Large Synoptic Survey Telescope Camera System Plan	Document No. **LCA-283-F** Author(s) Aaron Roodman Martin Nordby	Status LSST Camera APPROVED Effective Date 14 Feb 2018
	Subsystem Integration and Test, Systems Integration	
Document Title **LSST Camera Verification Test Plan**		

1 Change History Log

Revision	Effective Date	Description of Changes
A	Oct 7, 2011	Version for CD1
B	June 25, 2015	Revised for CD3
C	Dec 7, 2015	Revised for I&T Review December 2015
D	March 14, 2016	Revised for I&T Review March 2016
E	September 28, 2017	Revised to respond to I&T Review comments. Release per LCN-1551.
F	February 14, 2018	Revised to account for Guider ICD changes per LCN-1446

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5 Acronyms and Definitions

5.1 Acronyms

BFOA	Best Fit Optical Axis
CCS	Camera Control System
CG	Center of Gravity
DAQ	Data Acquisition
HCU	Hardware Control Unit
ICD	Interface Control Document
I&T	Integration and Test
IQ	Image Quality
LSST	Large Synoptic Survey Telescope

MCM	Master Control Module
MOI	Moment of Inertia
OCS	Observatory Control System
REB	Raft Electronics Board
RSA	Raft Sensor Assembly
RSS	Root Sum Square
SLAC	formerly Stanford Linear Accelerator Center
SMR	Spherically Mounted Retro-reflectors
TBD	To Be Determined
TBR	To Be Resolved

5.2 Definitions

Ass'y: signifies final integration of an on-telescope component

6 Applicable Documents

[1] LCA-40, "Camera Integration and Test Plan"

[2] LCA-48, "Camera Specification"

[3] LCA-38, "Camera System Engineering Management Plan"

[4] LCA-17, "Image Quality Error Tree"

[5] LCA-10147, "LSST Camera Assembly and Alignment Tolerance Stack-ups"

[6] LCA-11795, "BOT Specifications"

[7] LCA-13371, "I&T EO Algorithms"

[8] Rasmussen, A.P. et al., Focal plane metrology for the LSST camera, Proc. SPIE 6273, 62732U (2006)

[9] Bauman, Brian J, and Hong Xiao. "Gaussian Quadrature for Optical Design with Noncircular Pupils and Fields, and Broad Wavelength Range." *International Optical Design Conference 2010. Edited by Bentley* 7652 (July 2010): 98.

[10] M. Fisher-Levine & Andrei Nomerotski, PACCD 2014.

[11] LSE-130, "Support-Data Exchanges between Data Management and Camera".

[12] LCA-119, "Camera Mass Workbook".

[13] LCA-11976, "CCOB Specifications".

[14] LCA-XXXX, "Camera Operations Plan"

[15] Janesick, "Photon Transfer".

[16] Astier, 2013.

[17] LCA-10103.

7 Purpose and Scope

This document describes the plans for verifying system-level Camera requirements during Integration and Test (I&T), prior to Camera delivery. [Ref. 1] describes the context in which these tests are performed in the integration and test process, along with plans for managing the process. [Ref. 2] describes all camera system requirements that are addressed in this Plan. This document includes a description of verification plans for all requirements in [Ref. 2], whether by inspection, demonstration, test, measurement, analysis, or some other method, including assignment of verification to subsystem-level testing, or incorporating subsystem requirements verification as part of system-level testing.

Note that this Plan does not currently include verification methods for Camera interface requirements, except those that have been incorporated into [Ref. 2].

8 Verification Plan Overview

Camera and subsystem requirements have been developed and validated according to the processes described in [Ref. 3]. This process strives to ensure that requirements are flowed down to the level at which they can be verified and are fully separable from other requirements. This process leads to requirements with minimal ambiguity, and also provides clear understanding of the level at which they need to be verified. In general, requirements are verified at the level where they are levied. This may require simulators or test hardware to mimic missing components of other subsystems that are needed to fully verify a requirement. The need for such test hardware and its functionality is captured in subsystem interface documents.

Verification of interface requirements is also handled at the level where the requirement is levied, to ensure that interface agreements can be met at the next higher level of assembly. This may require interface simulators or test set-ups.

9 Requirements Verification Methods

Camera requirements defined in [Ref. 2] are verified through a series of tests and analyses described below. The requirements have been grouped by verification method to aid in the development of the test. These groupings are shown in [Ref. 2], as well as the tables in this document. The following verification work is planned for fully verifying camera requirements:

- Verification by Analysis
- Operations Plan Analysis
- Bench for Optical Testing (BOT)
- Metrology (BOT)
- Survey and Alignment
- Systems Dynamics Test
- Mass Properties
- Cryostat Functional Test
- Camera Functional Test
- Camera Calibration Optical Bench (CCOB)

I&T Report

Shipping Analysis

Fixture Proof Test

Pre-ship Review

These verification methods are discussed in the sections below.

10 Verification by Analysis

Certain high level Camera requirements can only be verified through analysis.

10.1 Camera Image Quality

The requirement on the Camera's image quality (IQ), listed in (Table 1), can only be verified through an analysis combining individual test results with calculations. [Ref 4] contains a detailed IQ error tree, tabulating each possible source of IQ degradation. The verification of the IQ requirement will be performed via an analysis that follows the logic of the error-tree. Each constituent requirement will be verified, either by an I&T level system test, the appropriate sub-system test, or in some cases only by analysis. The results of these measurements will be combined with the same methodology used in [Ref 4]: each contributing factor is measured and the results converted into the impact on mean FWHM in r-band through a sensitivity factor, then these individual factors are combined through a sum in quadrature (RSS). A number of the contributing factors may have measurement errors of similar order of magnitude to the value of the quantities themselves. In this case, one sigma (standard deviation) of the estimated measurement error may be included in the RSS.

Table 1 Camera Requirements verified by system-level Analysis.

ID	Title	Requirement	Verif Meth
C-044	Camera max image quality error	The maximum delivered image quality error for the camera shall be less than 0.30 arc-seconds FWHM	Test/Analysis

The IQ error tree has contributions from the following categories: Optical Fabrication, Raft Sensor Assembly, Assembly and Alignment, Gravity-Induced, Thermally-Induced, Pressure-induced, Vibration-induced. The IQ contribution from all of these are included as individual camera requirements and will be the subject of a more detailed discussion in the relevant sections of this document.

10.2 Operations Plans

The camera operations plan [Ref 14] will describe planned maintenance throughout the life of LSST. The plan will estimate the scope of the maintenance tasks necessary during planned downtimes. Requirements concerning operations are listed in (Table **2**). Note that these requirement do not invoke the need to verify by reliability analysis. Verification will be performed by an analysis that identifies likely hardware failures and identifies mitigations to minimize downtime caused by those failures.

Table 2 Camera Requirements verified by Operations Plan Analysis.

ID	Title	Requirement	Verif Meth
C-133	Camera unplanned downtime	The Camera shall be designed to facilitate unplanned repair activities expected not to exceed 10 days per year.	Analysis
C-205	Camera planned downtime	The camera shall contribute no more than 7 days of observatory downtime due to maintenance requirements	Analysis
C-001	Camera lifetime	The camera and all subsystems and components shall be designed to operate for at least 15 years	Analysis

10.3 Baseline Performance

Results from all relevant verification tests of camera performance, including such quantities as optical alignment, optical reflections, Camera throughput, CCD diffusion, cross-talk, noise, bad pixels, etc.., will be delivered to the LSST project, satisfying (Table 3). Models of the Camera, supporting the description of the baseline performance, are described in Section 13. Additional details about the information to be included may be found in [Ref 11].

Table 3 Requirement to deliver Baseline Performance

ID	Title	Requirement	Verif Meth
C-206	Baseline performance	The camera shall provide the initial baseline performance as determined during acceptance testing and system integration and test	Analysis

11 System-Level Verification Tests

Verification tests are performed at all stages of the Camera integration process. Tests made during integration ensure that camera components remain functional and provide a mechanism to identify problems early in the integration process. Verification tests performed at the end of major stages of integration serve to directly test that camera requirements are met. The tests performed by the I&T camera system act in concert with requirement testing done by the various component systems. I&T

tests emphasize system-level requirements, including those tests which can only be performed at system level, or where testing is needed to verify that performance at the component level is maintained at the system level.

11.1 Bench for Optical Testing

The Bench for Optical Testing (BOT) will consist of a variety of verification test equipment, designed to thoroughly assess the electro-optical characteristics of the CCDs and Rafts integrated in the cryostat, but without the full camera or optics. The BOT will include equipment for the following kinds of electro-optical tests:

- Dark images
- Flat Fields
- ^{55}Fe source
- Scene images: Multi-spot and single spot images
- CCOB Wide-beam images

This array of BOT tests will verify a number of the camera requirements:

- Noise requirements as described in (Table 4), using Dark images
- Linearity and Dynamic Range requirements as described in (Table 5), using Flat Fields
- Gain requirements as described in (Table 6), using ^{55}Fe source runs
- Crosstalk requirements as described in (Table 8), using Multi-spot images
- Dead Pixels as described in , using both Dark images and Flat Fields

The BOT electro-optical tests are performed when the first science rafts are installed in the cryostat and are repeated with each iteration of raft integration. These tests also represent the first time that multiple raft towers are integrated and read out in common by the full data acquisition system. During this stage of cryostat integration basic functionality will be demonstrated, CCS/DAQ read out and data processing exercised, and a number of requirements verified or re-verified. Next we describe the various BOT components together with their associated verification testing capabilities. Note that the electro-optical requirements for the BOT are described in a separate document LCA-11795. The current concept for the BOT is shown in (Figure 1).

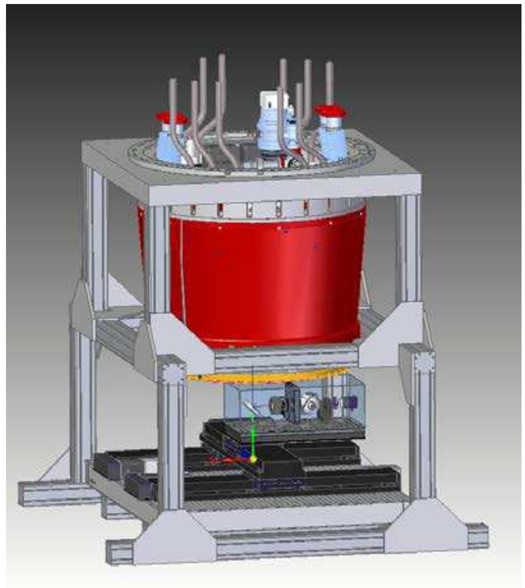

Figure 1 Concept for the BOT, showing the Scene Projector mounted on the XY stage.

11.1.1 Test Equipment & Capabilities

11.1.1.1 Dark Images

During cryostat-only testing, there will be no shutter available, and so the BOT will employ an exterior shroud to block all external light. Therefore all light sources and projectors in the BOT must be capable of turning off their light sources or must contain suitable shutters. Thus the BOT will be capable of taking Dark images (darks). Darks are used for several purposes: to verify the noise requirements, to assess dark current and thereby bad pixels and to collect bias images needed for the image analysis pipeline. Since the Science Raft sub-system definition of a bad pixel includes a requirement on the dark current of $< 5\ e^{-}/sec$, the BOT shroud must reduce the light level to well below this value, even when the Clean Room lights are on. Darks are taken as normal Camera images, with the desired integration time.

Dark images are also used to create Bias calibration images. An ensemble of many dark images are taken, each is overscan corrected, and the median value per pixel is calculated. The resulting Bias image is used in the image reconstruction pipeline.

11.1.1.2 Flat Fields

The BOT will have the capability to produce *flat fields*, with roughly uniform illumination across the entire focal plane. Note that uniformly illuminating the bare LSST focal plane is challenging because of the large size of the focal plane, and the lack of any optical system. We are considering two concepts to produce flat fields. First, our nominal concept is to place a luminescent screen comprised of leaky optical fibers followed by optical diffusers directly in front of the cryostat window. This concept is under test and should produce a reasonably flat field. A second concept, should it prove necessary, is to use a Lambertian point source placed at a distance of roughly a meter from the focal plane. This will also produce a smooth light distribution, albeit one with a $cos^4\theta$ fall-off in the illumination pattern.

We note that the Flat Field is not needed during I&T to produce a calibration gain-correcting image, since we will use the CCOB wide beam for this purpose. As a result, the Flat Field need not be highly uniform across the entire focal plane, but rather needs to be uniform and smooth in illumination just over a single CCD. Note that the light source must be turned off, being sure that there is no residual glow, or must be behind a mechanical shutter. Also, the light intensity must be independently monitored to normalize the flux in testing.

A concept under development for the flat field utilizes a leaky fiber placed in a spiral groove to emit light uniformly. The fiber is covered with an optical diffuser to yield more uniform illumination. The prototype Flat Field screen is shown in (Figure 2).

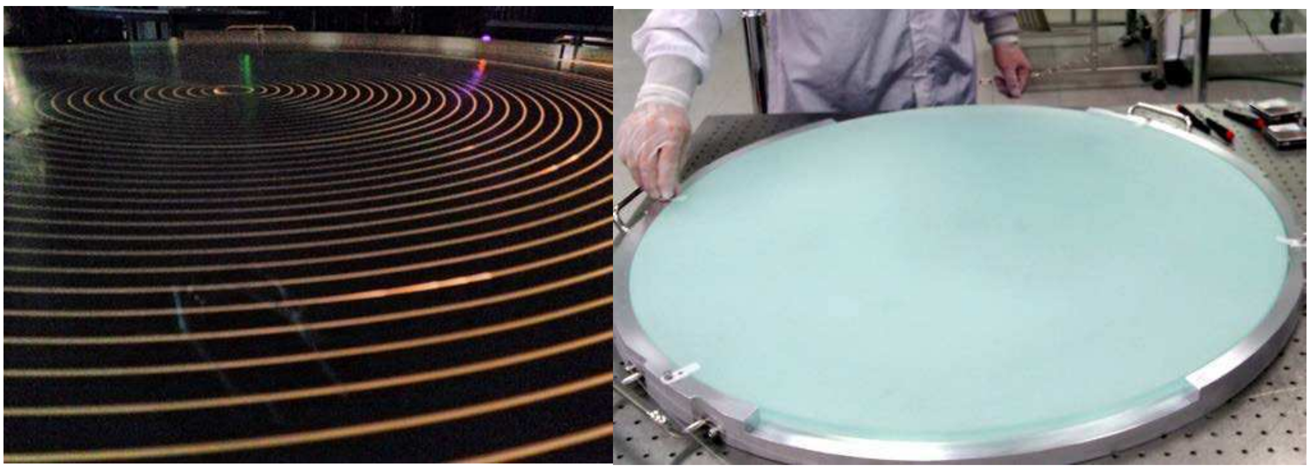

Figure 2 Prototype Flat Field Screen using a leaky fiber placed in a spiral grove, plus optical diffuser.

Flat fields will also be used to measure gain and noise through the *photon transfer* method, as described in the book *Photon Transfer* [15]. Briefly, since the signal measured in ADU is given by:

$$S_{ADU} = Gain\ N_{e^-}$$

then the variance of the signal is given by:

$$\sigma_S^2 = Gain * S_{ADU} + \sigma_{Noise}^2$$

Thus a plot of the variance σ_S^2 versus S_{ADU} should be linear, with slope given by the Gain in [ADU/electron], and intercept given by the square of the noise. The noise measured here should agree with that found in dark images. In practice, the variance is found by taking the difference of two flat field images, cancelling any illumination variations, and an ensemble is formed from all pixels in an amplifier, yielding a distribution with zero mean and variance of $2\sigma_S^2$.

In practice photon transfer curves deviate from linear variance due to the brighter-fatter effect [16] a space-charge effect in the CCD wells that causes the variance to be reduced for large signal sizes. Photon transfer curves may then be used to characterize the brighter-fatter effect for each CCD.

11.1.1.3 ^{55}Fe

Ultimately the cryostat window is the L3 optic. However, during cryostat installation and verification testing we will use a flat window (L3 flat) instead of the optic, because L3 will not be available at that time and also because the curved surfaces of L3 would interfere in BOT and metrology testing, as described below. The L3 flat will be attached to the cryostat with an identical cell, but we will also place a stand-off ring between the cryostat and the L3 flat's cell. This stand-off ring will have identical mounting features, but will allow us to place ^{55}Fe sources around the perimeter of the ring, such that the focal plane can be exposed to the ^{55}Fe x-rays, albeit at a large glancing angle. The ^{55}Fe sources will be placed inside electronically controlled shutters, allowing us to easily alternate between collecting ^{55}Fe data and the other BOT electro-optical tests, but without having to break vacuum or warm up the cryostat, both time consuming operations.

The decay of ^{55}Fe produces an x-ray with an energy of 5.9 KeV, the K-alpha line, with additional small lines at 6.5 KeV and 4.1 KeV. The 5.9 KeV x-rays have an absorption length of approximately $25\mu m$ in Silicon, and deposit their energy via the photo-electric effect producing an essentially point-like cloud of 1620 electrons. Diffusion in the CCD may then cause the ionization electrons to migrate to neighboring pixels, producing a cluster of more than one pixel. Note that since the ^{55}Fe x-rays may have a large range of incidence angles, from 10 to 80 degrees. At the most glancing angle, of 10^{o}, the average absorption depth in the CCD will be only $4\mu m$.

11.1.1.4 Scene Projector

The BOT will contain a moveable X-Y stage, capable of transporting a small optical bench across the entire focal plane. Different projectors or illuminators can be mounted on this optical bench. One such device will be a scene projector, capable of delivering an image with a size at least as large as a single CCD onto the focal plane. Various optical designs are possible, but perhaps the simplest is to illuminate a mask with the output of an integrating sphere and then project the image of the mask onto the focal plane with a commercial 35mm lens. By inserting different masks, various images can be projected onto the CCDs, including a multi-spot image, a single spot, an Air Force target, as well as any desired publicity image.

The scene projector will be used to project a pattern of large spots on a CCD, with one spot per amplifier, arranged such that each amplifier has a different region illuminated. This projector should also be capable of projecting spots comparable in size to the LSST seeing blur, ie. 3-4 pixels FWHM. The spot projector will be used to evaluate the full-well and linearity of each CCD with a point source, as a check of these measurements with flat fields, and will also enable us to study any local CCD properties such as edge effects or the midline stop, should this prove necessary during I&T. Lastly, it will provide an artificial star for the Guider CCDs should that prove to be necessary.

In addition, the CCOB reflection-based alignment study described below requires that we know the relative lateral position of the CCDs to an accuracy of a few microns or better. This can be done by illuminating the focal plane with pairs of spots. The projected distance between spots may be calibrated by placing all the spots onto a single CCD. Next, by illuminating neighboring CCDs with the spot array we can determine the spacing between CCDs.

11.1.1.5 CCOB Wide Beam

As noted above, the large size of the focal plane and lack of optical train makes it difficult to produce a single highly flat field illumination. Instead, the BOT will also include a special illumination instrument, the CCOB wide beam, that will project a highly reproducible spot suitable for determining the response of the entire focal plane. The CCOB wide beam's spot, roughly one CCD in size, must itself be accurately measured. Then this beam will be rastered across the focal plane, with overlapping spots, and the resulting images will be stitched together to produce an effective flat field in each of the filters bands. This resulting flat field will effectively measure the throughput of the entire focal plane. The CCOB wide-beam will be capable of producing a spot in each of the six LSST filter band.

The wide beam's light sources will be individual LEDs, with wavelengths for each of the six LSST filter bands, monitored by a NIST calibrated photo-diode. The CCOB wide beam must be designed to provide a highly stable, reproducible spatial profile. Lastly, the internal accuracy and repeatability of the beam flux is required to be at the 0.1% level, achieved using a NIST calibrated photodiode. The CCOB wide beam must be transported across the entire focal plane, and held at a constant distance from the focal plane, to yield the necessary stability in beam profile.

11.1.1.6 Pocket Pumping

The Science Rafts and associated Raft Electronics Boards (REB) are capable of clocking the CCDs to perform pocket pumping, used to search for pixels with traps. In such images, the CCDs are illuminated with the Flat Field and prior to readout charge is clocked repeatedly down and then back up a number of rows. This procedure causes electrons to fill traps, which slowly empty dumping charge in a different pixel's readout. Pocket pumping is used to locate bad pixels as described below in Section 11.1.2.6.

11.1.2 Expected Test Results & Verification Analysis

Data from all BOT electro-optical tests is collected by the Camera DAQ/CCS system. The DAQ/CCS collects both focal-plane data and auxiliary data from the BOT test equipment through the appropriate HCUs. The auxiliary data includes such quantities as the location of the BOT's XY stages, the flux in monitoring diodes, and temperatures of the BOT equipment, all of which are readout through HCUs. Each test must include an appropriate DAQ/CCS script, responsible for synchronizing the test equipment with the start and stop of the CCD readout. Since there in no single shutter for the focal plane during BOT testing, the synchronization of the various illumination sources is particularly critical.

