Large Synoptic Survey Telescope Camera System Plan	Document # **LCA-280-A** Author(s) Martin Nordby Don Arnett John Ku J Langton Subsystem/Office Systems Integration	Status LSST Camera APPROVED Effective Date: 26 Mar 2013

Document Title

LSST Camera Mechanical Standards

1. Change History Log

Revision	Effective Date	Description of Changes
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3. Acronyms

AMS	Aerospace Material Specification
ASME	American Society of Mechanical Engineers
BPV	Boiler and Pressure Vessel Code
CCS	Camera Coordinate System
EEE	Electrical, Electronic, and Electromechanical
FDR	Final Design Review
FEA	finite-element analysis
ICD	Interface Control Document
LSST	Large Synoptic Survey Telescope
MAWP	Maximum Allowable Working Pressure
MCS	Mount Coordinate System
MOP	Maximum Operating Pressure
MRR	Manufacturing Readiness Review
MTTR	Mean Time to Repair
MUF	Modeling Uncertainty Factor
	Society of Automotive Engineers
SLAC	SLAC National Accelerator Laboratory
TBD	To Be Determined
TBR	To Be Resolved
TCS	Telescope Coordinate System

4. Applicable Documents

[1] LCA-138, "LSST Camera Performance and Safety Assurance Plan"

[2] LCA-69, "LSST Camera Environmental Specification Supporting Analyses"

[3] "ASME Boiler and Pressure Vessel Code 2010, Section VIII Division 2: Alternative Rules for Construction of Pressure Vessels."

[4] SLAC-I-720-0A29Z-001-R023, "SLAC Environment, Safety, and Health Manual, Chapter 14: Pressure, Vacuum, and Cryogenic Systems;" September 9, 2008.

[5] BNL-81715-2008-IR, "Vacuum System Consensus Guideline for Department of Energy Accelerator Laboratories;" September 9, 2008

[6] NASA-STD-5001, "Structural Design and Test Factors of Safety for Spaceflight Hardware," June 21, 1996.

[7] DOE-STD-1090-2007, "DOE Standard: Hoisting and Rigging," 2007.

[8] ASME B30.20-2006, "Below-the-Hook Lifting Devices," American Society of Mechanical Engineers, January 2007.

[9] ASME BTH-1-2005, "Design of Below-the-Hook Lifting Devices," American Society of Mechanical Engineers, March 2006.

[10] ASME B31.5-2006, "Refrigeration Piping and Heat Transfer Components," American Society of Mechanical Engineers, July 2007.

[11] LCA-10008, "Camera Entities."

[12] ASME Y14.1, "Drawing Sheet Size and Format"

[13] ASME Y14.5M, "Dimensioning and Tolerancing"

[14] ASME Y14.5.1M, "Mathematical Definition of Dimensioning and Tolerancing Principles"

[15] ASME Y14.6, "Screw Thread Representation"

[16] ASME Y14.6M, "Screw Thread Representation (Metric Supplement)"

[17] ANSI/AWS-A2.4, "Standard Welding Symbols"

[18] ANSI B46.1, "Surface Finish"

[19] LCA-TBD, "Standardized Manufacturing Procedures and Drawing Notes"

[20] MIL-HDBK-5, "Metallic Materials and Elements for Aerospace Vehicle Structures"

[21] LCA-15, "LSST Camera Hazard List"

[22] LCA-10031, "Camera Mechanical Standards: Factors of Safety"

5. Purpose and Scope

This document defines standards to ensure the development of a unified, coherent, self-consistent, and standardized set of analyses, drawings, procedures, and manuals. This is one means by which the quality of the delivered camera is assured, through the uniform processes described herein. As such, it forms one part of the quality assurance plans described in Ref. [1] the "Performance and Safety Assurance Plan." The use of these standards also allows for uniform and full descriptions of the delivered Camera hardware and all equipment needed to integrate, test, and service it.

The standards and provisions in this document cover all parts, components, and assemblies of Camera deliverable items and associated support equipment. Note that this includes mechanical aspects of electrical, electronic, and electromechanical (EEE) parts and assemblies.

6. Analysis Methodology

6.1. Load Case Definitions

Camera and subsystem environments and loadings are delineated in their corresponding specification documents. These define ranges for operating, working limits, and survival ranges for temperatures, humidities, pressures, and loads and accelerations. The derivation of these environmental values is described in Ref [2], LCA-69, the "LSST Camera Environmental Specification Supporting Analyses." While Ref. [2] describes environments for camera hardware, it does not explicitly define load cases to be used in the design, analysis, and test of subsystem components and assemblies. This can only be done by the subsystem design engineer.

Load cases for the design, analysis, and testing of subsystem components needs to be done as part of the design maturation process. While environments and loads are delineated in the appropriate specification, the design engineer needs to explicitly define component load cases based on the designed use of the component. This should result in a table of load cases to be used in the analysis and test planning for every component.

