also surrounds the front face to reduce external radiation. By design, the FEE cage and grid are close in temperature (10–20°C) and have small radiative coupling. In each bay, close to the face, two opposing thermal straps are pre-attached, and tied directly to the cryoplate below. The excellent thermal conductivity of SiC helps keep the grid almost isothermal (<0.5°C variations) and limits induced mechanical distortions to ≪0.5μm. Heaters on the raft-plate straps and the grid-bay thermal straps can make small thermal adjustments.

One of the difficulties in constructing such a large FP is verifying its flatness. We have developed a technique that uses a pair of noncontact range finders to differentially measure the FP's surface figure against a smaller optical reference. We can then ‘stitch’ together the entire FP. This technique has been demonstrated in air with a standard deviation of ≪1μm, and we are verifying its use through a thick vacuum window, as required during camera assembly.[2]

Finally, we addressed the control of contaminates in the cryostat by segmenting the vacuum spaces to minimize molecular flow from regions with electronics. Temperatures are controlled to maximize cryopumping onto benign surfaces. We are also developing a dedicated facility to qualify all materials in the cryostat. It measures the outgassing species and rates, their temperature dependence, and the light absorption by molecules deposited onto optical surfaces. This characterization program is underway and will allow us to optimize the pump configuration for the camera.

The LSST's imager has had to deploy new materials and new approaches for its assembly, alignment, and testing to meet image-quality requirements over its 10yr lifetime. Our current work focuses on prototyping critical elements of the focal plane, as well as developing our metrology and contamination test programs.

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Rafe Schindler is a professor of physics. He is currently working on the design and prototyping of elements of the LSST camera.

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