Data analysis of the BOT data is performed by a collection of dedicated analysis scripts, custom written for each test. Many of these analysis scripts may be reused, or only lightly modified, from those used in sensor and raft testing performed by the Science Raft sub-system. These data needed and algorithms used in the Science Raft scripts is described in LCA-10103 and the code for the scripts is maintained at https://github.com/lsst-camera-dh/eotest .

Algorithmic details pertinent to the BOT tests described above are given in LCA-13711. Note that the data analysis scripts will produce graphical and tabular summaries for each test. These results will be curated to ease future data access, and to enable meta-analysis of trends.

11.1.2.1 Noise Requirements

The Noise requirements are described in (Table 4) and are verified by analysis of Dark images, yielding a noise RMS for each kind of raft and sensor. For both Science and Corner Rafts, we collect 15 second Dark images. The images are overscan and bias corrected, and bad pixels and columns, as defined below, are removed. Then the RMS of all good pixels is evaluated for each amplifier, on both Science and Corner rafts. The value of the RMS is compared and verified against the requirements in (Table 4).

Note that a small contribution from dark current R_{dark} will also be present in each dark image, which will contribute a small amount, ($\sigma_{dark} = \sqrt{R_{dark} * time}$) to the RMS. This contribution is determined by analyzing the signal level and RMS of dark images with a wide range of integration times. The baseline noise measurement is not corrected for this contribution, since the requirement assumes that dark current is present.

Table 4 Noise Requirements verified by the BOT tests.

ID	Title	Requirement	Verif Meth
C-036	Camera electronic noise	The electronic noise from the LSST Camera system shall contribute no more than 9 electrons per exposure to each pixel in the data from the science sensor array	Test
C-272	Read Noise	The camera read noise shall be less than 9 electrons for data from the ROI acquired at the nominal integration time of 50 msec. This specification includes dark current.	Test
C-179	Readout noise	Wavefront detector readout noise shall be less than 10 electrons in a 15 second exposure	Test

11.1.2.2 Linearity and Dynamic Range Requirements

The Linearity and Dynamic Range requirements are described in (Table 5). Flat fields are used to verify the requirements on linearity, by measuring the response as a function of the signal. The signal may be varied by either changing the exposure time under constant light intensity or alternatively by varying the light intensity directly. For each exposure time we average the signal per amplifier, after performing overscan and bias corrections and removing bad pixels. The average signal is plotted against the integration time for each amplifier. It is important to include zero exposure time images and short exposures at low intensity as well as to run the flux up to the CCD full well value. This yields a response curve with the average signal vs. exposure time for each amplifier. From the shape of this curve we directly verify the requirement that the linearity be better than 3% from zero to the minimum full-well level of 90k e^{-}.

With this data, the required dynamic range without saturating the CCDs may also be verified. The calculation of the necessary full well corresponding to a source *8 magnitudes* above the *5 sigma r band limiting magnitude* was performed in Document-10512, yielding a value of $90k\ e^{-}$. (An updated analysis using more realistic QE curves, and starting from the brighter LSR limiting magnitudes yields 107k e^{-} in the y4 band. This corresponds to a source with $2.5 \times 10^{6}\ e^{-}$, with a maximum central pixel fraction of 0.085 for 0.63" seeing, plus an additional 900 e^{-} from the sky. But the requirement is specified just in r band, so this does not place an additional demand on the dynamic range.) Note that we use the Gain per amplifier determined from either Photon Transfer or ^{55}Fe to convert the flat field signal from ADU to e^{-}. Then we verify that the full well is greater than the required flux level of $90k\ e^{-}$.

Table 5 Requirements on Signal Linearity and Camera Dynamic Range

ID	Title	Requirement	Verif Meth

C-123	Detector signal linearity	Maximum deviation of detector response from a linear fit up to full well < 3 % of full well signal	SS Verif; I&T Test
C-159	Camera dynamic range	The camera shall have a unsaturated dynamic range of at least 8 magnitudes above the 5-sigma r-band limiting magnitude in a standard 15 second exposure.	Test/Analysis

11.1.2.3 Gain Stability Requirements

The Gain Stability requirements are described in (Table 6). The ^{55}Fe data will be used to verify the gain stability requirements, since illumination sources are not sufficiently stable over such long periods needed to meet these tight requirements, while an x-ray source is ideally suited to such measurements. The focal plane will be exposed to the ^{55}Fe sources by opening the shutters located in the cryostat stand-off ring, and after an appropriate exposure duration, the shutters are closed and the focal plane is readout. The images are overscan and bias corrected, and then X-ray clusters are identified and the signal in a fixed sized window, typically 9 pixels, is summed. The number of ADU divided by 1620 e^{-} yields the Gain of the amplifier. This process is repeated over both a 1 hour and a 12 hour period. The RMS variation in Gain as a function of time is determined to verify the Gain stability requirements.

To verify gain stability at the 0.1% level requires that each individual measurement have a statistical uncertainly significantly better than this level, say at the 0.03% level. For a Fano factor for Si of 0.12, the uncertainty on the determination of the ^{55}Fe peak location should dominated by shot noise especially when summing over a fixed pixel aperture. For a fixed sum of 9 pixels for each x-ray cluster, we estimate $\frac{\sigma_{peak}}{Peak} = 1.7\%$ for shot-noise, plus a contribution from the charge diffusing outside this region. At this level of uncertainty we require around 5000 x-rays per measurement. Our source must be able to provide this number of x-rays per amplifier in of order one to two minutes, yielding many individual gain measurements over the desired 1 or 12 hour period.

Table 6 Gain Stability Requirements verified by the BOT tests.

ID	Title	Requirement	Verif Meth
C-394	12 hour stability	The video channel gain shall be stable to within 1% rms over a 12-hour observing period. Alternatively appropriate algorithms and telemetry data shall be provided to enable reconstruction of changes in video channel gain to within 1% rms over a 12-hour observing period	Test/Analysis

C-395	One hour stability	The video channel gain shall be stable to within 0.1% rms over a 1-hour observing period. Alternatively appropriate algorithms and telemetry data shall be provided to enable reconstruction of changes in video channel gain to within 0.1% rms over a 1-hour observing period	Test/Analysis

11.1.2.4 Image Quality and Diffusion Requirements

The requirement on CCD diffusion is included in the requirement listed in (Table 7). The corresponding section in LCA-17 allocates 0.233 arc-seconds FWHM to CCD diffusion, corresponding to $\sigma = 5\mu m$ diffusion for r-band light. This is by far the dominant contribution to the Camera IQ requirement. Therefore, while the CCD diffusion requirement is flowed to the Science Raft sub-system and verified there, this quantity will be measured during I&T as well. Note that we expect no change over time in the diffusion, an intrinsic property of the CCDs dependent just on the bias voltage.

Table 7 Image Quality Requirement from Raft Sensor Assembly, Including CCD Diffusion

ID	Title	Requirement	Verif Meth
C-047	I.Q. error due to Raft Sensor Assembly manufacturing, assembly errors	Maximum image quality error due to RSA manufacturing and assembly errors =0.242 arc-seconds	Test/Analysis

The CCD diffusion will be characterized from an analysis of the distribution of charge in the pixels from each ^{55}Fe x-ray clusters, using the same data taken for Gain stability. The ^{55}Fe images are overscan, bias and gain corrected, and bad pixels are masked. Clusters on the edges of the CCDs and along the mid-line stop are not used, due to known effective pixel size variation effects. The diffusion sigma will be measured for each amplifier and CCD, and the result converted to IQ FWHM, verifying this requirement.

Note an additional methodology to measure CCD diffusion uses cosmic rays making multi-pixel tracks through the Silicon, as described by (M. Fisher-Levine, 2015). Long dark images contain enough cosmic rays to make this measurement, which has been found to agree with results from ^{55}Fe x-ray, and has the feature that the diffusion as a function of absorption depth is also found. If time permits during I&T, suitable dark images will be collected to measure diffusion with this method.

11.1.2.5 Cross-Talk Requirements

The Cross-Talk requirements are described in (Table 8) and are verified using the multi-spot mask in the Scene projector. The CCD cross-talk may be measured using this arrangement of spots, since at any given time in the readout, the corresponding pixels are illuminated in only one amplifier, and the cross-talk may be evaluated in each of the other 15 amplifiers as well as in all other CCDs. The multi-spot image will be projected on each of the CCDs, both the 189 Science CCDs as well as the 8 Guider CCDs and 4 Wavefront CCDs, to evaluate both the intra-CCD and inter-CCD cross-talk and its stability.

Also note that large spots are needed, illuminating of order 10^4 pixels, so that the small cross-talk signal may be summed over many pixels. The multi-spot images are overscan, bias and gain corrected, then the cross-talk will be measured as:

$$X = \frac{\sum S_{victim}}{\sum S_{aggressor}}$$

The uncertainty in the measured cross-talk depends only on readout noise, not shot noise, since whatever shot noise is present in an aggressor pixel is reflected in the deterministic cross-talk signal in the victim pixel. Thus the uncertainty in the cross-talk is given by:

$$\sigma_X = \frac{\sigma_{read}}{\sqrt{N_{pixels}} S_{aggressor}}$$

For $N_{pixels} = 10^4$ and $S_{aggressor} = 5 * 10^4 e^-$, or about half of full-well, and 9 e^- read noise we see that the expected cross-talk uncertainty per image is only $\sigma_X = 2 \cdot 10^{-6}$ well below the required level of 10^{-5} for cross-talk stability.

One potential systematic effect is stray light from the projector. Besides designing the Scene projector to minimize stray light, we may also evaluate and subtract a smooth stray light illumination based on the observed signal outside the region where the cross-talk signal will occur.

The cross-talk may be characterized by a [3216,3216] matrix, with one row and column for each amplifier in the 189 Science CCDs and the 12 Corner Raft CCDs. Note that the Guide CCDs do not strictly need to be included, since in normal image taking they are not readout while the Science and Wavefront CCDs are readout, but for completeness we will include them in this analysis. The elements of the matrix are filled from the multi-spot measurements taken on each CCD. The appropriate terms of the matrix are used to verify the requirements on the cross-talk internal to each CCD interior to each raft as well as the magnitude of raft-to-raft cross-talk and the number of amplifiers affected. The cross-talk correction algorithm will be applied to the multi-spot images by the Camera DAQ and the resulting images compared against expectations, to verify and evaluate the cross-talk correction capability.

Lastly, we evaluate the cross-talk stability requirement by repeating the multi-spot scan of the entire focal plane at times separated by at least 14 days, during which the cryostat will be held at operating temperature. We expect that most elements of the full cross-talk matrix, for amplifiers in different rafts, will be at or below the measurement level of $\sigma_X = 2 \cdot 10^{-6}$ and hence will satisfy the stability requirement by default. For amplifiers in the same raft, the cross-talk value separated by 14 days will be compared, evaluating the stability as the difference in values. Differences less than the required stability level of $1 \cdot 10^{-5}$ will verify this requirement. While it is not expected, any pairs of amplifiers with larger cross-talk differences will require in depth study, to develop the necessary modeling to correct for such differences. As an example, the most likely source of such differences would be temperature changes in the raft electronics. Therefore, we will study such potential effects directly, to suitably model changes in cross-talk. We will plan to apply the DAQ Camera-level cross-talk corrections on the verification data and check that the victim regions are indeed corrected. In addition, we assume that the DAQ algorithm is independently debugged using artificial inputs.

Table 8 Crosstalk Requirements verified by the BOT tests.

ID	Title	Requirement	Verif Meth
C-376	Intra raft cross-talk	The pixel to pixel crosstalk within a single raft shall be less than 0.002	Test
C-377	Inter raft cross-talk	The raft to raft crosstalk shall be less than 0.0001, with a goal of 2.5e-5	Test
C-391	Crosstalk extent	For all pixels on a science raft, the camera shall have no more than 256 amplifiers on other rafts that each contribute crosstalk greater than 1e-5	Test
C-392	Crosstalk stability	The crosstalk from any pixel to any other pixel shall be stable to 1e-5 of a full scale pixel over a period of 14 days or the camera shall provide algorithms and telemetry to enable the reconstruction of the crosstalk to 1e-5 of a full scale pixel at any time during that period	Test
C-393	Crosstalk correction extent	The camera shall be capable of applying crosstalk corrections for each raft using all of the amplifiers within that raft.	Test

11.1.2.6 Dead Pixel Requirements

The Dead Pixel requirements are described in (Table 9) and will be verified by a combination of flat fields and darks. We define dead pixels in the same way as the Science Raft sub-system, as described in CCD-012:

- any pixel with more than $5e^-$/s of dark current
- any pixel with 500nm photo-response less than 80% of the mean
- any pixel in any column in which more than 20 contiguous pixels have more than $5e^-$/s of dark current
- any pixel in any column in which more than 100 contiguous pixels have a 500nm photo-response less than 80% of the mean
- any pixel in any column in which a pixel traps more than 200 electrons;

Flat Field images are used to locate pixels with response less than 80% of the median response for that amplifier. Note that this requires that the Flat Fields are uniform to much better than 20% over each amplifier. Likewise long-exposure dark images are used to locate pixels with more than 5e^-/s of dark current. Likewise, the BOT dark box must reduce any ambient light to much better than this level of dark current. As before, either Photon Transfer or ^{55}Fe is used to determine the Gain conversion from ADU to e^-, needed to convert the signal into the units of e^-. Lastly, pocket-pumping is performed after Flat Field images to locate pixel traps. All bad pixels inside the central circle are counted and compared against the 2% limit.

To estimate the additional number of pixels which may be lost over the 10 year survey duration, we compare the number of bad pixels per CCD, as measured either by the vendor or during Science Raft assembly, with the number found during I&T. We expect that the number of bad pixels should not increase much during this interval. However, from any changes in the number of bad pixels we will have some hard data for an extrapolation to the full 10 year survey. Further study may be required to determine the appropriate extrapolation in this case.

Table 9 Dead pixel Requirements verified by the BOT tests

ID	Title	Requirement	Verif Meth
C-170	Detector plane allowable dead pixels	The maximum percent of pixels on the detector plane within the central circle (diameter of 634.17 mm) that do not meet their requirements shall be less than 2% at delivery, with an additional loss of no more than 2% averaged over the 10-year survey lifetime	Test

11.1.2.7 Focal Plane Throughput Calibration

The requirement on the Focal Plane throughput and its calibration is listed in (Table 10). The as-built camera throughput is determined in two parts, first, during the BOT testing with the CCOB wide beam to calibrate the relative response for all pixels on the focal plane. Second, the absolute throughput at a selection of focal plane locations, with either high or medium fidelity, is measured with the CCOB narrow-beam, as described below in Section 11.8.2.1.

The CCOB wide-beam is rastered across the Focal Plane, with overlap spots. The profile of the illumination spot is calibrated, and each spot image is compared against this profile; the ratio of the two is a relative measure of the Focal Plane throughput. The overlapping spots thus provide a throughput measure

Table 10 Requirements on Focal Plane Throughput Calibration

ID	Title	Requirement	Verif Meth

C-027	Throughput as-built knowledge	The as-built camera throughput shall be measured separately from the telescope with relative accuracy of 0.25% over spatial scales of 1 degree on the focal plane (approximately the size of a raft) for light at a fixed angle of incidence and in LSST griz bands. The angular dependence of the throughput shall be measured over the range 14-26 degrees for at least one point on the focal plane. (TBR)	Test

11.2 Focal Plane Metrology

The dominant factor contributing to image blur in the LSST camera is diffusion in the 100 micron thick Silicon CCDs, with an allocation of 0.233 arcsec FWHM compared to an estimate of 0.186 arcsec FWHM in LCA-17. All other factors are sub-dominant, with contributions from a wide variety of factors. One of the largest of these secondary contributions is from the flatness of the focal plane, especially since the fast F#/1.2 LSST optics has a corresponding narrow depth of focus. The allocation for focal plane flatness is not called out explicitly in LCA-48, but rather is contained inside the IQ error budget requirements C-047 and C-053. In turn, the total focal plane flatness requirement is allocated over three sections in LCA-17: those for *Sensor: Flatness* (0.062 arcsec), *Raft Assembly* (0.022 arcsec) are contributors to C-047 and *Detector Plane Assembly* (0.044 arcsec) is a contributor to C-053. The conversion factor from FWHM to peak-to-valley flatness deviation is 0.0033 arcsec/micron, calculated assuming a uniform distribution of focal plane heights. Thus the RSS of these three factors corresponds to a total flatness allocation of 0.079 arcsec FWHM or $\pm 12\mu m$ peak-to-valley deviation. (Note that this allocation includes some camera system level margin, above the nominal $\pm 11\mu m$ peak-to-valley height requirement. Thus we speak of only the $\pm 11\mu m$ requirement below).

The Focal Plane Metrology is tasked with verifying this overall focal plane flatness requirement. In addition, the requirements demand very small focal plane flatness deviations from both gravity vector variation and thermal variation, which will be verified by separate analysis. Both guide and wavefront sensors place additional requirements on their z-position with respect to the science rafts, and these too are verified by the metrology system. No specific requirements are placed on the lateral alignment of the sensors or rafts, aside from the obvious requirement that they do not interfere with one another, besides those discussed in Section 11.1.1.4. Thus the metrology measurement is only made in the vertical, or z, direction. The requirements verified by Metrology are listed in (Table 11)

Table 11 Requirements verified by the Focal Plane Metrology test

ID	Title	Requirement	Verif Meth
C-047	I.Q. error due to Raft Sensor Assembly manufacturing, assembly errors	Maximum image quality error due to RSA manufacturing and assembly errors =0.242 arc-seconds	Test/Analysis

C-053	Assembly and alignment error	Maximum image quality error due to assembly and alignment errors = 0.088 arc-seconds	Test/Analysis
C-285	Z axis position	Each guide sensor shall have 95% of its active area contained in a vertical band that is +/- 30 microns to a plane defined by the science sensors for all operational conditions	Test
C-200	WFS focus displacement	The wavefront detectors within a wavefront sensor shall be offset each other by a nominal offset of 3.0 mm.	Test
C-416	WFS Z direction separation error	The z direction separation between the two wavefront detectors shall have an error of +/- 0.1 mm.	Test
C-417	WFS Z direction pixel location	The average of the z locations of all the pixels of the two wavefront detectors of the wavefront sensor shall be within +/-25 microns of the best fit detector plane over all operating conditions	Test
C-305	WFS focus variation	The z direction surface of each wavefront detector shall be contained within +/- 15 microns of its nominal position and shall have 95 percent of the sensor area contained within +/- 5 microns of the best fit plane for that half wavefront sensor	Test

The focal plane consists of 21 science rafts and 4 corner rafts, each tension mounted to the cryostat grid, with an tooling ball interface. The grid holds the three tool balls for each raft in a ball cup integral to the grid, and the tooling balls fit into three v-blocks at the back of the raft sensor plate assembly to form a kinematic mount. Adjustability is provided by the choice of tooling ball diameter, and the balls can be swapped out if necessary to adjust the raft height. The vertical dimension requirements on the grid and rafts imply that no tooling ball adjustment should be necessary, so this capability is a risk reduction measure. Thus there is the capability to remove rafts and then change tooling balls to adjust the overall raft height if necessary.

11.2.1 Test Description

The focal plane metrology measurements must be made in a variety of conditions: without the L3-flat at room temperature and atmosphere, with the L3-flat at room temperature under vacuum, and at operating temperature. In addition, the metrology measurements will be made after each batch of rafts are installed in the cryostat. Therefore the metrology measurement must be relatively rapid to allow for so many repeated measurements, and to allow feedback during the raft installation procedure.

Only non-contact metrology is permissible with CCDs, and precision of 1 micron is required. The large size of the focal plane makes it difficult to perform height measurements over the entire aperture, so the metrology measurement utilizes a stitching technique to combine individual metrology exposures.

Lastly, the complicated geometry of the cryostat and the desire to keep the CCDs downward facing at all times while not in vacuum leads us to a custom coordinate measuring device. To achieve these goals, with high precision, the metrology facility utilizes a reference surface, and makes strictly differential measurements between the focal plane and the reference surface.

An appropriate data acquisition strategy, algorithm and demonstration has been provided. It calls for short duration, differential scans of limited, overlapping, apertures. Each aperture setting requires a repositioning of the reference surface used in the differential measurement, whose size need only match the aperture. The positioning of the reference is arbitrary (and needs not be known) but only must be stable over the duration of the scan. This approach obviates tight thermal control of the assembly room (and building) over the measurement duration, which would be on the order of several hours.

Metrology scans performed through a representative vacuum barrier have been demonstrated in Ref [8], albeit with a finite penalty (as compared to similar, closer range scans) within the measurement tolerances. This is due to limitations in the longer range displacement sensors and the finite density inhomogeneities exhibited in normal optical glass.

11.2.2 Metrology Test Equipment and Analysis

The focal plane metrology test will be implemented as part of the BOT. A computer controlled XY stage will carry the dual, upward and downward pointing, displacement sensors. The BOT will include the precision reference flat and support structure, designed to minimize thermal and vibrational height variations of the reference flat for the duration of each scan. The Laser displacement sensors, manufactured by Keyence, provide the necessary non-contact metrology, sufficient standoff distances, operation through the L3-flat and the required precision.