Load case definitions need to incorporate the full range of combined loads and environments. In particular, this may include combined seismic and pressure loading, over the full operating temperature range. These combinations depend on the actual operating conditions of the component, so it is important to clarify how and why the loads and environments combine or do not combine. Also, component loads may result from assembly-level analysis which help to define the worst-case loading for the component and establish bounding loads for defining the component load cases. Finally, component load cases may also be derived from expected loading and acceleration conditions during subsystem transport, handling, assembly, and test. These need to be internally derived as part of the load case definition process.

An additional factor to include in the definition of load cases for component design is whether and how large a Modeling Uncertainty Factor (MUF) should be included. Depending on the precision of the analysis that went into generating the load cases, an additional multiplier may be needed to cover uncertainties in the derivation process or in the predictability of the loading. The MUF can also be used to factor in conditions such as low-level dynamic loading, starting/stopping transients, or other difficult-to-model values. These should be explicitly discussed in the derivation of the MUF's for a component.

Finally, load case definitions should include reference to the appropriate factors of safety to be used in the analysis and testing. Factors of safety are described in Section 6.4, below. This defines the factors of safety to use for different materials, applications and load types, so the load case definitions provide the point where the appropriate factor of safety is chosen, based on the component material and load condition.

6.2. Material Standards in Component Analysis

Raw materials, purchased parts, and joining methods must be specified using industry or other standards. Furthermore, these standards need to be used in both the design and analysis of the component, as well as in its procurement, fabrication, and testing. This section defines how such standards are used in component analysis, while Section 11, below, provides a description of the preferred standards to use and how they should be used in component manufacturing and testing.

6.2.1. Raw Materials

For raw materials, materials standards need to define the chemical composition, manufacturing method, test methods, and acceptable range of properties of the resulting material. Such standards should clearly define any material temper, heat-treatment, or curing needed to achieve a given range of properties. Here, the important issue is that the material properties being used in the design and analysis of the component on paper are actually the properties that the raw material will have after completion of manufacturing. While any standard can be used, often SAE, AMS, and MIL-STD standards provide more explicit identification of material properties for a given manufacturing method, so they are preferred.

6.2.2. Purchased Parts

Parts such as bolts, pins, nuts, and washers should also be specified explicitly. This must include allowable working loads or stresses for the part, as well as standards to be used in fabricating the part. The analysis of all such parts needs to clearly define the specification(s) to be used in procuring the part, and this should also be clearly called out on the drawing and procurement documents. See Section 10.2.3, below for more information on how to call out parts standards on an assembly drawing. Once again, the goal here is to remove all ambiguity about the pedigree of the procured hardware, and to assure that the safe working loads of the actual hardware matches the allowable loads used in the design and analysis of that hardware.

6.2.3. Joining Methods

Methods for joining parts include welding, brazing, soldering, bonding, and crimping, among others. Whenever possible, such joining methods should invoke industry standards for the process, which may include allowable working stresses or loads for the as-joined assembly. If standards are not used, or do not fully define the joining process, test and inspection processes, and allowable working loads of the completed joint, then a custom process may be needed. This process should include, among other things, allowable working loads of the completed joint that can then be used in engineering analysis. The process specification should also factor in the test method to ensure that the allowables are actually being met, to assure that the as-designed joint will behave as analyzed if it is assembled per the specified process.

One source to help in establishing allowable stresses for an item or joint is Ref [20], MIL-HDBK-5. Here, “B-basis” allowables should be used for materials or joints with redundant load paths, while “A-basis” should be used for single failure point items or joints. The MIL-HDBK-5 definition of these bases are:

B-basis: at least 90% of the test population values is expected to equal or exceed the statistically calculated mechanical property value, with a confidence of 95%.

A-basis: The lower value of either a statistically calculated number, or the specification minimum (S-basis). The statistically calculated number indicates that at least 99% of the population is expected to equal or exceed the statistically calculated mechanical property with a confidence of 95%.

Other options exist for establishing allowable stresses for unique joints where testing is required, but they should be evaluated for their appropriateness and referred to in subsequent analysis work.

6.3. Analysis Requirements

6.3.1. Analysis of Pressurized Vessels and Components

6.3.1.1. Applicability

Pressure vessels with a maximum allowable working pressure (MAWP) under 15 psi are not required to be designed, fabricated, or tested to Ref. [3], the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel (BPV) Code, Section VIII. For custom pressure vessels over 15 psi, the BPV must be used. For pressurized components and purchased systems, the BPV or other industrial code may be used. The focus of specifying the use of standards is in collecting material information and certifications, and test reports of pressure tests. This is especially the case for custom procured components.