Note that the BOT contains a single large optical flat, but we expect to conduct short duration scans over sub-apertures of this optic. However, using a single optical flat has several advantages. First, it provides a simple mechanical assembly, instead of having to mount a second XY stage for a smaller optic. Second, the thermal path from focal plane to the optical flat, critical for the metrology measurement is made simpler again omitting an XY stage. Third, the large flat allows us to register the surface of the focal plane to the cryostat grid fiducials located at the edge of the grid, even when only one Raft is installed.

Additionally, the design of the Metrology system now does not include provision for measurement of the focal plane at different altitude or azimuth angles; the only measurement performed is at Zenith pointing. Analysis of the Focal Plane, Rafts and Grid indicate that the expected deviations due to changes in the gravity vector are a pure solid body motion due to the Grid to Cryostat flexures. Any additional deviation at the Grid itself are negligible. The gravitational deviations in the flexures will be independently measured by the Cryostat sub-system, and no change is expected in actual operation. Since the metrology measurement only measures the Focal Plane with respect to Grid fiducials, we expect no measureable effect under different gravity vectors, and therefore have decided to omit such a test. There are considerable simplifications of the metrology system and BOT which result as well as savings in time. We return to this subject in the discussion of the Survey and Alignment, in Section 11.3.

Requirements for the Focal Plane metrology system are described in LCA-11795, and the BOT plus Metrology system is shown in (Figure 3).

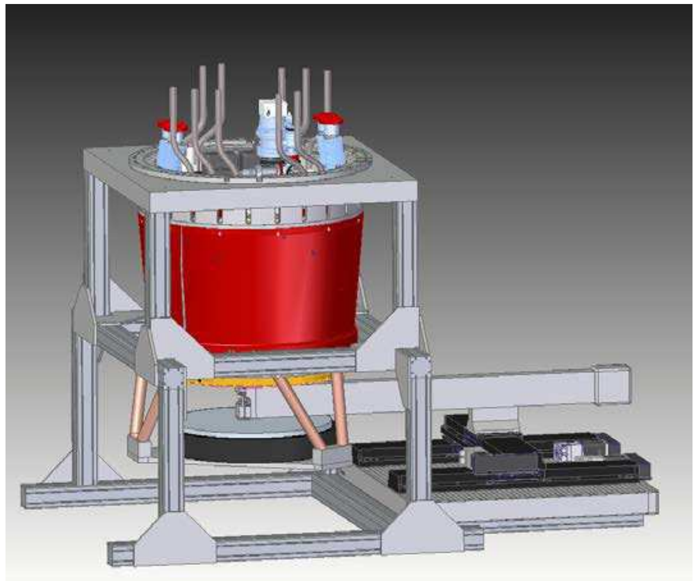

Figure 3 Metrology System in BOT

Data from the Keyence sensors are recorded along with the XY positions of the moveable stage. Each sub-aperture is covered with a fine transverse mesh of points, and some locations are repeated to provide redundancy. It is critical that the distance and orientation between the focal plane and optical reference remain constant for the duration of the scan.

Multiple scans cover the focal plane, as shown in (Figure 4), and are then stitched together to form the Focal Plane Height map. The stitching operation, in this case, is essentially an automated compilation of the available data and a linear regression analysis performed on each independent data set, see Ref [8] for a simulation of this analysis. With a finite number of scans, combined with a finite number of reference positions, a large number of methods are available to compute the surface height of a given point in the focal plane (by one method per reference, or calibration path). Two possible sub-aperture arrangements for collecting the metrology data, along with the derived statistical print-through artifact pattern for an instance using the sub-aperture arrangement, are shown in (Figure 4). The amplitude of a print-through height artifact is shown, and scales with the amplitude of the system's measurement error distribution, but is only contributes an additional 30% of that error.

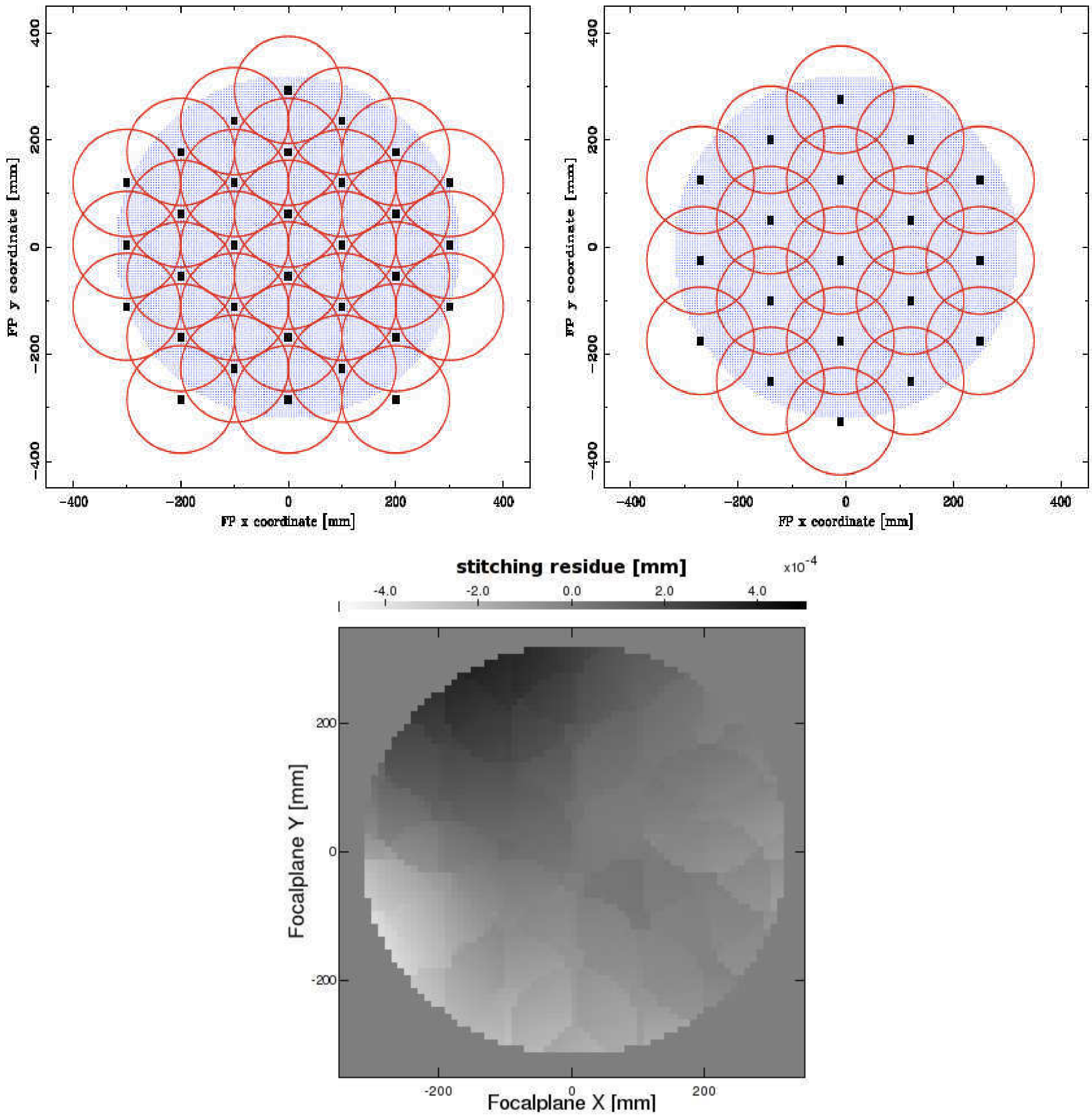

Figure 4: Example sub-aperture configurations for the focal plane surface height metrology stitching operation. An instance of the computed print-through pattern (from the 32 sub-aperture data acquisition) is shown on the bottom.

11.2.3 Metrology Results

The entire focal plane metrology algorithm has been simulated, as described in Ref [8]. The results of the metrology test will be a high fidelity height map of the focal plane, such as that shown in (Figure 5). This height map will be directly used to verify the requirements listed in . The requirements listed on the Wavefront and Guider sensors are straightforward to verify from the height map. But verification of the two image quality requirements need more explanation.

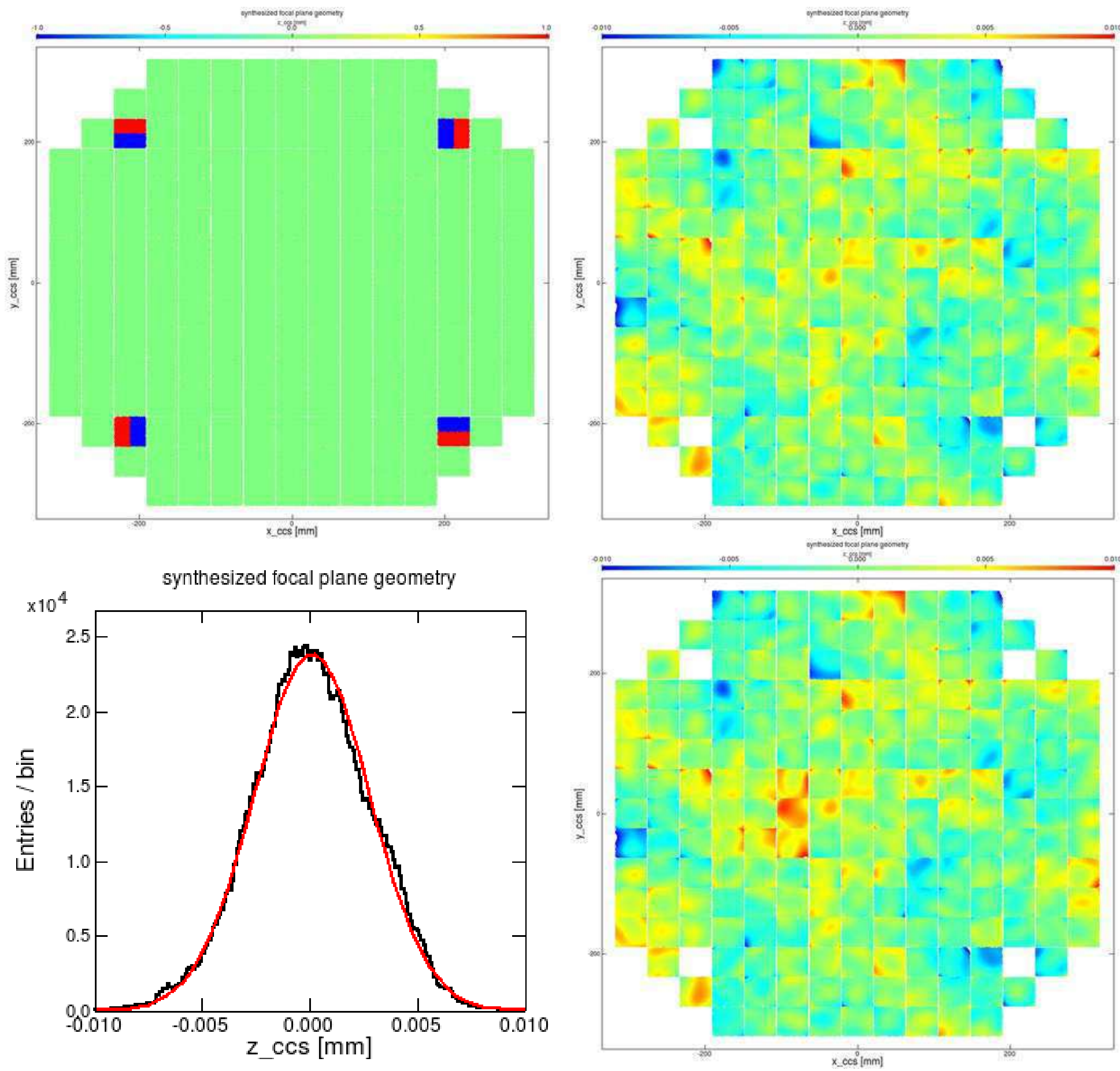

Figure 5: An instance of the synthesized, hierarchical focal plane model for LSST. The top left figure shows the surface height of the wave front sensors, while the top right shows detail at the ~few micron level. The overall focal plane axial deviation distribution is given in the lower left figure. The lower right shows a case where a kinematic load path stack height (under R12) changes by +5 microns.

At issue is that from the viewpoint of I&T verification, the separation into contributions from the sensor or raft level, versus those from the grid and kinematic balls, is not necessary relevant. Thus given the high fidelity height map, there is no unique separation into these three separate contributions to focal plane flatness. Of course, since these categories flow down separately to the sensors, rafts and grid, they are necessary for the allocation of flatness to these sub-assemblies. Note that the conversion factor of 0.0033 [arcsec FWHM/micron height] was calculated assuming a flat distribution of heights, for each contribution. Combining the contributions in a system test will yield a more Gaussian distribution, even if the individual components are flat. Thus we are likely to see tails in the height distribution. We use the RMS to convert from flat to Gaussian distributions. The RMS of a flat distribution inside $\pm 11\mu m$ is $6.4\mu m$, and so a $\pm 1.7\sigma$ level, corresponding to 91% confidence limits, is equal to $\pm 11\mu m$. Thus we adopt the following method to verify the combined contributions to the image quality requirements (C-047 and C-053) as listed in : assuming a Gaussian distribution, we demand that greater than or equal to 91% of the points in the height map, uniformly distributed transversely on the CCD surfaces, fall within the allowed range of $\pm 11\mu m$. This then will verify the relevant portions of requirements C-047 and C-053, from (Table 11).

The guide and focus sensor requirements described in the remainder of are verified directly from the Focal Plane height map.

Lastly, the Metrology instrument is used to measure the location and orientation of the Focal Plane with respect to the Grid fiducial monuments. These monuments are located on the edge of the Grid, rise to a height level with the CCD surface, and can be located with the Keyence sensors. The height of these Grid fiducials is also measured along with the Focal Plane height map, and is used to transfer the Focal Plane location to the global Camera coordinate system in the Survey and Alignment program.

11.3 Survey and Alignment

The Survey and Alignment program is used to verify the many requirements of mechanical position and stability of the optical elements and focal plane in the Camera. These requirements are listed below in (Table 12) , (Table 13) , (Table 14) and (Table 15).

The alignment of Camera optical elements is performed using conventional laser-tracking optical surveying methods. Each optical element includes fiducials, typically spherically mounted retro-reflectors (SMRs), which are used to perform the survey and alignment. The locations of the optics themselves, with respect to the SMRs mounted on the optical element's cells, are determined independently by the optics sub-system. The location and orientation of the focal plane with respect to fiducials on the cryostat front face is determined by the focal plane metrology system described in Section 0, as well as surveys performed by the cryostat sub-system. The Survey and Alignment program ties together the Camera optical elements and focal plane just through the use of the SMR fiducials.

11.3.1 Survey & Alignment Equipment and Methods

The relevant Camera elements: the L1, L2 and L3 lenses, filters, and focal plane include several adjustable interfaces. The focal plane supporting structure, the cryostat grid, is connected to the cryostat via three flexures which are aligned to set the correct focal plane to cryostat front face distance and orientation. A one-time adjustment of this distance is made to optimize the as-built telescope plus camera optical performance, based on measurements from the three mirrors. After this adjustment, no further modification of the focal plane alignment is envisioned. The L3 optic, which doubles as the cryostat window, mounts directly on the cryostat front face and so has no adjustable degrees of freedom. The L1 and L2 optics are designed and constructed as an integrated pair, and the optics subsystem is responsible for delivering these optics aligned together. The L1+L2 structure is connected to the cryostat via the camera body structure and six adjustable struts comprising a kinematic mount. Lastly, the filter locations are defined by the online clamp mechanism in the Filter Auto Changer, which can also be adjusted.

The Survey and Alignment program is designed in concert with the available adjustable interfaces. Since the focal plane and L3 are fixed in location by the time I&T performs the optical alignment, the L1+L2 structure and the filter are adjusted with respect to the focal plane and L3. Additionally, we define the Best Fit Optical Axis (BFOA) as the line normal to the best fit focal plane and passing through the L3 vertex. The transverse location of the focal plane with respect to the optical axis is not tightly specified, so the transverse location of the BFOA is optimally defined via the fixed L3 optic. On the other hand, the image quality is much more sensitive to the tip and tilt angle of the focal plane than that of L3 so the BFOA is defined using the orientation of the focal plane alone. The Survey and Alignment program then needs only place the L1+L2 structure and the filter with respect to the BFOA, using the SMR fiducials located on each of these components, and to measure the location of all elements.

The Survey and Alignment program uses conventional laser tracking metrology utilizing SMRs to place and measure the location of the Camera optical elements. SMRs are located on the L1, L2 and L3 cells, the Cryostat, the Filter cells, the filter exchange mechanism (TBR) and on the Camera back flange. Numerous SMRs are placed azimuthally on each of these locations, so that each element can be fiducialized given the restricted lines of sight to these structures. However, the laser tracker head will be re-positioned at various azimuthal and longitudinal locations around the Camera to establish a grid of overlapping angle and range measurements which can then be used to determine the relative position of the SMR fiducials. Evaluation of the lines of sight and the set of overlapping measurements have been made, together with the accuracy and precision expected with laser tracking metrology, with estimated accuracy of order 20 microns for each of the elements and degrees of freedom. The Survey and Alignment process will be conducted inside the large new Class 1000 LSST clean room located at IR-2, whose 20 foot hook height is capable of holding the fully assembled Camera in Zenith orientation. A CAD model of the location of the laser tracking equipment and sight lines is shown in .

In addition to the laser tracking metrology, some elements of the Survey and Alignment program may make use of a Faro arm to measure difficult to reach locations. As an example, the repeatability of the Filter placement could also be verified via such a device, should it prove difficult to sight the Filter SMRs themselves.

11.3.2 Survey & Alignment Analysis

During surveying, the laser trackers captures all information about the range and offset angles of the fiducial targets being measured. This is initially used to establish the measured position of the laser tracker with respect to fixed fiducials in the room, then to measure the positions of the SMR fiducials. Multiple measurements of each fiducial are taken with the laser tracker in different positions, then post-processing produces a measured position of the point relative to a room coordinate system, as well as a measurement error.

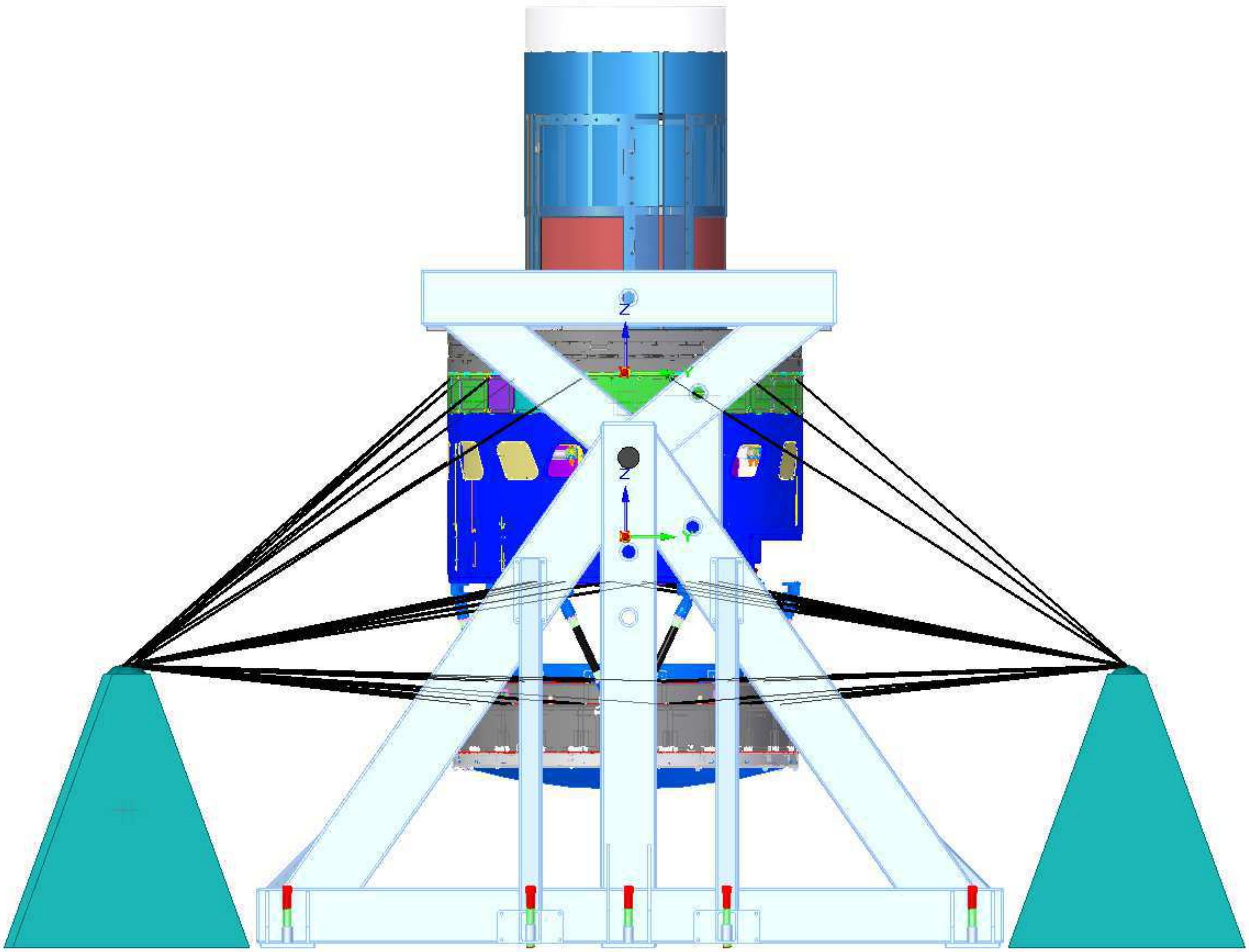

Figure 6 Model of Camera on the Integration Stand, showing the location of Laser Trackers and sight lines.

Thus we measure the position of each SMR, $\vec{x}_{SMR}$, in the room coordinate system. The optics subsystem will supply the location of each optical element together with the locations of the corresponding SMRs, $\vec{r}_{SMR}$ and $\vec{r}_{optics}$, in the relevant optics coordinate system for L1+L2, L3, and Filters. We combine these measurements by matching the SMR locations in each coordinate system, extracting a translation vector, $\vec{T}$, and rotation matrix, $\hat{R}$, between coordinate systems, with a least-squares fit, as:

$$\hat{R}\,,\vec{T}\colon \min \sum_i \left\| \vec{x}_{SMR,i} - \left(\hat{R}\vec{r}_{SMR,i} + \vec{T} \right) \right\|^2$$

Then we use the translation vector and rotation matrix to find the location of the optics in the room coordinate system, as:

$$\vec{x}_{optics,j} = \left(\hat{R}\vec{r}_{optics,j} + \vec{T} \right)$$

An similar analysis is performed for the focal plane, now using cryostat sub-system measurements of the SMRs on the outside of the cryostat with respect to the grid fiducial monuments and the Metrology measurements of the Focal Plane with respect to the grid fiducials.

11.3.3 Survey & Alignment Test Verification

11.3.3.1 Position Requirements

The nominal locations of L1-L2, Filter, L3 and Focal Plane are specified in (Table 12). The measurement made of the SMRs together with sub-system measurements and analysis as described above yield the measurements that verify we are aligned to these nominal locations.

Table 12 Position requirements of Camera optical elements verified by the Survey and Alignment test program

ID	Title	Requirement	Verif Meth
C-054	Filter 1st surface Z-position	Filter 1st surface Z-position = 871.452 mm in the Camera Coordinate System	Inspection
C-074	L1 first surface Z-position	L1 first surface Z-position = 0 mm in the Camera Coordinate System	Inspection
C-082	L2 first surface Z-position	L2 first surface Z-position = 494.872 mm in the Camera Coordinate System	Inspection
C-089	L3 first surface Z-position	L3 first surface Z-position = 943.452 mm in the Camera Coordinate System	Inspection
C-287	Detector Plane Position	The detector plane Z-position = 1031.952 in the Camera Coordinate System	Inspection

The nominal alignment relies on the nominal optical model of the Camera. The nominal optical model will be updated with as-built values for the optics at the time of the Survey and Alignment program, with the Optics sub-system delivering the as-built parameters for the optics as well as measured wavefront information. Finally, the optical model will include the measurements from the Survey and Alignment process. Additionally we will track the relevant uncertainties for each element and degree of freedom.

11.3.3.2 Precision, Accuracy & Stability Requirements

Next, specifies the requirements on precision, accuracy and stability of the alignment. The precision and accuracy requirement is cast as a requirement on IQ, with 0.088 arcsec FWHM allocated in LCA-17 to alignment, but we note that a constituent contribution from *Detector Plane Assembly* has already been assessed above in Section 11.2 for Focal Plane Metrology; removing this in quadrature leaves 0.076 arcsec FWHM for the solid body locations of L1+L2, L3, Filter and Focal Plane.

The optical alignment requirements are specified in terms of the FWHM of the image blur instead of directly in terms of the uncertainty of the optical elements. The full as-built optical model, together with uncertainties in the underlying measurements, is used to evaluate the impact on Image Quality (IQ) using the Zemax optical program. The image blur is evaluated at a number of focal plane locations and wavelengths in the r-band and the mean of the RMS of the image blur is calculated using Gaussian Quadrature, as described in [Ref 9]. The RMS is converted to FWHM using the typical Gaussian factor of 2.355. Note that the IQ is optimized inside Zemax by adjusting the Camera hexapod degrees of freedom, just as the LSST Active Optics will do in reality. The active system will also adjust the M1, M2 and M3 mirror figures and the M2 hexapod to optimize IQ, but to be conservative we do not use these additional degrees of freedom in this evaluation. Lastly, the difference in quadrature between the

IQ calculated for the measured positions of the optical elements and focal plane, including one standard deviation of the measurement uncertainties, against the nominal position IQ is calculated. The measurement uncertainties are included by repeating this calculation a number of times, each iteration with a different random draw from the uncertainties. This ensemble yields a range of ΔIQ , we take a value containing 67% of the ensemble. This then is the contribution to IQ to be compared against the contribution of 0.076 arcsec FWHM.

The next requirement in (Table 13) is on the IQ change from gravity induced motion. The maximum zenith angle for consideration is 75^{o} (although we note that the estimates for the *Correlated Gravity Induced* in LCA-17 used just 60^{o} zenith angle). Also, the contributions in LCA-17 are broken into *Correlated Gravity Induced,* 0.018 arcsec FWHM, from correlated decenter and tilt in L1+L2, Filter, L3 and Focal Plane, and *Non-Correlated Gravity Induced,* 0.060 arcsec FWHM, with 0.059 arcsec of this from the variation in decenter and tilt at different rotator angles. The separation between these categories is due to assuming that the Camera Hexapod look-up-table is a function of just Zenith and Azimuthal angles, and not also the Rotator angle. To mimic this methodology, we take the measured change in alignment of L1+L2, Filter, L3 and Focal Plane at an intermediate Zenith angle (nominally 75^{o} , but may lie anywhere between 0^{o} and 90^{o}) and a Rotator angle of 0^{o}, compared to Zenith pointing, and then apply the Zemax and Active Optics methodology above to extract the contribution to IQ, extrapolating to find the gravity induced change at 75^{o}. This change will be compared against the *Correlated Gravity Induced,* 0.018 arcsec FWHM. Next, we compare the measured change in alignment at the intermediate Zenith angle, but at a Rotator angle of 60^{o} or 90^{o}, against that at Rotator 0^{o}, and again applying the Zemax and Active Optics methodology to extract the contribution to IQ. This change will be compared against the *Non-Correlated Gravity Induced,* 0.059 arcsec FWHM. Note that the remaining 0.013 arcsec FWHM of the *Non-Correlated Gravity Induced* component is from gravitational stresses in the optics, and this contribution can only be verified through Analysis, using FEA methods. This contribution will be verified through updated analysis of the stresses in the optics, updating Document-8162 and Document-8525.

The two requirements on Filter positioning repeatability in (Table 13) will be verified by cycling the filter, or filter blank, and measuring the change in location via the SMRs or the Faro arm.

Lastly, we note that the alignment of the optical elements will also be measured at horizon pointing, to establish a benchmark which may be useful to re-verify the alignment prior to installation of the Camera.

Table 13 Precision, Accuracy & Stability Requirements verified by the Survey and Alignment test program

ID	Title	Requirement	Verif Meth
C-053	Assembly and alignment error	Maximum image quality error due to assembly and alignment errors = 0.088 arc-seconds	Test/Analysis
C-048	I.Q. error due to gravity-induced motion	Maximum image quality error due to gravity-induced motion = 0.062 arc-seconds	Test/Analysis

C-023	Filter positioning for photometric precision	The light impinging on a particular pixel passes through a circle approximately 100mm in diameter on the surface of the filter. The knowledge of position of the center of that circle on a specific filter for any pixel shall be better than 1.65mm in all camera orientations and after filter changes.	Test/Analysis
C-094	Filter positioning repeatability	Filters must be placed into the optical beam with a repeatability of filter placement of < 0.1 mm.	Test
C-226	Camera envelope	The camera assembly shall stay within the envelope described in LSE-18 sheets 1 and 2. (See the Camera Opto-Mechanical Definition Drawing LCA-126)	Test/Analysis

11.3.3.3 Other Survey & Alignment Requirements

Other Survey & Alignment Requirements are listed in (Table 14). The Survey and Alignment program, coupled with information from the Camera CAD model and detailed sub-system drawings, will verify that the stay-clear envelope of the camera is obeyed. In addition Survey and Alignment will measure the relative location of the BFOA and all optical elements with respect to the Camera back flange, which the Camera to Observatory interface, and verify that this measurement lies within its tolerance. Likewise, the detailed CAD drawings, with as built locations for the focal plane, as described in LCA-13381 will be used to verify the CCD fill factor requirement in (Table 14).

In addition, there are four requirements in for the adjustability of the Focal Plane and Filter, and for the number and visibility of the SMRs: these are all verified by demonstration or inspection.

Next requirements on interfaces verified by the Survey & Alignment program are listed in (Table 15). The location of the BFOA with respect to the rotator is measured explicitly in the SMR based laser tracking described above. The definition of the tip/tilt angle obeys the Camera coordinate system definition. Analysis of the stay-clear volumes is needed, using survey information, to verify that these stay clears are obeyed.

Table 14 Requirements verified by the Survey and Alignment test program through analysis, demonstration or inspection

ID	Title	Requirement	Verif Meth
C-238	Detector plane central fill factor	The CCD device fill factor within the central circle (diameter of 634.17 mm) shall be at least 85 percent.	Analysis
C-003	Detector plane-L3 gap adjustability	the gap between the detector plane and L3 shall be capable of being adjusted one time by +/- 3.5 mm	Demonstration

C-002	Detector plane+L3+Filter gap adjustability to L1	the detector plane + L3 + Filter shall be capable of being adjusted one time by +/- 5 mm with respect to L1	Demonstration
C-323	Retroreflectors	The camera shall provide the number of sphere mounted retroreflectors (SMR's) at the locations and with the dimensions described in LSE-18 sheet 4. (See the Camera Opto-Mechanical Definition Drawing LCA-126)	Inspection
C-325	Retroreflector visibility	Lines-of-sight for at least 6 of the SMR's specified in C-323 shall be visible during the installation/removal of the camera with the L1 lens cap installed.	Inspection

Table 15 Requirements on Interfaces verified by Survey and Alignment

ID	Title	Requirement	Verif Meth
C-400	Optical axis	The as-built best-fit optical axis of the camera during operation shall not deviate more than +/- 600 microns of decenter, +/- 400 microns of piston, and 250 micro-rad of tip/tilt from its nominal position and orientation with respect to the rotator interface datums as defined by LSE-18 sheet 2.	Test
C-401	Tip/tilt angle	The camera shall provide the tip/tilt angle of the rotator interface with respect to a coordinate system centered on the best-fit detector plane.	Test
C-404	Removal envelopes	The volumes for removal of the camera Auto Changer, Filter Loader, and Shutter shall stay within the lift envelopes defined in LSE-18, sheet 7. (See the Camera Opto-Mechanical Definition Drawing LCA-126)	Analysis

11.4 System Dynamics Test

The System Dynamics Test measures the primary natural frequencies and identifies the primary modes of the Camera in its final configuration, including the transmissibility of vibration through the Camera structures and subassemblies. This test verifies the requirements shown below in (Table 16). We evaluate the IQ contribution from an analysis of our measurements. The first mode requirement is verified directly from the test results, while the image quality error due to vibration sources and camera induced vibrations requires post-test analysis of the frequency response.

11.4.1 System Dynamics Test Equipment and Analysis

The System Dynamics Test equipment consists of a number of accelerometers and a shaker/stinger for exciting the camera structure. Accelerometers will be mounted throughout the Camera, including both permanently mounted and temporarily mounted instruments. At a minimum, accelerometers will be located on major structural elements of the camera, such as: L1+L2, Filter Exchange Mechanism, Shutter, Cryostat housing, Refrigeration Heat Exchangers in the Utility Trunk, the Refrigeration inlets, as well as the Rotator and Camera Integration stand itself. Three-axis accelerometers will be used in each location.

The shaker is used to excite the structure for the test. A shaker is attached to specific locations on the camera with a *stinger*, a rod used to transmit the vibrational energy into the camera structure. When the vibrations are transmitted through the stinger, the camera natural frequencies will be amplified and measured. An accelerometer placed between the shaker and the camera will record the excitation force so transfer functions and transmissibility can be determined. A common data acquisition system is needed to measure the phase of the Camera excitation with respect to the shaker.

In addition to exciting modes of the camera with the shaker/stinger, vibration of the camera during normal operation will be measured. Accelerometer measurements will be made under a range of normal imaging conditions, including: 15 second exposures with shutters opening and closing, filter exchanges, and (TBC) changes in camera orientation on the Camera Integration stand. The vibrational excitation due to these sources is expected to be quite small, so high sensitivity accelerometers will be needed to record any signal.

The shaker/stinger load cell and Camera accelerometers will be readout by a high frequency multi-channel DAQ, yielding both the frequency and phase of the motion at each mount point. We expect that some accelerometers will be permanently mounted on the camera and readout through HCUs and the CCS, however, most accelerometers will be temporary ones affixed just during this testing.

11.4.2 System Dynamics Verification

The System Dynamics test verifies the requirements shown in (Table 16). Pre-test analysis uses the integrated finite-element analysis (FEA) structural model of the Camera plus Camera Integration Stand. The FEA model is used for predicting the mode shapes and vibration frequencies of the various vibration modes of the Camera. This is important both to determine the optimal location and orientation of the accelerometers, as well as the most sensible locations for shaking the structure. The model can then generate predictions of the expected frequency and phase response at each accelerometer location.

The stinger/shaker test will yield curves of the transfer function, or Q(f), for each accelerometer mount point as a function of frequency ranging from 2 to 100 Hz. The lowest peak of the transfer function is the natural frequency. Thus the measured natural frequency for the camera as a whole, as well as each significant component, can be compared against the 24 Hz requirement. Each of these natural frequency measurements will also be compared against predictions of the FEA model, to validate the model.

Likewise, any measured vibrations from known internal sources such as the Refrigeration system or Shutter cycles will be measured. In particular, we do expect some small vibration from boiling of the refrigeration fluid at the cryo-plate inside the Cryostat. This vibration can potentially be transmitted though flexures to the Cryostat housing, and from the Cryostat housing through the Grid flexures to the Focal Plane. This particular source of vibration will be measured by accelerometers mounted on the side and front flange of the Cryostat at the most sensitive location, most likely at points where the cryo-plate attaches through flexures to the housing. Next the validated FEA model may be used to estimate the motion of all optical components and the Focal Plane, from both these internal sources and from any external sources. Quantitative estimates of sources of vibration external to the Camera must be provided by the Observatory. The analysis simply will use the RMS of the vibration amplitude of the Focal Plane to yield the estimated FWHM contribution to IQ, compared to the required level of 0.061 arcsec FWHM.

Finally, the measurements and validated FEA model will be combined to estimate the power spectrum of vibrations produced by the Camera and imparted to the telescope structure. To verify the requirement on IQ degradation from Camera sources of vibration we require the observatory to provide an integrated telescope transfer function and an IQ calculation methodology.

Table 16 Requirements verified by the Systems Dynamics test

ID	Title	Requirement	Verif Meth
C-052	I.Q. error due to vibration	Maximum image quality error due to all sources of vibration = 0.061 arc-seconds	Test/Analysis
C-249	Natural frequency	Neither the camera nor any camera component with mass over 153 kg shall have natural frequencies less than 24 Hz when the camera is mounted on a fixed base with interface features as defined in C-322	Test
C-412	Camera Induced Vibrations	The Camera shall not impart vibrations on the Telescope that will degrade the image quality more than 20 mili-Arcsec	Analysis

11.5 Mass Properties

The Mass Properties test combines measurements of Camera weight and centers of gravity (CG), with analysis of moments of inertia (MOI) and torque based on subsystem measured masses and detailed CAD models.

11.5.1 Test Equipment and Analysis

The equipment for the Mass Properties test consists of four load cells along with a data acquisition system to read them. Given that the Camera sub-system allocations are only approximately 150kg above the current mass estimates, compared to the 3060kg limit, the mass measurement must have a precision of order 1kg., and may require absolute calibration. The position of the load cells must be well located and measured since this directly affects the uncertainty of the center of gravity and MOI measurements. The position of the load cells must be surveyed with respect to the interface between the Integration Stand and the Camera, with a precision much better than the 10mm z-axis CG requirement. Given that the current margin in the CG is only 1mm in one of the directions, implied that the load cells must be placed and known to of order 0.5mm or better.

Analysis of the CG, MOI and torque relies on the detailed mass workbook [Ref 12] containing the thorough accounting of sub-system component's mass and location. I&T must receive verification of the measured weight of all sub-system components, and must ensure that the mass workbook contains the correct as-built location and CG of each component. These must include both Camera components as well as servicing and maintenance equipment. The locations must also be consistent with the Camera CAD model. The weight and CG of the Camera Integration Stand must be added to the mass workbook as well.

11.5.2 Mass Properties Verification

The weight, CG, MOI and torque requirements being verified with this suite of tests are listed below in (Table 17).

The Camera on the Integration Stand is set on four load cells at the four support points of the stand. The stand is measured empty prior to the start of integration, so the "no-load" weight and Z- and X center of gravity for the stand is measured. After the Camera is fully integrated, the entire assembly is re-measured on the load cells. While on the load cells, the Camera is rotated with respect to the stand by ± 90 degrees to determine both the X- and Y-direction CG. Given the current design of the Camera Integration Stand, we expect that the CG in the Z-direction will have to be verified by analysis, since the load path runs very nearly through the Camera CG itself. However, the Likewise the Camera altitude is changed with respect to the stand, to determine the Z-direction CG.

After testing is complete, the weight and CG of the Camera alone is calculated by backing out the empty weight and CG of the stand. The resulting weight is compared against the 3060kg maximum, and the resulting CG compared against the listed requirements. These values are also compared against the expectations from the mass workbook. Good agreement is needed to be confident in the verification by analysis of the MOI and torque.

The MOI and torque of the Camera is verified using the detailed accounting of the measured weights of all camera components from the mass workbook, applied to an analytical model of the Camera MOI and torque. This analysis must also include an uncertainty estimate, based on the data in the mass workbook.

Note that the Z-axis torque requirements must be obeyed at all times while the Camera is being assembled on the rotator. These limits will be verified by analysis, given the current state of assembly. The assembly procedure indicates that there is no period in the assembly when the Camera torque will be greater than 60% of these values.

Lastly, the weight and CG of all servicing equipment as included in the mass workbook will be used to calculate the weight and torque of the Camera with such equipment attached, and these compared against the corresponding requirement.

Table 17 Camera requirements verified by the Mass Properties test

ID	Title	Requirement	Verif Meth
C-227	Camera weight	The maximum weight of the camera components mounted on the telescope shall be 3060 kg	Test

C-229	Camera and Servicing equipment weight	The maximum weight of the camera components mounted on the telescope and all servicing equipment mounted to the Camera on its front end shall be 3810 kg	Test
C-324	Operational mass variations	During operation, the allowed change of the camera mass shall be no more than 30.6 kg	Test
C-230	Center of gravity	The center-of-gravity along the Z-axis of the camera assembly shall be >1350 mm from the origin of the CCS	Test
C-231	Radial CG	The center of gravity (CG) of the camera assembly must be within 10 mm, radially, of the CCS Z-axis	Test
C-234	Moments of inertia	During normal operations, the mass moments of inertia of the camera assembly shall not exceed: Ixx = 3500 kg-m^2, Iyy = 3500 kg-m^2, Izz = 1000 kg-m^2, around the camera center-of-gravity	Test/Analysis
C-402	Torque imparted by camera (pinned)	The maximum torque imparted by the camera around the camera Z-axis carried by the telescope hexapod-rotator assembly during servicing and maintenance of the camera with the locking pins engaged shall not exceed 1500 N-m .	Test/Analysis
C-403	Torque imparted by camera (un-pinned)	With the telescope hexapod and rotator functioning normally, the maximum torque imparted by the camera around the camera Z-axis shall not exceed 500 N-m. This is the maximum allowed torque imparted by the camera while the rotator is rotating or unlocked.	Test/Analysis

11.6 Cryostat Functional Testing

Cryostat Functional Testing uses the Focal Plane coupled with the DAQ and CCS themselves to verify a host of operational requirements. For some of these functional test minimal external instrumentation or software is required, as these make use of the Camera or its instrumentation itself. However, a few of the tests do require some dedicated test equipment as well. These tests are divided into a number of individual categories, and for each the verification tests and analysis are described below.