6.3.1.2. Pressure Levels

Ref. [2] defines three pressure levels for the pressure and vacuum vessels in the Camera:

Maximum Operating Pressure (MOP): the maximum pressure at which the component must function normally and meet all performance requirements. Since the camera has a pressure vessel inside another pressure vessel, the MOP needs to bound the worst-case combination of operating pressures for both vessels, which may result in a maximum over-pressure as well as a maximum vacuum- or under-pressure.

Maximum Allowable Working Pressure (MAWP): the peak pressure the component will ever need to endure during a non-standard situation or failure. The component must be able to survive the MAWP with no residual damage, but is not required to meet its performance requirements

Test pressure: the pressure to which the component is proof-tested. It must survive the Test pressure, but with reduced margins allowed, as described in Section 6.4 and following.

The relationship between these pressure levels is defined in Ref. [3] and specified in Ref. [4], SLAC-I-720-0A29Z-001-R023, "SLAC Environment, Safety, and Health Manual, Chapter 14: Pressure, Vacuum, and Cryogenic Systems." These are:

MAWP = MOP + 15%

Test = MAWP + 10% for pneumatic testing of vessels under internal pressure

Test = MAWP for test of vacuum vessels (no overpressure necessary)

6.3.1.3. Design and Analysis Details

Wherever possible, low-pressure vessels and vacuum vessels should use the BPV as a guideline for design and analysis. For hand analysis, Section VIII Division 1 of the code should be used. When finite-element analysis (FEA) is used, Section VIII Division 2 of the code is applicable. Furthermore, Ref. [5], BNL-81715-2008-IR, "Vacuum System Consensus Guideline for Department of Energy Accelerator Laboratories," may also be used as a guide for design and analysis of vacuum components

Pressure and vacuum vessels need pressure-relieving devices like burst disks. For vacuum vessels, these can be installed on the temporary vent line, but it is preferred to design them into the main chamber.

Burst disk sizing needs to consider both burst pressure and flow capacity to account for a worst-case over-pressure scenario.

For every pressure vessel or pressurized system, the following information needs to be developed as part of the design and analysis package:

Design and analysis package: load cases, design and analysis of welded/brazed and bolted joints, analysis of burst disks or relief valves,

Materials and parts used: define specifications for procuring and testing; expected certifications; this applies to raw materials as well as bolts and weld filler metals

Fabrication method: welding, brazing, and heat treating plans; in-process and final inspection methods

Testing: proof test set-ups and test plans

In-use inspection plan: plan for periodic inspection, including pass/fail criteria

This information must be fully complete by the Manufacturing Readiness Review (MRR), but should be presented at every major component review leading up to the MRR.

6.3.2. Seismic Analysis

6.3.2.1. Applicability

During the integration, commissioning, and operation of the LSST Camera, it will be operated at SLAC and at the LSST summit facility in Chile, both of which are seismically active regions. Thus, the Camera and all subsystem components must be designed to meet the seismic load cases called out in subsystem specifications and derived in Ref. [2]. These seismic loads apply to three classes of hardware:

The Camera and subsystem components at all stages of integration and test and in any standard orientation of the Camera

Support hardware, handling, and transport fixturing that is used at SLAC or on the summit

Subsystem components and sub-assemblies that are assembled and tested at SLAC

The only time when components and assemblies do NOT need to be designed to withstand seismic loads is during limited-duration configurations during operation and maintenance. Ref. [2] details the rationale for this, which is based on the incremental additional risk exposure to a seismic event during these transient configurations.

In short, Ref. [2] defines the following EXEMPTIONS from the requirement to design and analyze for seismic stability:

During operations and maintenance, any configuration or state lasting less than 1 hour—this includes filter exchanges and filter swap-outs

During on-telescope trouble-shooting and repair, any configuration or state lasting less than 6 hours

During integration and test (I&T), any configuration or state lasting less than 2 hours

6.3.2.2. Design and Analysis Details

Table 1 defines the factors of safety that should be used for all load cases and materials, including seismic loads. Note that even though the factor of safety that is used for seismic loads is less, the larger loads associated with seismic accelerations often defines the worst-case load condition, with the lowest margin, for a component.

Note that the static-equivalent accelerations already include uncertainty factors to ensure that peak accelerations for the return period of the design earthquake are adequately bounded. Thus, any MUF used in the analysis should not include further factors for ground acceleration. However, the MUF SHOULD be used to capture any uncertainty associated with the dynamics of the loading or concern about vibrations of components. All components are required to have a first-mode frequency above 24 Hz, so vibrational coupling should not be an issue, but there may still be concern about component response to lower-frequency vibrations. This is where the use of a MUF in the analysis may be appropriate.