The Cryostat Functional Testing occurs with just the Cryostat, but not the complete Utility Trunk, prior to the Cryostat's installation into the Camera Body, and will occur during the BOT and Metrology testing. The Cryostat Functional Testing does make use of the DAQ and CCS system to conduct many of the functional tests. Some of these tests require signals test normally come from the Observatory Control System (OCS). During I&T, these signals will instead originate in a CCS control module and be sent directly to the CCS's Master Control Module (MCM).

11.6.1 Cryostat and Focal Plane Temperature

The functional requirements on the temperature control of components in the cryostat, on the guide sensors and on the wavefront sensors, and the resulting impact on IQ are listed in (Table 18).

The Focal Plane temperature is set by the Cryostat thermal control system, with 4 heaters located on each Raft Sensor Assembly (RSA) baseplate and an additional 36 heaters on both the cryo-plate and cold-plate. Each CCD contains a discrete IEC-751 class A RTD temperature sensor, and each RSA contains another three RTDs as well. All these temperature monitors are included in the Camera telemetry. Thus the requirements on temperature status and design temperature are verified by demonstration. In normal operation, which we define to be continuous 15 second exposures followed by full focal plane read-out, we monitor the CCD temperature to verify that the control system can maintain the temperature with less than $10\ ℃$ spatial variation across the focal plane, and with each CCD stable to within $\pm 0.25\ ℃$ over a 12 hour period. The absolute knowledge of the temperature is set by the tolerance of the RTDs, between $0.35 - 0.50\ ℃$, with differential measurements better than this level. The chief variable contribution to the thermal load on the Focal plane is expected to be due to changes in the amount of radiation from the L3 window which in turn is a function of the window temperature. We will stress the thermal control system by making these measurements when the air temperature external to the window varies by $0.2\ ℃/hr$ over 12 hours, or with a swing of 6 ℃ total, mimicking the required maximum rate of change of Camera body temperature.

The Camera must also provide telemetry and models to reconstruct the temperature at any point on the Focal Plane compared to a previous reference, to within $0.5\ ℃$. If the thermal control system can maintain the Focal Plane temperature to this tolerance over the complete operating temperature range of between 5 and 30 ℃, then this requirement will automatically be met. However, we do not plan to expose the entire cryostat and refrigeration system to this range of temperatures during verification testing.

Instead, we will verify through FEA temperature models that the spatial temperature variation is sufficiently regular that we can simply scale the temperature at any point by the change in temperature at the RTD location on that or nearby CCDs. We define the spatial temperature variation at time $t_1$as

$$\Delta T(t_1) = T_{pixel\ i,j}(t_1) - T_{RTD}(t_1)$$

Then we expect that at some later we will have

$$\Delta T(t_2) = \Delta T(t_1) + [T_{RTD}(t_2) - T_{RTD}(t_1)]$$

Support for this approach is seen in the FEA temperature models, where the heater power was set to 0, 4 and 8 Watts, and the resulting temperature distribution is observed to be quite stable spatially. The temperature range over the Raft is -109.0 to -110.4 ℃ for 0 Watts, -102.3 to -103.9 ℃ for 4 Watts, and -95.6 to -97.4 ℃ for 8 Watts. Note that this temperature model assumes that each of the 4 RSA heaters has the same power, should this not reflect the operating conditions, suitable modeling will be needed of the range of heater configurations.

Measuring the actual spatial variation in temperature on the CCDs is not possible, but we note that this variation and any dynamic changes in it are relevant only due to the concomitant changes in quantum efficiency (QE) at wavelengths greater than 900nm. As a result, it is possible to map out the spatial dependence of the temperature dependent QE variations. At roughly the 50% QE point of 965nm, the change in QE per degree is roughly $0.5\%/K$, rising to $0.8\%/K$ at a 25% point at 1000nm and $1.7\%/K$ at 1050nm where the QE is below 5%. Thus suitable flat field illumination at 1000nm would be sensitive to the overall temperature induced QE variations as well as to changes in the spatial temperature distribution. We will infer $\Delta T_{pixel\ i,j}$ resulting from a change in the Focal Plane temperature set-point by measuring the change in throughput under uniform illumination at 1000nm. Under a change in temperature of $\pm 4K$ we expect a change in throughput of roughly 3%, and by measuring spatial changes in the throughput at better than 0.4% we are sensitive to temperature variations at better than the 0.5K level, as required.

Finally, we will also check the overall thermal model by comparing RSA and RTM temperature measurements with the expected values, and also by comparing the temporal response caused by ramping the cryo-plate or cold-plate set-points against expectations.

The last requirement listed concerns the thermal impact on IQ. Essentially all of this contribution is verified in Camera Functional testing, but a tiny contribution is allocated for Focal Plane mechanical distortions. We note that these are verified by the Metrology Test described in Section 11.2.

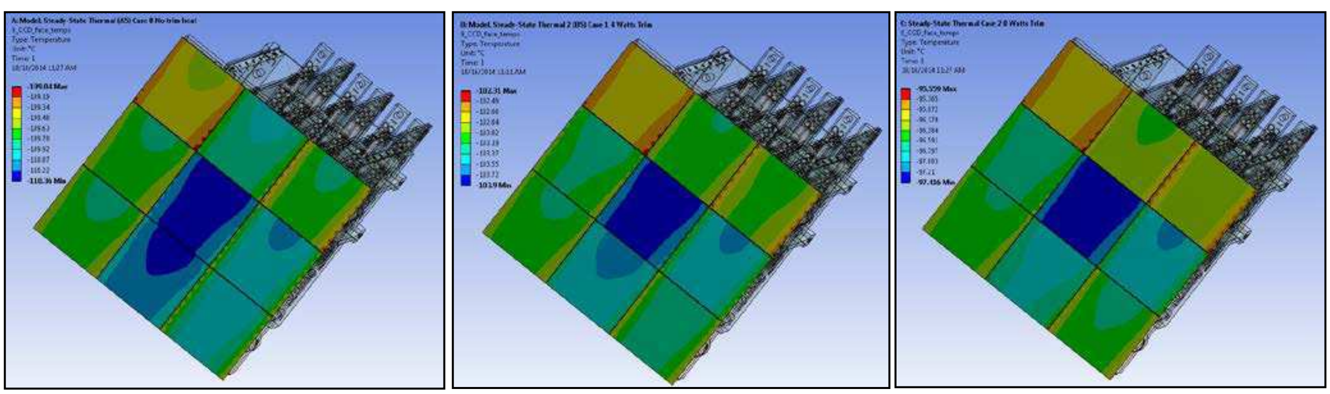

Figure 7 FEA Temperature Model for Science Raft, at different heater levels of 0, 4 and 8 Watts. Study from S. Bellavia, presented at the CD3 review.

Table 18 Cryostat Temperature Requirements

ID	Title	Requirement	Verif Meth
C-034	Detector plane max temperature spatial variation	The temperature of detectors shall vary < 10 degrees C spatially across the detector plane	Test

C-035	Detector temperature stability	Detector temperatures shall remain stable to <= +/- 0.25 degrees C over an observing run lasting no more than 12 hours.	Test
C-189	Temperature status	Temperature measurements shall be provided to the OCS	Demonstration
C-368	Detector plane design temperature	The camera detector plane design temperature shall be -100 deg C.	Demonstration
C-369	Back end electronics design temperature	The camera back end electronics design temperature shall be -40 deg C	Demonstration
C-032	Detector plane temperature knowledge	The camera shall provide sufficient telemetry and models to enable reconstruction of the temperature at any point on the active portion of the sensor surface to an accuracy of 0.5 degrees Kelvin relative to the temperature at a reference time no more than 30 days in the past. The temperature measurements shall be accurate to within 5 degrees Kelvin on an absolute scale	SS Verif; Test/Analysis
C-051	I.Q. error due to thermally-induced motions	Maximum image quality error due to thermally-induced motions = 0.039 arc-seconds	Test/Analysis

11.6.2 Guider Functional Requirements

The functional requirements on the Guider are listed in (Table 19).

All these requirements are verified by operating the Guider while taking nominal exposures and readouts of the entire Focal Plane. We note that these requirements may be verified without any particular illumination of the Guider sensors.

Table 19 General Functional Guider Requirements

ID	Title	Requirement	Verif Meth
C-259	Guide sensors	The camera shall provide guide sensors to support telescope guiding	Inspection
C-271	Number of sensors	The camera shall provide 8 sensors	Inspection

C-288	Full guide sensor data delivery	The Camera shall transport guide image data as defined in LSE-68 when the full guide sensors are read out in the same manner as science sensors are read out.	Demonstration
C-284	Diagnostic mode	The camera shall implement a diagnostic mode that will provide access to and control of the guide sensor data collection parameters through a camera provided control panel that allows at a minimum changes of integration time, binning, ROI dimensions and ROI locations in accordance with CA-TS-GDR-ICD-0006.	Test
C-330	Guider data format	The guider data shall be provided in an ordered pixel image format	Test
C-331	Bit depth	The guider data shall be represented in at least 18 bits	Test
C-428	Binning	The camera shall support binning factors of 1 to 3. The single binning factor will be used for all sensors.	Test, Demonstration
C-382	Metadata	The metadata that accompanies the guide image shall include a spatial identifier per CA-TS-GDR-ICD-0047, a unique identifier per CA-TS-GDR-ICD-0028, firmware and software versioning per CA-TS-GDR-ICD-0049, binning factor per CA-TS-GDR-ICD-0041, image location per CA-TS-GDR-ICD-0030 and all parameters controlled by the diagnostic mode	Demonstration
C-336	Registration	The calibration data shall include the transformations of guide sensor pixel location (row, column) to (X,Y) science focal plane coordinates for each guide sensor	Test

11.6.3 Guider Timing Requirements

The timing requirements on the Guider to be verified during Cryostat Functional testing are listed in (Table 20).

The DAQ system synchronizes all timing to the Focal Plane from a master clock whose signals are fanned out, and are ultimately received by the Source-Communication-Interface (SCI) implemented in the REB's FPGA. The synchronization is done within a one system clock-tick, planned to be 10ns for a 100MHz clock. The DAQ has a requirement to synchronize the read-out among REBs to with 100 nsec., and plans to verify that requirement with a test utilizing a custom board to simulate the 71 REBs, as described in the DAQ verification test plan LCA-10789. We will verify the synchronization of the ROIs by analysis of the time jitter in the OTMs and in the operation of the REBs, where we assume that each Corner Raft REB is running an identical sequence of commands. These are expected to be very small contributions, so verification by analysis is warranted.

The Guider data is made available as read-out, and in normal operation will be received by the Telescope Control System. During I&T, with no TCS, verifying that the Guider data is properly received and also that it is delivered with the required latency will require a dedicated piece of software to receive the Guider data. The latency will be tested using software timers in a custom Guider data module or it may be possible to run the Guider component of the TCS in a stand-alone mode. Minimal functionality for a Guider data module would be to receive the Guider data, check its timing and then save all ROIs for offline examination. Note that the associated metadata with guider data is minimal and will be precompiled making satisfying the delivery within 1 msec trivial.

All DAQ packets are time stamped using the 100MHz system clock, so the time tag for the Guider will be at the 10nsec level, easily satisfying the 1msec Time tag requirement.

Lastly, the 9Hz ROI readout will be tested explicitly in normal Focal Plane operation during the I&T testing period.

Table 20 Guider Timing Requirements

ID	Title	Requirement	Verif Meth
C-278	Integration synchronization	The start of integration for all ROIs shall be synchronized to 1 msec	Analysis
C-275	Delivery latency	The latency from the end of the sensor readout to the delivery of image and metadata shall be < 1msec for ROI sizes of 50 by 50 pixels	Test
C-334	Time tag	The camera shall provide sufficient time information with the data from each guide sensor to allow the reconstruction of the image generation start/stop times to within 1 msec.	Test
C-273	ROI readout rate	The camera shall deliver the ROI data at rate no slower than 9Hz for integration times of 50 msec and ROI dimensions of 50 x 50 pixels	Test

11.6.4 Guider Region of Interest Requirements

Requirements on the Guider's Region of Interest (ROI) are listed in (Table 21).

These requirements are tested by operating the Guider along with full Focal Plane readout. The size of the ROI will be varied to test that up to a 50x50 pixel ROI may be used with 9Hz readout. Also the location of the ROI will be moved across the Guider CCDs to ensure that operation across multiple segments. Note that the ROI position will not cross the CCD midline, so the maximum number of segments will be two.. While these tests may be adequately performed without special illumination of the Guider CCD, we will use the BOT's scene projector to place an artificial star on each Guider while performing these Guider ROI functional tests.

Lastly, the requirement that the ROI definition be provided at least 200 msec prior to the start of the exposure will be tested with DAQ and CCS software timers.

Table 21 Requirements on the Guider Region of Interest

ID	Title	Requirement	Verif Meth
C-310	Windows per sensor	The camera shall provide the capability to read out 1 window in each of the guide sensors	Test
C-315	Region of interest	The camera shall use the Region of Interest (ROI) specified by the telescope as the location of the ROI (in pixels), the dimensions of the ROI (pixels), the integration time and the binning factor.	Test
C-281	ROI Dimensions	The camera shall accommodate ROI dimensions from 10 by 10 to 400 by 400 physical pixels (no binning) using the data interface defined in this ICD, or full CCD (using the LSE-68 data interface). The nominal ROI dimensions will be 50 by 50 physical pixels.	Test
C-316	ROI definition lead time	The camera shall be able to process the ROI definition and prepare for ROI readout when that definition is provided at least 200 msec before the start of the exposure	Test
C-327	Guider control parameters	The camera shall accept the guider control parameters from the OCS as defined in LSE-71, initGuider command.	Test
C-328	ROI delivery	The camera shall read out the unique region of interest for each guide sensor and provide that data to the TCS	Test
C-379	ROI locations	The camera shall be capable of reading out ROIs that cross segment boundaries	Test

11.6.5 Wavefront Sensor Requirements

Requirements on the Wavefront sensors are listed in (Table 22).

All these requirements will be verified by operating the Wavefront sensors together with the full Focal Plane. The read-out time and the timing of the transmission of the Wavefront data will again be verified by DAQ time tags, looking at the data offline. The cross-talk requirement will be explicitly verified for the wavefront sensors, together with the science sensors. The cross-talk studies will not discriminate against the wavefront sensors, but will include them equally.

Table 22 Wavefront Sensor Functional Requirements

ID	Title	Requirement	Verif Meth
C-212	Wavefront sensor position	The camera shall provide 4 wavefront sensors located near the corners of the inscribe square to the 3.5 degree FOV.	Inspection
C-178	Readout time	The wavefront data readout time shall not be greater than 2 seconds	Test
C-304	Data latency	The wavefront data shall be transmitted to the Telescope and Site subsystem within 3 seconds after the beginning of the readout	Test
C-240	Bit depth	The wavefront data shall be represented in 18 bits	Test
C-145	Wavefront data to DM	The camera shall provide wave front data to DM	Test
C-213	Wavefront sensor data	For the purposes of archiving and buffering the wavefront sensor imaging data shall be treated the same as science image data.	Demonstration
C-302	Wavefront data exchange	The camera subsystem shall directly provide to the Telescope and Site Subsystem wavefront data from each of the 4 locations of the inscribed square of the LSST's minimal 3.5 degree field-of-view	Demonstration
C-414	WFS readout simultaneity	The camera shall perform the readout of the wavefront sensors in synchronization with the science sensors	Analysis
C-415	WFS Crosstalk Correction	The camera shall, upon request, apply crosstalk-correction to the wavefront sensor data. The correction shall be applied independently to each wavefront sensor.	Test

11.6.6 Science Sensor Requirements

Requirements on the Science sensors are listed in (Table 23).

Again, this requirement is verified by operating the Focal Plane with nominal readout, showing by histogram that the ADCs in the REBs are using all 18 bits. May be verified by pointer to the Science Raft sub-system data.

Table 23 Science Sensor Functional Requirements

ID	Title	Requirement	Verif Meth
C-215	Image bits per pixel	The imaging system shall acquire science data with a significance of 18 bits per pixel	Test

11.7 Camera Functional Testing

Camera functional verification testing, by definition, addresses those requirements that can only be verified with the fully integrated Camera. By the end of Camera integration all components are assembled and in operation. These functional tests are performed with just the Camera itself. In the sections below these various Camera functional tests are described.

11.7.1 Requirements on DAQ/CCS to OCS Interface

Requirements on the DAQ/CCS to OCS interface are listed in (Table 24).

These requirements are verified by operating the full Camera. To collect data without the OCS, a CCS module acting as an OCS simulator is used to exercise the OCS interface. During I&T this module sends its commands directly to the MCM. The normal OCS to CCS bridge will be tested separately by a pathfinder with the OCS. Thus the full chain will be tested in these two sections.

During the functional testing, all commands defined in LSE-71 will be sent to the camera and the correct response verified. The ability to handle the concurrent commands will be verified by demonstrating that the abort and stop commands will be accepted at any timeSelected commands will be sent to the camera when it is not in the ready state to demonstrate that those commands are rejected. The complete complement of commands will be tested at the CCS level.

A power up will be demonstrated, and the ability to respond to OCS commands will be verified by sending a command to the camera less than 1 minute after power up and observing the proper response

Table 24 Requirements on DAQ/CCS to OCS Interface

ID	Title	Requirement	Verif Meth
C-136	Commanding from OCS	The camera shall support commands from the OCS to power-up and initialize the camera, to change filters and to take exposures using the Command/Action/Response (CAR) model as detailed in LSE-70 "LSST Observatory Control System Communication Architecture and Protocol"	Test
C-320	Concurrent commands	The Camera shall be able to receive and act on the following commands at any time, including when executing any command and in any state: abort, stop. Upon completion, the stop command returns the Camera to a well defined state while the final state after an abort is not defined. The Camera shall reject all other commands unless in the ready state. See LSE-71 (OCS-Camera ICD).	Test
C-317	Interface to OCS	The camera shall instantiate a standard OCS publish/subscribe interface as defined in LSE-70 "LSST Observatory Control System Communication Architecture and Protocol"	Test
C-195	Camera Power Up	Upon activation, the camera shall be ready for communication with the OCS without further human intervention. This activation process shall take less than one (1) minute	Test
C-319	CCS command set	The camera shall respond to the commend set defined in LSE-71 "OCS Command Dictionary for the Camera"	Test

11.7.2 Exposure Timing and Synchronization

Requirements on the exposure timing and synchronization are listed in (Table 25).

The exposure timing and synchronization requirements are tested by operating the full Camera, DAQ and CCS. CCS synchronizes its timers using the Precision Time Protocol (PTP), distributed over Ethernet, and with better than microsecond level jitter. In particular the shutter will time-stamp measurements of the shutter blades via the Hall probes, and these times will define the beginning and end of exposures. Most likely the shutter controller will be given the exposure duration and its HCU will manage the start and stop for the exposure. CCS will handle the transmission of the exposure duration requested from the OCS down to the shutter HCU; verification during I&T will test the CCS stand-alone operation. No explicit test will be made of this synchronization, which uses an established computer time protocol, so that verification will be made by analysis of the PTP standard.

We note that there is no explicit camera requirement on the synchronization between the start of the CCD charge integration (or the last CCD clear) and the opening of the shutter, nor of the closing of the shutter and the start of CCD read-out. Nonetheless these processes must be time synchronized, such that the integration covers the full extent of the period when the shutter is open for any pixel. We expect to verify by analysis that this condition is satisfied during Camera I&T.

The requirement on minimum exposure duration will be explicitly tested by commanding both 1 second exposures as well as the minimal possible exposure expected from an analysis of the shutter mechanical capabilities. The exact exposure duration will be measured using the shutter timing profiles. Longer duration exposures will be tested as well, for example both 30 second and 5 minute exposures will be taken to verify this requirement. The visit timing requirement will be tested by operating in a continuous 15 second exposure mode, and verifying from both CCS time-stamps and shutter timing profiles that the time between the CCS command to begin an exposure and the time when the shutter is closed on the second exposure of the visit is less than 34 seconds.

The CCS will be able to collect zero-time, bias, or closed shutter exposures, darks, and both kinds of images will be taken during I&T

Table 25 Exposure Timing & Synchronization Requirements

ID	Title	Requirement	Verif Meth
C-378	Integration time	The camera shall support integration time (single value shared by all sensors) of 5 milliseconds to 200 milliseconds. The nominal integration time is 50 milliseconds.	Test
C-214	Visit timing	The camera shall complete each visit (not including the readout of the last exposure in the visit) within 34 seconds	Test
C-016	Min exposure duration	The camera shall be able to obtain a single exposure with an effective minimum exposure time of no more than 1 second, with a goal of an effective minimum exposure time of 0.1 second	Test
C-146	Closed-shutter exposures	The camera shall be able to perform exposures without opening the shutter	Test
C-174	Maximum exposure duration	The camera shall be capable of exposures longer than the nominal duration of 15 seconds, but single image specifications need not be met.	Test
C-175	Bias/zero exposures	The camera shall be able to perform a zero duration exposure	Test
C-137	Time synchroniization	Computer clocks used to produce timestamps shall be synchronized to an observatory master clock.	Analysis

C-426	tlm time tags	The camera telemetry shall include time-stamp fields that support both scientific and engineering analysis of the state of the camera during operation.	Demonstration

11.7.3 Guider Timing and Synchronization

Requirements on the guider timing and synchronization verified during Camera Functional Testing are listed in (Table 26).

The start of Guider readout is synchronized with the start of exposure and shutter opening by the DAQ and ultimately the master clock. The timing is verified by examining the Guider data time-stamps from normal data taking of the Guider plus full Focal Plane. These tests will be conducted in the same manner as the Guider Timing tests performed during the Cryostat Functional testing, in Section 11.6.1.3

Table 26 Guider Timing and Synchronization

ID	Title	Requirement	Verif Meth
C-380	Readout start	The camera shall coordinate the start time of the ROI integration to be no later than 10 msec after the start of an exposure	Test
C-381	Data delivery	Guide data delivery shall continue until total closure of the shutter	Test

11.7.4 Filter Exchanges

Requirements on filter exchanges verified during Camera Functional Testing are listed in (Table 27).

Filter exchanges will be performed with the fully assembled Camera to verify that each change requires less than 90 seconds from the receipt of the command to the publication of the complete event The filter change test will cycle through all 5 filters and the telemetry that indicates the filter in use will be examined to confirm that 5 filters are available. Likewise the process for Filter swaps will be performed while the Camera is mounted on the Camera Integration Stand, verifying that with an established procedure the swap may be completed in 1.5 hour.

Table 27 Requirements on Filter Exchanges

ID	Title	Requirement	Verif Meth
C-004	Filter complement	The camera shall accommodate 5 filters on board the camera at any time	Test

C-216	Filter swap in place	The internal filter complement of the camera shall be reconfigurable without requiring the removal of the camera from the telescope.	Test
C-005	Filter exchange duration	The camera shall require less than 90 seconds to change between any two filters that are resident inside the camera	Test
C-006	Filter swap-out duration	The Camera shall allow for swapping out any of the on-board filters for a new filter during the day, with a total time to swap out the filter of 1.5 hours after safe access to the Camera has been established	Test
C-225	Filter in use status	The camera shall positively identify the filter that is currently in position for use	Test

11.7.5 Camera Telemetry

Requirements on the Camera telemetry are listed in (Table 28).

During the Camera Functional testing, the Engineering Facilities DB (EFD) will not be used. The interface to the EFD will be separately tested during a dedicated pathfinder. During the I&T, the telemetry will be stored in a local Camera specific data-base instead. Trend analysis will be performed during I&T, using local tools.

The requirement that the telemetry shall include all metadata necessary for analysis can only be verified by analysis, for obvious reasons. In fact, the necessary analysis is actually the Camera design itself, which includes all metadata thought to be necessary.

The functional testing to demonstrate reception of all commands from LSE-71 will demonstrate that the required list of events is published.

Table 28 Requirements on Camera Telemetry

ID	Title	Requirement	Verif Meth
C-247	Camera telemetry	The camera shall publish telemetry using the Observatory specified protocol as defined in LSE-70 "LSST Observatory Control System Communication Architecture and Protocol"	Demonstration
C-318	Other Observatory subsystem telemetry	The camera shall be capable of obtaining telemetry from other Observatory subsystems either by subscription or direct query of the EFD	Demonstration

C-209	Camera State Notification	The Camera shall publish events whenever change of state happens, including camera conditions that limit or prevent operations. In particular, the camera shall publish the following events: • startIntegration • startReadout • endReadout • startShutterOpen • endShutterClose	Demonstration
C-373	Telemetry list	The telemetry to be provided by the camera shall be defined in the Camera Telemetry and Event List (LSE-165).	Analysis
C-144	Camera meta-data availability	The camera telemetry shall include all required information (metadata) needed for the scientific analysis of the survey data.	Analysis
C-299	Telemetry analysis	The camera shall provide trend analysis specific to the camera design using the provided toolkit	Analysis

11.7.6 Camera Alarms

The requirements for Camera Alarms are listed in (Table 29).

The Camera hardware health and associated alarms must be functional during I&T to ensure the safe operation of the instrument. These alarms must be exercised as part of Camera operation. In particular, the camera alarms in both the Hardware protection system and the CCS will be tested by setting the limits to artificially trip an alarm.

Table 29 Requirements on Camera Alarms

ID	Title	Requirement	Verif Meth
C-210	Camera Status	The Camera shall assess and report an overall hardware health status for major camera components.	Test
C-321	Alarm publication	The camera shall publish alarms whenever a monitored value exceeds the limits defined for the current configuration	Test

11.7.7 Alert Processing

Requirements on camera telemetry needed for Alert Production are listed in (Table 30).

As above, the OCS is not available during I&T, but instead a simulator module is used as part of CCS. The latency of the needed telemetry may be timed using software timers inside the CCS.

Table 30 DM Telemetry for Alerts Requirements

ID	Title	Requirement	Verif Meth
C-421	Alert processing telemetry latency	Camera telemetry data specified as required for DM's Alert Production, enumerated in document LSE-130 , concerning times through the end of the readout of an image shall be published via the OCS middleware within 300 msec of the conclusion of readout. The Camera should generally publish this data within time 300 msec of its acquisition.	Test
C-422	Alert processing telemetry latency	All Camera Conditions telemetry data required by DM shall be published through the OCS middleware within 10 seconds of its measurement time	Test

11.7.8 Camera to DM Interface Requirements

Data flow functional and performance requirements, listed in (Table 31), will be demonstrated with end-to-end tests of the Camera to DM interface. The cross-talk corrected data will be studied to verify that the cross-talk has been corrected at the necessary level. This will include readout of crosstalk corrected and raw image data. The identifiers from a sequence of images will be examined to confirm that the identifiers are based on time and are unique.

Table 31 DM Interface Requirements

ID	Title	Requirement	Verif Meth
C-374	Interface to DM	The science data, guider data and wavefront data shall be provided to DM as defined in the Data Acquisition Interface between Data Management and Camera (LSE-68)	Demonstration
C-217	Science image delivery	The camera shall deliver each image with a unique identifier per device per exposure	Test
C-218	Raw Image Data	The camera shall provide raw pixel data in response to a request for one or more specific images	Demonstration
C-219	Cross-talk corrected image data	The camera shall provide cross-talk corrected pixel data to client subscribers	Test

11.7.9 Thermal Environment and Control

Requirements related to the Camera's thermal environment and control are listed in (Table 32).

Thermally induced changes in IQ are almost entirely due to variation in the index of refraction of the optics. As such the requirement on thermal impact on IQ is verified by analysis, using the known dependence of the index of refraction with the estimated temperature variation across each optic. We do not expect to be able to directly measure the radial thermal gradient across each optic, although it is conceivable that the gradient across L1 or L3 could be measurable with a high quality IR camera.

The remaining thermal requirements are verified with a mixture of tests and analysis. The full Camera plus Integration Stand is so large that implementing a temperature controlled chamber is daunting and our analysis indicates that this is unnecessary.

The requirement that the Camera Body be capable of changing the average temperature by $0.2℃/hr$ is verified by explicit test. We plan to thermally insulate the entire Camera, with a suitable clean-room compatible material. Next we command the purge system to change the temperature of the Camera Body by $0.2℃$ or $0.4℃$ and test that the Camera Body temperature can be changed by this amount in the required one or two hours. The thermal insulation isolates the temperature of the Camera from that of the Clean Room, allowing for a test of just the Camera thermal control. Since the temperature of the L1 lens must also be monitored, we will try to probe its temperature during this test with an IR camera, but the small temperature variation may not be possible to detect with such a device. During this test we also verify that the Utility Trunk (UT) is capable of changing its temperature by the required $1.0℃/hr$.

The operating temperature range of $5 - 30$ ℃, the wider survival temperature range, and the requirements on rate of temperature change are verified by a combination of Camera-wide analysis and sub-system test. Our current analysis indicates that the refrigeration system, moving components inside the Camera such as the Shutter and Filter Exchange Mechanism, and UT electronics are potentially sensitive to the temperature range and rate of change. However, in each case explicit sub-system testing or qualification over this temperature range is required. Analysis of these tests will be performed to ensure that no system level temperature dependence is present and that the sub-system testing is sufficient.

Table 32 Thermal and Temperature Control Requirements

ID	Title	Requirement	Verif Meth
C-051	I.Q. error due to thermally-induced motions	Maximum image quality error due to thermally-induced motions = 0.039 arc-seconds	Test/Analysis
C-134	Camera body temperature control	The camera shall be able to change the average temperature across the surfaces of the camera body and L1 lens at a maximum rate-of-change of 0.2 C/hr, allowing it to follow the dome air ambient temperature within +/- 1 C	Test
C-326	Utility Trunk heat load	The camera shall release no more than 200W heat load in the telescope top end plenum during observing operations	Test

C-398	Camera Turn-on	The camera shall be capable of powering on and establishing communications with the OCS when the dome temperature is between -10 and +30 deg C.	Test/Analysis
C-407	Utility trunk outer temperature	During observing operations, the camera utility trunk outer surfaces shall follow the air temperature inside the top end assembly to +/- 5 Deg C. This applies during a maximum rate-of-change of the top end assembly temperature of 1 Deg C per hour.	Test
C-337	Working temperature range	The Camera Assembly shall meet all requirements over the temperature range from -5 deg C to +30 deg C.	Test/Analysis
C-390	Refrigerant line temperatures	During normal operations, the supply and return refrigerant temperatures shall not deviate from the current dome air temperature by more than -15 C to + 4 C, given a chilled water temperature range of -5 to -10 C below ambient dome temperature.	Test/Analysis
C-339	Survival temperature range	The on-telescope portions of thecamera shall survive while off or in any on state when exposed to the survival temperature range as low as -10 deg C or as high as 35 30 deg C	Test/Analysis
C-340	Operational temperature rate of change	The on-telescope portions of the camera shall meet all requirements when exposed to a temperature rate of change of 0.7 deg C per hour	Test/Analysis
C-341	Marginal temperature rate of change	The on-telescope portions of the camera shall operate when exposed to a temperature rate of change up to 2 deg C per hour but need not meet performance requirements	Test/Analysis

Lastly the requirement on the temperature of the refrigeration supply lines will be performed with an explicit measurement, albeit one performed at the normal temperature of the Clean Room and IR2.

11.7.10 Camera Humidity Requirements

The requirements on humidity are listed in (Table 33).

The humidity requirements are verified by analysis of all components sensitive to humidity. This includes mechanisms in the Camera Body as well as all non-Cryostat electronics. In particular, we analyze the effect of exposing the Camera to humidity above the dew point. As with temperature, we will not be able to directly exposure the entire Camera to a high humidity environment, but will instead analyze relevant subsystems, and or assess sub-system testing, to verify these requirements.

Table 33 Camera Humidity Requirements

ID	Title	Requirement	Verif Meth
C-346	Operational humidity	The on-telescope portions of the camera shall meet all requirements when exposed to relative humidities between 30% and 90%	Analysis
C-347	Survival humidity	The on-telescope portions of the camera shall survive when off or in any on state when exposed to relative humidities between 30% and 100%	Analysis

11.7.11 Camera EMI Requirements

The requirements on EMI are listed in (Table 34).

As the EMI requirements state all COTS parts must be compliant with the relevant FCC standards. Custom parts are designed with standard best practices. Documentation of sub-system delivered components will demonstrate compliance with the EMI requirements.

Table 34 Camera EMI Requirements

ID	Title	Requirement	Verif Meth
C-291	EMI	The camera shall not emit electromagnetic radiation that significantly interferes with itself (as defined by meeting its performance specifications) or the operation of other observatory subsystems. Off-the-shelf electronics devices shall be compliant with FCC part 15 Class B standards or shall have shielding or other mitigation. Custom designed camera electronics shall take advantage of all reasonable good practices in design and fabrication to minimize interference.	Inspection

C-292	EM susceptibility	The camera shall not be susceptible to electromagnetic emissions from itself or other elements in the observatory. Off-the-shelf electronics devices shall be compliant with FCC part 15 Class A standards or shall have shielding or other mitigation. Custom designed camera electronics shall take advantage of all reasonable good practices in design and fabrication to minimize susceptibility.	Inspection

11.7.12 Camera Operational Requirements

Camera operational requirements are listed in (Table 35).

Remote and stand-alone operation are effectively the operating conditions for the Camera during I&T. No other observatory sub-system is present during I&T. Likewise, Camera operation will be performed in the IR2 control room, which mimics any remote site.

The power requirement is tested explicitly by measuring the wall plug power to the Camera during normal image collection of the full Camera. Likewise the power-up sequence, as well as power-down sequences, will be exercised in the course of operating the Camera. The known safe state for each subsystem will be documented and initialization into that state will be verified.

On the other hand, both light emission and operational load requirements are verified by analysis. The range of loads, including the limiting seismic loads, can only be verified by detailed analysis of the Camera. Essentially all of that analysis is performed during the Camera design. On the other hand, light emission must be analyzed as the Camera is designed as well as during I&T. A *Light Workbook*, in analogy to the Mass workbook, will be created listing all unavoidable light sources in the Camera. Since components such as the Hardware Protection Module, built from commercial pieces, will probably include monitoring LEDs, we tally the location of each such emitter and analyze the light emission mitigation implemented for each source.

Table 35 Operational Requirements

ID	Title	Requirement	Verif Meth
C-260	Remote operations	The camera shall be remotely operable from any of the LSST Facilities or other Project designated site	Demonstration
C-207	Stand alone operations	The camera shall maintain technical health, safety and status without any other subsystem operational	Demonstration

C-293	Light Emissions	Light sources within the camera shall not escape out of the camera or cause camera performance to go out of specification	Analysis
C-235	On-telescope power	The on-telescope power consumption shall comply with the Utilities and Services Interface between the Camera and Telescope (LSE-64)	Test
C-352	Operational loads	The camera shall perform within specification while subject to any of the operational load cases listed in Table 1 of the LSST Camera Environmental Specification (LCA-68).	Analysis
C-297	Camera initialization	The camera at power up shall be initialized into a known safe state without human intervention	Demonstration

11.7.13 Camera Safety and Maintenance Requirements

Camera operational requirements are listed in (Table 36).

The Camera Safety system must be present throughout I&T, and must be thoroughly enmeshed in Work Planning and Control (WPC) during I&T. In particular, the Hardware Protection System must be operational during I&T to power-up the Camera. The protection system will be exercised during I&T to ensure that it is functional, and this check should be performed on the Cryostat prior to raft installation.

Preventive maintenance procedures must be developed by the time Camera Functional Testing occurs so that these procedures can be exercised during I&T. Such procedures will include such things as Shutter removal and reinstallation, Filter Exchange Mechanism removal and reinstallation, as well as Refrigeration system care and feeding.

Table 36 Camera Safety and Maintenance Requirements

ID	Title	Requirement	Verif Meth
C-296	Safety System	The camera shall implement a non-software based safety system in areas where injury or harm to personnel and or equipment can occur	Test
C-224	Engineering and maintenance	The camera shall support operations necessary for engineering and maintenance	Demonstration
C-298	Maintenance recommendations	The camera team shall provide a preventive maintenance program to the Observatory	Inspection

11.8 Camera Calibration Optical Bench

The Camera Calibration Optical Bench (CCOB) is the test bench that verifies the integrated throughput requirements at the camera system level. In addition, the CCOB will be capable of measuring camera reflection patterns, which when combined with analysis, will provide a verification test of the camera's optical alignment. Lastly, the CCOB will be used to verify the camera baffling and search for glints. The camera specification requirements verified by the CCOB are summarized in (Table 37).

Table 37 Camera Throughput Requirements verified by the CCOB test

ID	Title	Requirement	Verif Meth
C-165	Camera u-band throughput	The camera optical hardware throughput in the u-band, averaged over 10 years, shall be greater than 0.065.	Test
C-162	Camera g-band throughput	The mean camera optical throughput in the g-band, averaged over 10 years, shall be greater than 0.170.	Test
C-164	Camera r-band throughput	The mean camera optical throughput in the r-band , averaged over 10 years, shall be greater than 0.135.	Test
C-163	Camera i-band throughput	The mean camera optical throughput in the i-band, averaged over 10 years, shall be greater than 0.097.	Test
C-167	Camera z-band throughput	The mean camera optical throughput in the z-band, averaged over 10 years, shall be greater than 0.065.	Test
C-166	Camera y-band throughput	The mean camera optical throughput in the y-band, averaged over 10 years, shall be greater than 0.024.	Test
C-261	Baffling	The camera shall be baffled such that there are no direct specular paths to the focal plane from celestial sources that are outside the nominal field of view	Test/Analysis
C-027	Throughput as-built knowledge	The as-built camera throughput shall be measured separately from the telescope with relative accuracy of 0.25% over spatial scales of 1 degree on the focal plane (approximately the size of a raft) for light at a fixed angle of incidence and in LSST griz bands. The angular dependence of the throughput shall be measured over the range 14-26 degrees for at least one point on the focal plane. (TBR)	Test

11.8.1 CCOB Equipment

The CCOB consists of a calibrated optical pencil beam source moveable across the camera aperture in both position and angle. The CCOB will utilize a four-axis (X-Y-Theta-Phi) movable stage covering the full aperture of the camera, with margin to cover rays just beyond the field of view, and capable of reaching the full 26 degree outer angle of the LSST beam, again with a few degrees of margin. We note that the camera alignment will be performed with the camera mounted vertically, ie. with the camera facing downward, and the CCOB will be mounted below the camera in this orientation. A stretch goal is for the CCOB to be capable of operation with the camera mounted horizontally. The CCOB and Camera will be covered in a light-tight shroud to prevent any stray light from reaching the focal plane.

The CCOB will utilize a narrow pencil-beam with approximately a millimeter radius. The beam's light source will be a either a broad-band Hg arc lamp, coupled with a commercial monochrometer, or a wavelength tunable laser, to produce a narrow-band wavelength selectable beam. It will be monitored with a NIST calibrated photo-diode, to enable an absolute calibration of the light intensity on the camera. The CCOB optical source will be mounted on a four-axis moveable stage, so that both the location and angle of the beam may be selected. The CCOB narrow beam serves several purposes. First, it is the tool used for the final verification of the camera throughput requirements, second, it enables a test or check of the camera optical alignment based on an analysis of the beam's ghost or reflectance pattern, and lastly it allows a direct test of the camera baffles.

All CCOB tests are performed by acquiring an LSST camera image. We anticipate that the camera will operate much as it will for science images: the shutter will define the time duration of the image and the full focal plane will be read out. In addition the CCS/DAQ system, integrated with the camera, is used to read out the image, and the associated processing capabilities are used to analyze the image. A filter will be used for most of the CCOB images, as appropriate.

The requirements for the CCOB test equipment are described in LCA-11976.

11.8.2 CCOB Verification Tests

11.8.2.1 Camera throughput

The camera optical throughput is required to be greater than a certain level in each of the 6 LSST filter bands. (The current levels (as an integral over the full camera wavelength range) are 0.065, 0.170, 0.135, 0.097, 0.065 and 0.024 in u, g, r, i, z, and y bands) This requirement is verified by the CCOB narrow-beam measurements described below. The focal-plane only contribution to the throughput is also checked using the CCOB wide-beam, described in Section 11.1.1.5

The full LSST beam input on the camera at L1 is an annulus approximately 0.6 meters in diameter subtending angles between 14 to 26 degrees from the optical axis. Reproducing this full beam profile in a single light projector is highly impractical, but we can use the CCOB narrow-beam to synthesize the LSST beam. To evaluate the throughput at a single field position, we will direct the beam along an ensemble of input positions and angles, sampling the full LSST beam phase-space. Given that the optical components will have passed individual requirements for throughput and uniformity, this sampling method will be sufficient to reasonably evaluate the throughput. The beam for each phase-space sample should impinge on the same focal plane location, to within a few pixels. For each image the monitoring NIST diode will be readout, so each image will have a known beam flux. The throughput will be calculated as

$$\epsilon = \langle \frac{\sum_{pixels} ADU * Gain \, [\frac{e^-}{DN}]}{beam \; intensity \; [photons]} \rangle$$

where the average is taken over all phase-space samples. The number of counts is corrected using standard CCD-level algorithms: overscan, bias and flat-field corrections. The Gain is determined by photon-transfer using flat-field images or ^{55}Fe from the Cryostat verification. Note that the throughput is defined as an integral over the full wavelength range for each filter, reaching to the point where the filter transmission goes to zero. The formalism defined in LCA-18 will be used to calculate this integral.

The verification of throughput will be performed in two steps. First, a high fidelity test of throughput will be made at a single Focal Plane location, using 15 wavelengths in each of the 6 bands and 100 aperture spots. Second, a lower fidelity test will be performed, but at one location per raft. This test will use 9 wavelengths per band and 10 aperture spots. The density of points is limited by the available time for these measurements and we estimate that the above program will require 20k images, corresponding to a full week of continuous image taking.

11.8.2.2 Baffling and Ghosting

The CCOB narrow beam is used to measure the ghost pattern on the focal plane. Its narrow beam is appropriate for this measurement, since its small size allows closely spaced reflection patterns to be resolved. The narrow beam is incident on a range of positions and angles, and the ghost pattern can be compared against the predicted pattern from the camera instrument model. An example of the ghost pattern in shown in (Figure 8). These patterns and the flux ratios in each reflection may be used as inputs to the observatory optical models, such as those using FRED or Zemax.

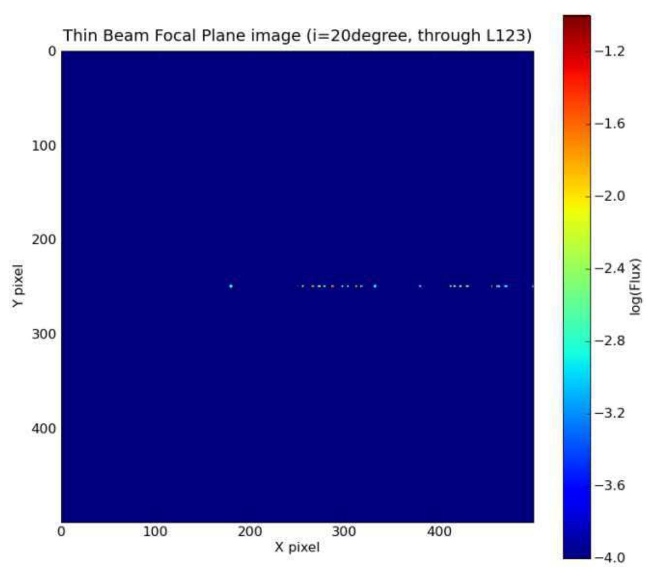

Figure 8 Predicted pattern of ghost images from CCOB narrow beam for a ray tilted at 20deg incidence angle.

In addition, the camera baffling is directly tested using the narrow CCOB beam. The beam is incident at a range of positions and angles, outside the camera field of view, and the camera is read-out to search for any flux incident on the focal plane.

11.8.2.3 *Beam-based Verification of Optical Alignment*

The relative alignment of the optical components, L1, L2, L3 and the filter, internally and with respect to the focal plane is characterized in two ways. The optical alignment is directly measured with conventional metrology, described in Section 0, using reference points on the optical element's frames. These measurements combine with sub-system level measurements of the relative positions of the optics with respect to their cells to yield alignment of the entire optical system. In addition, the optical alignment can be verified from the pattern of ghost images. The position of individual ghost images, which depend on the relative position and angle of the surfaces where reflections occur, is analyzed to extract the relative position and angle of each optical element. As such, this verification test method is complementary to the survey test, as it directly depends on optical paths within the camera.

A technique to extract optical alignments from image quality is described in document LCA-XX. In brief, the focal plane is readout and the ghost pattern measured for four input rays, two in the XZ and two in the YZ plane. Up to 21 ghost images are observed, with an estimated uncertainty on the ghost centroid of 0.5 pixels. An optical model converts the optical alignment on L1, L2, L3 and filter into a predicted pattern of ghost images. Using this model and the measured images, a non-linear minimization is performed to extract the true optical alignments. The position and orientation of the CCOB beam are nuisance parameters of the fit. Simulated trials demonstrate that the expected uncertainty is much better than the camera requirements, with statistical errors under one micron.

12 Camera Analysis at completion of I&T

Finally, the requirements verified by analysis for the completion of the Camera are described in the sections below.

12.1 Fixture Proof Tests

The requirements on fixtures are listed in (Table 38).

The lift frame will be used to move the camera on and off the Camera Integration Stand, and will be explicitly tested prior to use. The lift frame will be provided and tested by the Camera Body sub-system. All handling fixtures will be analyzed for safety under the range of possible loads.

Table 38 Requirements on Fixtures

ID	Title	Requirement	Verif Meth
C-406	Camera lift frame	The camera shall provide a below-the-hook lift frame to mount/de-mount the camera from the integrating structure while on the floor in the summit facility.	Demonstration
C-367	Loads	Lifting and handling fixturing and storage and transport containers shall be designed to safely support all camera hardware when subject to the loads listed in Table 3 of the LSST Camera Environmental Specification (LCA-68).	Test/Analysis

12.2 Pre-Ship Review

The requirements verified only during pre-ship review are listed in (Table 39).

Table 39 Requirements for Pre-Ship Review

ID	Title	Requirement	Verif Meth
C-399	Mounting hardware	The camera team shall provide the mounting hardware between the Camera Mounting Flange and the Rotator Mounting Flange as defined in LSE-18 sheet 2. (See the Camera Opto-Mechanical Definition Drawing LCA-126)	Inspection
C-424	Utilities ICD	The camera shall be compliant with the Camera to Telescope Utilities ICD (LSE-64)	Audit
C-425	Facilities ICD	The camera shall be compliant with the Camera to Telescope Facilities ICD (LSE-65)	Audit

12.3 Shipping Analysis

The requirements on Shipping the Camera are listed in (Table 40).

All of the shipping requirements are verified by a dedicated analysis.

Table 40 Camera Shipping Requirements

ID	Title	Requirement	Verif Meth
C-359	Transport temperature range	During transport, the camera shall survive the transportation temperature range of -15 degC to 40 degC	Analysis
C-361	Transport wind speed	During transport, the camera shall survive a maximum wind speed of 45 m/sec	Analysis
C-348	Transport humidity	During transport, the camera shall survive the transport relative humidity range of 10% to 100% at the exterior of the shipping container	Analysis
C-351	Transport pressure rate of change	The camera shall survive a pressure rate of change of +120/-60 kPa/hr	Analysis

C-358	Transport accelerations	The camera shall be designed to survive transportation loads listed in Table 4 of the LSST Camera Environmental Specification (LCA-68), or be shipped in special containers and/or transported on "Air-Ride" trucks that include an isolation system.	Analysis

13 Camera Models

Here we list the Camera Models which must be developed in the course of I&T.

13.1 Focal Plane & CCD module

This model includes all leading physical terms affecting the conversion of light incident on the Focal Plane into the recorded conversion distribution and readout signal. This includes such things as the three dimensional description of the image height/surface, anti-reflective coating, photon transport and absorption in Silicon, diffusion and the brighter-fatter effect, and the mapping between pixels and the Camera coordinate system to list just a subset. (The primary author and designer for this code is Andy Rasmussen.) To date, parametric constraints for the code have been informed by a wealth of laboratory data, and the code has been used to evaluate many of the contributions to image quality and throughput expected from the CCDs. The parameters of this model will be adjusted to match the performance of the focal plane, either with individual CCD parameters or averaged parameters, as appropriate. This model will be used to calculate the expected average image quality of the focal plane, incorporating all effects, to provide another view of the baseline IQ verification as described in Section 10.1 . Lastly, we note that the Focal Plane model aims for high fidelity, and as such is not meant for production simulation.

13.2 As-built Optical Model

I&T will collect the necessary information for an as-built optical model. While the IQ requirements will be verified as described in Section 10.1, the as-built optical model will encapsulate the baseline performance requirement and will support further investigation of the camera IQ.

The as-built optical model will include data provided by the Optics sub-system, described below as well as measurements from the Survey & Alignment program, see Section 11.3. In particular for all optical elements this will include the as-built: the position and orientation with respect to the optical axis, the radius of curvature, aspheric departure and wedge, and the measured OPD or phase. In addition the location and orientation of the Focal Plane and Back Flange will be included.

13.3 Focal Plane Temperature Variation Model

This issue is described in Section 11.6.1. The sum of that effort is a Focal Plane temperature model.

13.4 Cross-talk Variation Model

This issue is described in Section 11.1.2.5. Should the cross-talk vary in time, a model will be required to characterize the changes.

13.5 Electronic Gain Variation Model

This issue is described in Section 11.1.2.3. Should the electronic gain vary in time, a model will be required to characterize the changes.

14 Sub-System Deliverables to I&T

Several pieces of data, characterizing the instrument, are required by I&T from subsystems. These are described here.

14.1 Bad Pixel Map – Science Raft

I&T requires a bad pixel map, as measured during sensor or raft testing, for each of the CCDs. This map should contain the location of all bad pixels, including the type of failure. The map is used to compare against the bad pixels found during I&T, as described in Section 11.1.2.6 .

14.2 QE Map – Science Raft

The quantum efficiency (QE) is not measured during I&T, only the integrated throughput. However, to support the measurement of throughput, it will be quite useful to access the QE maps measured during sensor testing. In particular, the throughput should agree with the combination of QE maps plus expectation for the transmission the optical elements plus filter.

14.3 Focal Plane Temp. map – System Engineering

The discussion of Focal Plane temperature requirements in Section 11.6.1 assumes that the finite element model of the temperature variation of the Focal Plane is available. The existing model will be sufficient if the ultimate operating conditions, in terms of cryostat heaters, is as modeled. Should the operating conditions be different, a new finite-element model may be required to verify the Focal Plane temperature requirements.

14.4 As-built Optical Model – Optics

As described above the optics sub-system will provide measurements needed for the as-built optical model. Information needed from the optics sub-system include: the as-built radius of curvature, aspheric departure and wedge (as appropriate) for L1, L2, L3 and the Filters, the lens prescription data, glass type and index and clear aperatures. In addition, measured OPD or phase for each element (or their equivalent) should be provided in a form amenable for use in Zemax. Also the relative position and orientation of L1 and L2 is required. Lastly, the location of all SMRs on the cells for each of the optical elements with respect to a suitable coordinate system is required.

14.5 Cryostat Metrology

The cryostat sub-system will provide the metrology information necessary to tie the focal plane height to the Best Fit Optical Axis. The Grid has six posts, with surfaces at the height of the CCDs, which will be measured with respect to both the ball grid array and to the SMRs on the front surface of the Cryostat itself.

In addition, the Cryostat sub-system will provide data on the solid-body motion of the grid with respect to the front surface of the Cryostat under gravitational loads, over the full range of operating angles.

14.6 Mass Workbook Data

Each sub-system will provide mass, center-of-gravity, and moment of inertia data. This data is collected by Systems Engineering and used to update the Mass Workbook. The sub-system information may be a combination of measurement and analysis as appropriate.

14.7 Power Workbook Data

Each powered component will provide power usage data. The data is collected by Systems Engineering and used to update the estimates for Camera power consumption.

14.8 Shutter Data

The shutter will supply results of tests of the repeatability of the blade positions, search for light leaks and a modal assessment.

15 Sub-System Requirement Verification

The I&T sub-system is also responsible for acceptance of each piece of camera hardware, and given that role, we include here a brief synopsis of the verification activities in each sub-system with reference to the appropriate sub-system documentation. Note that Systems Engineering plays a critical role in the complete requirement verification chain, including both the flow down of requirements and assessing that each sub-system's testing will adequately verify the needed requirements.

15.1 Science Raft

A description of the Science Raft verification testing is contained in several documents outlining the testing performed at each stage of the science raft assembly. LCA-10051 describes the CCD electro-optical testing apparatus (TS-3) and LCA-10103 describes the software algorithms used in electro-optical CCD testing, LCA-10050 describes the CCD metrology testing (TS-2), LCA-10064 describes integrated raft electro-optical testing (TS-7), and LCA-10061 describes raft-level metrology testing (TS-5). A summary of the Science raft electro-optical tests from LCA-10064 is shown as Figure 9.

C-SRFT-	description	prior test	REC+RSA req'd?	image req'd	
-133	initialization	TS-REB	N	none	REC ELECTRONICS
-169	CCS control	TS-REB	N	none	
-149	power-up time	TS-REB	N	none	
-090	image delivery to DAQ	TS-REB	N	none	
-049	telemetry	TS-REB	N	none	
-134	0 second exposure	TS-REB	N	none	
-116, -118	average power	TS-REB	N	none	
-117,-119	peak power	TS-REB	N	none	
-188	heater power	TS-REB	N	none	
-151	heater setpoint	TS-REB	N	none	
-152	heater update rate	TS-REB	N	none	
-154	CCD temp. update rate	TS-REB	N	none	
-073	read noise	TS3	Y	fe55-acq	SENSORS
-053	pixel rate	TS3/TS-REB	Y	fe55-acq	
-036	dark current	TS3	N	dark-acq	
-047	chg. Diffusion	TS3	N	fe55-acq	
-064	linearity	TS3	Y	flat-acq	
-058,-122	CTE	TS3	Y	sflat-acq	
-001 – -006	QE	TS3	N	qe-acq	
-007	non-defective pixels	TS3	N	flat-acq + dark-acq	
-059	crosstalk	NEW TEST	Y	spot	THERMAL
-170,-171	gain stability	TS3/TS-REB	Y	d^2(fe55-acq)/$dT_{RSA}dT_{REC}$	
-060	crosstalk stability	NEW TEST	Y	d^2(spot)/$dT_{RSA}dT_{REC}$	
-150	trim heat authority	NEW TEST	Y	ΔT	
-153	CCD temp. precision	TS-REB	Y	none	

Figure 9 Science Raft requirements verified in Test Stand 7

All test results are collected via e-Travelers, test results are summarized in an automatically generated document, and both raw data and selected data products are archived in the Data Catalog.

Almost all Science Raft requirements are reverified at the Cryostat level, or are subsumed in Cryostat or Camera level requirements, and so are included in the tables describing the requirements verified by I&T above.

15.2 Corner Raft

A description of the corner raft verification test plan is given in LCA-13372. The scope of Corner Raft tests is very similar to that of the Science Raft sub-system, with tests using the same equipment in most cases. As for the S.R., all test results are collected via e-Travelers, test results are summarized in an automatically generated document, and both raw data and selected data products are archived in the Data Catalog.

15.3 Optics

Since the optics components, L1+L2, L3, L3 flat and Filters, are under design-build contracts, in each case the vendor will ultimately be responsible for the appropriate verification test plans. For each contract a Test Readiness Review (TRR) will be conducted to allow the Camera team to approve the test plans. As part of the contract bidding process, the Optics sub-system has prepared Statement's of Work (SOW), which together with the requirements lay out the necessary information for vendors. The requirements for the optics sub-system are described in LCA-53. All these requirements are verified by the vendors, and described in test plans. The L1+L2 test plan is described on the Confluence page: https://confluence.slac.stanford.edu/display/LSSTCAM/L1-L2+Vendor+FDR , and the L3 and L3 flat test plan is described on the Confluence page: https://confluence.slac.stanford.edu/pages/viewpage.action?pageId=211798342, and the Filter test plan documents are LCA-13387, LCA-11751 and LCA-11807. All vendor data for the optics subsystem will be captured by a LLNL system, and then transferred into the eTraveler system.

15.4 Cryostat & Refrigeration

The requirements for the Cryostat and Refrigeration system are listed in LCA-51. When a document that describes the verification test plan for the Cryostat and Refrigeration sub-system is prepared it will be referenced here. Some of the tests which must be done at the sub-system level include the vacuum performance and contamination level of the bare cryostat, ie. without rafts installed. In addition, the operation of the refrigeration system will be demonstrated by the sub-system.

15.5 Camera Body, Shutter, Exchange Mechanism

The Filter Exchange requirements are described in LCA-49, the Shutter requirements in LCA-56 and the Camera Body requirements in LCA-55. The Camera Body test plan is LCA-10807, where tests of the purge system and the environmental, mass and modal requirements are described. The shutter and exchange mechanism will undergo a battery of tests, whose document will be referenced here.

15.6 DAQ & CCS

15.7 Hardware Protection System

The certification of the hardware protection system is described in LCA-13494. This system is critical for the start of cryostat level I&T, since no work can take place without the protection system in place. This document describes a suite of tests to verify that the protection system is working correctly, with tests for each input to the master protection module.

16 ICD Verification Matricies

The camera requirements (LSE-59) and the majority of the subsystem requirements (LSE-66: Guider Interface between the Camera and Telescope, LSE-67: Wavefront Sensor Interface between the Camera and Telescope, LSE-69: Interface between the Camera and Data Management, LSE-71: OCS-Camera Software Communication Interface, LSE-80: Mechanical, Thermal, and Access Interfaces Between the Camera and Telescope) are flowed directly to the Camera Specification (LSE-48). Three exceptions (LSE-64: Utilities and Services Interfaces between the Camera and Telescope, LSE-65: Summit Facility Interfaces between the Camera and Telescope and LSE-68: Camera Data Acquisition Interface) are called out by reference. The following 3 tables contain the verification matrices for these ICDs.

Table 41. LSE-64 Verification Matrix

Table 42.LSE-65 Verification Matrix

Table 43. LSE-68 Verification Matrix

Table 41. LSE-64 Verification Matrix

			responsibility (Primary or indirect)		Verification						Verification discussion
ID	**Title**	**Specification Summary**	tscope	cam	Cam	I&T	Cryo	DAQ	CCS	Aux Elx	
CA-TS-UTI-ICD-0030	Disconnects at Stationary End of Cable Wrap Provider	Telescope provides disconnects	P								This has changed with the new approach, ICD needs update
CA-TS-UTI-ICD-0002	Camera Lines	Camera provides lines to an area near the back of the utility trunk		P	I						Redundant with LSE-18 and -80
CA-TS-UTI-ICD-0001	Top End Camera Cable Wrap Provider	The telescope provides the top end camera cable wrap.	P								
CA-TS-UTI-ICD-0024	Top End Camera Cable Wrap Sizing	Telescope provided top end camera cable wrap sized to accommodate all of the utility lines, cables, and fibers	P								
CA-TS-UTI-ICD-0025	Top End Camera Cable Wrap Minimum Bend Radii	Cable wrap bend radii to support cyclic life of the cables	P								
CA-TS-UTI-ICD-0026	Top End Camera Cable Wrap Twisting	Cable wrap twisting limited to manufacturers specs	P								
CA-TS-UTI-ICD-0027	Top End Camera Cable Wrap Support and Restraint	The top end camera cable wrap lines, cables, and fibers are supported and restrained appropriately	P								
CA-TS-UTI-ICD-0028	Top End Camera Cable Wrap Forces	Limits to forces on cables	P								
CA-TS-UTI-ICD-0029	Top End Camera Cable Wrap Auxilliary Support	Support for lines extending to the disconnect	P								
CA-TS-UTI-ICD-0003	Refrigerant Lines	The Telescope shall provide, install, and test dedicated camera cryo-circuit and cold-circuit refrigerant lines from the connections on the back of the Utility Trunk to the dome lower enclosure where they connect up to lines coming from the facility (defined in LSE-65). If custom fittings (not commercially available) are required for these lines, they shall be provided by the Camera team for installation on the summit.	P	P	I		I				Inspection of the custom fittings prior to delivery

CA-TS-UTI-ICD-0005	Cryo Refrigerant Lines	Cryo refrigerant line characteristics	P	I	I		I				Refrigeration system must operate with the lines as defined in the document. Pathfinder test on telescope, demo of camera ops during I&T (but does not demonstrate the path). So how do we gain confidence?
CA-TS-UTI-ICD-0006	Cold Refrigeration Lines	Cold refrigerant line characteristics	P	I	I		I				
CA-TS-UTI-ICD-0007	Refrigerant Lines Temperature Differential	Refrigeration lines compatible with temperature differential	P								
CA-TS-UTI-ICD-0008	Refrigerant Temperature Differential	Temperature limits on refrigeration exiting the camera		P	T		T				Flowed directly to C-390
CA-TS-UTI-ICD-0032	Refrigerant Peak Pressure	Peak pressure in refrigerant lines		P	T		T				Peak pressures verified by test at cryostat level, and again at camera level
CA-TS-UTI-ICD-0009	Refrigerant Compatibility	Refrigerant line compatability with refrigerants	P	P			T				Camera has selected lines. Compatibility with refrigerant demonstrated at the cryostat level.
CA-TS-UTI-ICD-0010	Stainless Steel Tubing	Tubing materials and manufacturing requirements	P								
CA-TS-UTI-ICD-0045	Stainless Steel Tubing Fittings	Limits use of fittings	P								
CA-TS-UTI-ICD-0011	Quick Disconnects	Refrigerant lines have quick disconnects	P	I	I		I				to be replaced by connector and fitting definitions, camera will inspect connector on bulkhead plate
CA-TS-UTI-ICD-0033	Continuous Flexible Hoses	Locations where flexible refrigerant lines are allowed	P								
CA-TS-UTI-ICD-0034	Flexible Refrigerant Hose Liner	Flexible refrigerant hoses characteristics	P								Requirement to be updated
CA-TS-UTI-ICD-0044	Flexible Line Testing	Camera team tests the selected flexible line tubing to ensure it is compatible with the designed refrigeration system		P			T				written on the camera, Martin has a comment. I would expect all lines would be tested, not just the flexible ones. -0006 has a proof test of 600 psi
CA-TS-UTI-ICD-0012	Hose Fittings	Hose fitting characterists	P								
CA-TS-UTI-ICD-0013	Hose Purging and Testing	Hose purging and testing requirements	P								
CA-TS-UTI-ICD-0031	Completed Circuit Purge, Proof Test and Leak Test	Telescope tests the refrigeration circuit at initial installation	P								

CA-TS-UTI-ICD-0014	Optical Fiber Lines	Telescope provides optical fibers for CCS and DAQ communications	P								
CA-TS-UTI-ICD-0035	DAQ Optical Fibers	DAQ optical fiber characteristics, length and disconnect counts	P	I	D			T			Check with Mike, could be analysis or test at daq level
CA-TS-UTI-ICD-0036	CCS Optical Fiber	CCS optical fiber characteristics, length and disconnect counts	P	I	D				T		see above - would be verified the same way
CA-TS-UTI-ICD-0015	Signal Copper Lines	Signal copper line characteristics	P	I	D					T	Aux Elx tests details at subsystem, camera demonstrates functionality at the camera level.
CA-TS-UTI-ICD-0016	Signal Copper Line Connector Type	Cable connector definition, including keying	P	P	I					I	Inspection to confirm connector
CA-TS-UTI-ICD-0017	Power	Supplied power characteristics (phase configuration, voltages)	P	P	T					T	Per C-235
CA-TS-UTI-ICD-0037	Power Consumption	Camera power draw limits		P	T						Per C-235
CA-TS-UTI-ICD-0018	Power Cable Connector	Power cable connector details	P	I	I					I	Inspection to confirm connector
CA-TS-UTI-ICD-0038	Compressed Air Coupling - Camera Supplied	Compressed air connector	P	P	I		I				Inspection to confirm connector
CA-TS-UTI-ICD-0019	Compressed Air	Compressed air characteristics	P	I	D		T				Cryostat tests limit at subsystem level, camera demonstrates functionality at the camera
CA-TS-UTI-ICD-0039	Camera Compressed Air Quality	Compressed air per ISO 8573-1 Class 1.3.1.	P								
CA-TS-UTI-ICD-0020	Compressed Air Coupling - Telescope Supplied	Compressed air connector definition	P	I			I				
CA-TS-UTI-ICD-0040	Glycol Supply	Parameters of telescope provided glycol	P	I							Glycol usage monitored during camera test
CA-TS-UTI-ICD-0041	Glycol Return	Camera to use a mixing valve and limits on camera use of glycol		P	T		T				Glycol usage monitored during camera test
CA-TS-UTI-ICD-0042	Glycol Line Connector - Telescope Side	Telescope glycol connector definition	P								
CA-TS-UTI-ICD-0043	Glycol Line Connector - Camera Side	Camera glycol connector definition		P	I		I				Inspection to confirm connector
CA-TS-UTI-ICD-0021	Power Outlet	Electrical power provided on service platform	P								I&T review
CA-TS-UTI-ICD-0022	Ethernet Network	Wired internet access avaliable 1 meter from camera on deployed platform	P								I&T review

CA-TS-UTI-ICD-0023	Interlocks	Safety interlocks available on platform within 1 meter of camera	P							use should be in maintenance plans

Table 42.LSE-65 Verification Matrix

			Responsibility (Primary or indirect)		Verification						Verification discussion
ID	Title	Specification Summary	tscope	cam	Cam	I&T	Cryo	DAQ	CCS	Aux Elx	
ID: CA-TS-FAC-ICD-0001	Transportation/Shipping Environment	Environments for the camera during transportation		P		A					
ID: CA-TS-FAC-ICD-0073	Transportation Limiting Dimensions	Puclaro Tunnel limiting dimensions for shipping container		P		I					
ID: CA-TS-FAC-ICD-0002	Dimensions, Floor Capacity and Lighting Conditions	Telescope & Site team provided Receiving Area has the dimensions, floor capacity, and lighting conditions.	P								
ID: CA-TS-FAC-ICD-0003	Receiving Area Floor Condition	Receiving area floor is bare or epoxy-painted concrete.	P								
ID: CA-TS-FAC-ICD-0004	Crane Capacity, Hook Height and Coverage	Telescope provides crane in the receiving area with defined capacity, coverage and hook height	P								I&T review
ID: CA-TS-FAC-ICD-0005	Receiving Area Environmental Control	Defines temperature, rate of temperature change, humidity, and pressure environment.	P	I		I					I&T review, Flowed to camera components via LCA-69
ID: CA-TS-FAC-ICD-0006	Receiving Area Mechanical Utilities	Compressed air and water characteristics in the receiving area	P								
ID: CA-TS-FAC-ICD-0007	Dimensions, Floor Capacity and Lighting Conditions	Telescope & Site team provided Staging and Test Area has the dimensions, floor capacity, and lighting conditions.	P								
ID: CA-TS-FAC-ICD-0008	Staging and Test Area Floor Condition	The staging and test area floor shall be non-shedding and easily cleanable.	P								
ID: CA-TS-FAC-ICD-0009	Crane Capacity, Hook Height and Coverage	Telescope provides crane in staging and test area with defined capacity, coverage and hook height	P								
ID: CA-TS-FAC-ICD-0010	Staging and Test Area Temperature Control	Staging and Test Area environmental contidions	P	I		I					I&T review, Flowed to camera components via LCA-69
ID: CA-TS-FAC-ICD-0011	Staging and Test Area Mechanical Utilities	Compressed air, water, and glycol characteristics in the staging and test area	P								
ID: CA-TS-FAC-ICD-0012	Staging and Test Area Power Utilities	Electrical power outlet definitions	P								
ID: CA-TS-FAC-ICD-0013	Dimensions, Floor Capacity and Lighting Conditions	Telescope and Site team provided White Room with dimensions, floor capacity, and lighting conditions	P								
ID: CA-TS-FAC-ICD-0066	White Room Door Curtain	Telescope and Site team provided hanging plastic-strip curtain to cover the white room door opening when the outer door is open.	P								
ID: CA-TS-FAC-ICD-0014	White Room Ante-Room Dimensions	Telescope and Site provided White Room Ante-Room dimensions	P								
ID: CA-TS-FAC-ICD-0015	White Room Floor Condition	The Telescope and Site provided static dissipative flooring on the White Room floor.	P								
ID: CA-TS-FAC-ICD-0016	White Room Window	Window between the White Room and Staging and Test Area.	P								
ID: CA-TS-FAC-ICD-0017	White Room Ante-Room Window	Window between the Ante Room and Clean Room.	P								

ID: CA-TS-FAC-ICD-0018	White Room Airlock	The Telescope and Site team shall provided pass-though port between the ante room and the clean room	P								
ID: CA-TS-FAC-ICD-0019	Crane Capacity, Hook Height and Coverage	Telescope and Site team provided bridge crane in the White Room with defined characteristics.	P								
ID: CA-TS-FAC-ICD-0020	White Room Crane Particulate Control	Requirements on crane to control particulate contamination	P								
ID: CA-TS-FAC-ICD-0021	White Room Ceiling Hoist	White room hoist characteristics	P								
ID: CA-TS-FAC-ICD-0022	White Room Environmental Control	White room temperature range, humidity range and temperature drift	P	I		I					I&T review, Flowed to camera components via LCA-69
ID: CA-TS-FAC-ICD-0067	White Room Supplemental Cooling	Allowed heat load from camera equipment in the white room	P	P		I					note reqmt is written on telescope, cam heat load is defined
ID: CA-TS-FAC-ICD-0023	White Room Particulate Control	The white room is an ISO class 8 particulate controlled room	P								
ID: CA-TS-FAC-ICD-0068	White Room Grounding Bars	Ground bar characteristics	P								
ID: CA-TS-FAC-ICD-0047	White Room Camera Umbilicals	Camera provides all the umbilical lines to connect from the camera utility trunk to the bulkhead panel in the white room.		P		I					
ID: CA-TS-FAC-ICD-0024	White Room Mechanical Utilities	Glycol, compressed air and nitrogen characteristics	P								
ID: CA-TS-FAC-ICD-0025	White Room Power Utilities	Camera power feed with characteristics matching power provided to the camera when it is on-telescope	P								See LSE-64, req id xxxxx
		White room electrical power outlet definitions	P								
ID: CA-TS-FAC-ICD-0026	White Room Network Utilities	Network connection for control and data	P								
ID: CA-TS-FAC-ICD-0027	Dimensions, Floor Capacity and Lighting Conditions	Clean Room dimensions, floor capacity, and lighting conditions	P								
ID: CA-TS-FAC-ICD-0028	Clean Room Floor Condition	Telescope and Site team provided static dissipative flooring on the Clean Room floor.	P								
ID: CA-TS-FAC-ICD-0029	Clean Room Wall Conditions	Window between the Clean Room and White Room.	P								
ID: CA-TS-FAC-ICD-0069	Clean Room Ceiling Conditions	Clean room ceiling is constructed out of cleanable surfaces.	P								
ID: CA-TS-FAC-ICD-0030	Crane Capacity, Hook Height and Coverage	Camera team provides any lifts, cranes, or hoists for use in the Clean Room		P							
ID: CA-TS-FAC-ICD-0031	Clean Room Environmental Control	Clean room temperature range, humidity range and temperature drift	P								I&T review, Flowed to camera components via LCA-69
ID: CA-TS-FAC-ICD-0070	Clean Room Supplemental Cooling	Allowed heat load from camera equipment in the clean room	P	P		I					note reqmt is written on telescope, cam heat load is defined
ID: CA-TS-FAC-ICD-0032	Clean Room Particulate Control	The clean room is an ISO class 7 particulate controlled room	P								
ID: CA-TS-FAC-ICD-0071	Clean Room Grounding Bars	Ground bar characteristics	P								
ID: CA-TS-FAC-ICD-0033	Clean Room Mechanical Utilities	Clean room compressed air and gaseous nitrogen characteristics	P								
ID: CA-TS-FAC-ICD-0034	Clean Room Power Utilities	Dedicated power and facility outlet definitions	P								

ID: CA-TS-FAC-ICD-0035	Clean Room Network Utilities	Network connection for control and data	P									
ID: CA-TS-FAC-ICD-0072	Computer Room Dimensions and Hardware	The Telescope and Site team provides space for 3 full racks in the computer room and provides the racks	P									DAQ must fit in one rack, CCS must fit in two racks
ID: CA-TS-FAC-ICD-0036	Control Room Dimensions and Hardware	The Telescope and Site team shall provide space for one workstation in the control room. The camera team shall be responsible for furnishing and installing the workstation.	P									
ID: CA-TS-FAC-ICD-0038	Control Room Environmental Control	No special provisions for this area are anticipated as necessary to support the needs of the camera.	na									
ID: CA-TS-FAC-ICD-0039	Control Room Power Utilities	Control room power for dedicated power and wall plugs.	P	I				T	T			Per C-371
ID: CA-TS-FAC-ICD-0040	Dimensions, Floor Capacity and Lighting Conditions	Utility Room dimensions, floor capacity, and lighting conditions	P									
ID: CA-TS-FAC-ICD-0041	Fork Lift/Pallet Jack Access	Telescope and Site team provides access from the receiving bay to the Utility Room by fork truck or pallet jack.	P									
ID: CA-TS-FAC-ICD-0042	Utility Room Environmental Control	Utility room temperature range	P									Flowed via LCA-69
ID: CA-TS-FAC-ICD-0043	Utility Room Mechanical Utilities	Utility room compressed air, glycol, and gasseous nitrogen characteristics	P									
ID: CA-TS-FAC-ICD-0048	Lines and Cable Trays	Telescope provides refrigeration lines terminated in a bulkhead panel, camera provides hoses connecting from this panel to the refrigeration units	P	P			I					
ID: CA-TS-FAC-ICD-0044	Utility Room Power Utilities	Definition of dedicated power and wall circuits	P									flowed via LCA-275
ID: CA-TS-FAC-ICD-0045	Utility Room Network Utilities	network connection for control.	P									
ID: CA-TS-FAC-ICD-0046	Utility Room Oxygen Alarm	Telescope and Site team provided oxygen alarm	P									
ID: CA-TS-FAC-ICD-0049	Refrigerant Lines	Refrigerant line sets routing. Any custom fittings provided by camera	P	I			I					Custom fittings by inspection
ID: CA-TS-FAC-ICD-0050	White Room Refrigerant Panel	Refrigerant lines in white room terminate in a bulkhead	P									
ID: CA-TS-FAC-ICD-0051	Cryo Refrigerant Lines	Cryo refrigerant line properties	P									See LSE-64, reqid xxxx
ID: CA-TS-FAC-ICD-0052	Cold Refrigeration Lines	Cold refrigerant line properties	P									See LSE-64, reqid xxxx
ID: CA-TS-FAC-ICD-0053	Lines Temperature Differential	Refrigeration lines compatible with temperature differential	P									
ID: CA-TS-FAC-ICD-0054	Camera Temperature Differential	Temperature limits on refrigeration exiting the camera		P								See camera requirement C-390
ID: CA-TS-FAC-ICD-0055	Refrigerant Compatibility	Refrigerant line compatability with refrigerants	P									
ID: CA-TS-FAC-ICD-0056	Stainless Steel Tubing	Tubing materials and manufacturing requirements	P									
ID: CA-TS-FAC-ICD-0057	Flexible Tubing	Flexible refrigerant lines are allowed only where necessary	P									

ID: CA-TS-FAC-ICD-0058	Hose Purging and Testing	Hose purging and testing requirements	P								
ID: CA-TS-FAC-ICD-0059	Optical Fiber Lines	Telescope provides optical fibers for CCS and DAQ communications	P								
ID: CA-TS-FAC-ICD-0074	DAQ Optical Fiber Lines	DAQ optical fiber characteristics	P								See LSE-64, reqid xxxx
ID: CA-TS-FAC-ICD-0075	CCS Optical Fiber Lines	CCS optical fiber characteristics, length and disconnect counts	P								See LSE-64, reqid xxxx
ID: CA-TS-FAC-ICD-0060	White Room Optical Fiber Panel	White room optical fiber panel	P								I&T provides umbilical that links this point to the camera
ID: CA-TS-FAC-ICD-0061	Sheathed Optical Fiber	Fiber cables to be sheathed for protection	P								
ID: CA-TS-FAC-ICD-0062	Signal Copper Lines	Signal copper line routing, connectivity and characteristics	P								
ID: CA-TS-FAC-ICD-0063	Computer Room Signal Panel	Defines the signal line runs to the Computer room	P								
ID: CA-TS-FAC-ICD-0064	White Room Signal Panel	White room bulkhead for signal copper lines	P								
ID: CA-TS-FAC-ICD-0065	Signal Copper Line Connector Type	Signal connector definitions	P								See LSE-64, reqid xxxx

Table 43. LSE-68 Verification Matrix

			Responsibility (Primary or indirect)		Verification						Verif. Req.
Req-ID	Title	Requirement summary	tscope	cam	Cam	I&T	Cryo	DAQ	CCS	Aux Elx	
CA-DM-DAQ-ICD-0075		Camera software delivered as a library with defined characteristics.		P							
CA-DM-DAQ-ICD-0058		Camera to provide a class interface representing the structure of the data.		P							
CA-DM-DAQ-ICD-0059		Image to have a unique identifier to allow association of the image with metatada in the EFD		P							Pathfinder exercise will demonstrate all 6 items
CA-DM-DAQ-ICD-0060		Image identifier to have defined characteristics.		P							
CA-DM-DAQ-ICD-0080		The image data format and its API to include "structural metadata", sufficient to assemble the amplifier segments from the readout of the full focal plane into a representation of the focal plane as a whole.		P							DAQ test
CA-DM-DAQ-ICD-0081		Image data pixel values to be delivered as 32-bit signed integers in a specified order including per-scan and post-scan data.		P							Pathfinder test will demonstrate ability to keep the required data available and to provide that data to users on request. Partition will be configured to hold just a few images, ….
CA-DM-DAQ-ICD-0047		Camera to maintain a buffer of recently acquired image data and shall provide access to images in that buffer to other LSST subsystems.		P							
CA-DM-DAQ-ICD-0082		A single interface to support retrieval of science, wavefront, and full-frame guide sensor images, with API differences limited to those required for the specification of which sensor(s) to access in a retrieval.		P							The full set of errors will be verified by verification of design/interface documentation (which one??). Selected errors will be exercised during pathfinder testing.
CA-DM-DAQ-ICD-0097		Error reporting from the APIs implementing this interface to be by means of return codes for all non-fatal errors.		P							Early pathfinder tests will verify the basic functionality. Later pathfinder test will desmonstrate a full night's observing

CA-DM-DAQ-ICD-0084		The Camera to provide an interface that allows a client to subscribe to notifications of the availability of data from a new image in the buffer with defined interface characteristics		P							Pathfinder exercise will read the same image multiple times. Error testing (data not available) per CA-DM-DAQ-ICD-0097
CA-DM-DAQ-ICD-0086		The Camera to provide an interface that allows any image in the buffer, specified by the client providing its container ID and spatial ID, to be read non-destructively.		P							Early pathfinder tests will demonstrate access to container ID based on the image name.
CA-DM-DAQ-ICD-0098		The Camera to provide an interface that permits looking up the Container ID for an image based on its Image Name.		P							is this at DAQ level on pathfinder level?
CA-DM-DAQ-ICD-0085		The Camera to provide an interface that allows the partitioning of the data in the buffer into named sets.		P							During a pathfinder test the DM will query for a list of valid container IDs for a selected partition. The returned list will be compared to the partition directory, including verification of the order of the container IDs
CA-DM-DAQ-ICD-0099		The Camera to provide an interface that can be used to query the complete list of valid Container IDs for a given partition.		P							During a pathfinder test an image will be marked for deletion by the DAQ. A subsequent read for that image will be attempted and the correct error message verified.
CA-DM-DAQ-ICD-0100		The Camera to provide an interface that allows marking an image for deletion.		P							See CA-DM-DAQ-ICD-0094
CA-DM-DAQ-ICD-0089		The buffered interfaces for image data retrieval to provide for the optional application of crosstalk correction to the data to be read.		P							During a pathfinder test the DM will perform a sequence of readouts cycling through all allowed subunit sizes. Sustained operations with subunit size of a raft will be demonstrated, ???? Including simulated loads for the expected user complement.
CA-DM-DAQ-ICD-0091		The Camera to permit the selection of a subunit of the focal plane for readout		P							Will a pathfinder test have 4 consumers?
CA-DM-DAQ-ICD-0092		The Camera to support simultaneous access to the image store by at least four privileged consumers for which its performance guarantees (for latency and throughput) are met		P							The DAQ subsystem test will measure the latency across all specified conditions
CA-DM-DAQ-ICD-0093		The Camera to complete the delivery of an available image within time daqLatency of each request based on a notification		P							Testing at the DAQ level per XXXX, For early pathfinder tests, DM will load the buffer with data from an external source. DM will request the image data and verify that the returned data matches the data from the external source.

CA-DM-DAQ-ICD-0094		The Camera to provide an interface that allows the buffer to be loaded with image data from an external source, and for this data to be retrieved using the interfaces specified in this section.		P							During pathfinder tests: DM will provide crosstalk coefficients to the camera, ensuring unique coefficients for each ampilfier Data will be requested with and without crosstalk correction applied. DM will confirm the image metadata is as expected for the raw and crosstalk corrected images DM will independently apply the crosstalk to the raw data. DM will verify that the crosstalk corrected data is as expected (note due to floating point differences this may not be an exact comparison)
CA-DM-DAQ-ICD-0051		The Camera to provide for optional crosstalk correction to image data retrieved.		P							See CA-DM-DAQ-ICD-0094
CA-DM-DAQ-ICD-0057		The Camera to support crosstalk correction across all the amplifiers within a raft, allowing for different levels of crosstalk between each pair of amplifiers.		P							See CA-DM-DAQ-ICD-0094
CA-DM-DAQ-ICD-0053		Crosstalk-corrected image data to have the same format as raw image data, except as noted in specific requirements herein.		P							See CA-DM-DAQ-ICD-0094
CA-DM-DAQ-ICD-0055		Crosstalk-corrected images to have the same numerical representation as raw images.		P							See CA-DM-DAQ-ICD-0094
CA-DM-DAQ-ICD-0054		Images obtained from the camera to contain metadata stating whether or not crosstalk correction has been applied.		P							See CA-DM-DAQ-ICD-0094
CA-DM-DAQ-ICD-0056		The crosstalk-correction algorithm applied by the Camera to be capable of being implemented in a form that can be applied by Data Management in its pipeline processing environment		P							See CA-DM-DAQ-ICD-0094
CA-DM-DAQ-ICD-0052		The constants to be used in the crosstalk-correction algorithm for science sensor data to be supplied by Data Management. The Camera to permit these constants to be changed as part of its normal configuration process. That process shall ensure that provenance data for the constants are maintained.	P	P							See CA-DM-DAQ-ICD-0094, with the addition of: At the end of the sequence a new set of crosstalk coefficients will be loaded by DM. DM will load images into the buffer. DM will request images in the earlier set and confirm that the original crosstalk coefficients are applied. DM will request images from the new set and confirm that the right coefficients are applied

CA-DM-DAQ-ICD-0096		The Camera to store, for each image in the image store, the identity of the crosstalk-correction constants in force at the time of image acquisition, and shall, by default, apply those constants whenever that image is retrieved with crosstalk correction. Some limitations apply		P								TBD
CA-DM-DAQ-ICD-0095		The Camera to provide a mechanism for overriding the default crosstalk-correction constants to be applied when retrieval of crosstalk-corrected data is requested.		P								TBD