6.3.3. <u>Critical Items and Single-Failure Point Components</u>

6.3.3.1. Applicability

Components and joints that constitute a single-failure point require special attention, since the impact of a failure could be significant. As part of the analysis, all such points in a design need to be identified, including those points where there are multiple items—such as a bolt pattern—but the failure of one cannot be absorbed by the other items in the set.

Single-failure points should be identified as critical items in Ref. [21], the "Camera Hazard List," unless the impact of the failure is considered inconsequential. Listing such points assures that the steps in assuring they are implemented in a suitable way are covered and the final hardware will perform safely.

6.3.3.2. Design and Analysis Details

Components that have been identified as critical items require particular attention during the design process, through manufacturing, and on into final test and operation and maintenance. This attention may also be needed for other items whose failure would impart significant risk of loss of uptime or system damage. Such critical items need to be designed to address the criticality of the component regarding meeting up-time requirements and mitigation of hazards. A graded approach should be used both in the design development and downstream planning processes, depending on the criticality of the component. This planning process will incorporate the following as part of the planning package that is reviewed at Final Design Review (FDR) and the MRR.

Design and analysis package

Ensure that the design minimizes the scope and magnitude of potential failures to reduce the overall effect of a failure. The design should also focus on reducing the risk of failure. Special attention should be given in the design and analysis of welded, brazed, bonded, and bolted joints to ensure that joint behavior is understood for the full range of assembly workmanship conditions.

For parts with a higher likelihood of failure, design work should also put an emphasis on ease of maintainability. This will be factored into the development of the preliminary design to assure that servicing and replacement of components is thought out.

Materials and Parts

Analysis work should use clearly understood materials and properties to assess margins. Part of the clear definition of materials is the selection of specifications for procuring and testing and testing them. This is a critical aspect of the assurance process, since it provides one of the sole continuous threads from engineering analysis through part fabrication and test. Specifying materials also includes defining expected certifications and testing, if any. This applies both to raw materials as well as bolts and small hardware, and joining agents such as weld filler metals, braze alloys, and bond adhesives and surface cleaners.

Fabrication Methods

Critical item assurance plans also include defining processes for manufacturing and fabricating components. This includes defining assembly process steps for welding, brazing, and bonding, as well as heat treating and surface finishing procedures. In-process and final inspection methods are also included in the definition of manufacturing processes, since they help to assure that the final product meets the expectations of the original analysis.

Testing

The final step in defining processes for critical components is to select or develop the tests needed to verify the end product. This may include early qualification test set-ups to demonstrate that the design meets its requirements or reliability goals. Test definition should always include workmanship and inspection testing for parts and assemblies as well as verification testing for larger sub-assemblies. All such tests serve to demonstrate that the design and manufacturing processes for critical items is well-controlled. This provides a key step in the process of assuring that parts and sub-assemblies function as designed.

Prototype Test

Some critical items and components may require prototyping to qualify their performance, compare against analysis, or establish empirical limits for allowable uses. This is particularly important where stresses, deflections, thermal cycling, or cyclic lifetime are difficult to assess analytically or where understanding performance or functional behavior is essential to ensuring that the design will meet reliability requirements.

Develop Maintenance and Recovery Plans

The design of critical items should also accommodate plans and processes for maintenance and repair. Such plans should factor in the modularity of the unit, how it may be serviced in situ, and how/whether a spare can be installed and re-tested with minimal impact on uptime. This can be summarized in an estimate of Mean Time to Repair (MTTR)

Plans for maintenance should also include in-use inspection plans. This includes clarifying how a part can be inspected or monitored while in service to look for incipient failures. Plans should also factor in processes for periodic inspection, including pass/fail criteria

Write Operations and Maintenance Documentation

The final step of the development process is scoping and detailing procedures for operating, servicing, maintaining, and testing components and sub-assemblies. There are three goals to the development of this documentation:

Incorporating lessons-learned: recording lessons from prototype and production unit fabrication, assembly, and testing, so downstream maintenance procedures benefit from the experience of the earlier work.

Recording procedural steps: laying out the details of operations, servicing, and maintenance to reduce the impact on the loss of "institutional memory" as people move to other projects

Preserving design intent: making sure that the original design intent is reflected in downstream operations. This reduces the risk of degraded performance and increasing mishap risks down the line as less and less of the initial design intent is remembered and the rationale for certain procedures may not be otherwise clear.

6.4. Factors of Safety and Allowable Stresses

Factors of safety (a.k.a.: safety factors) vary for different types of materials, different load configuration, the criticality of the application, and the load conditions. Ref [22], LCA-10031, "Camera Mechanical Standards: Factors of Safety" lists the multipliers to be used in determining the correct factor of safety for a given combination of these variables. This is copied for reference in Table 1. Once the appropriate minimum factor of safety is established, it is used in calculating margins for camera components. There are four aspects of a component that enter into the determination of an appropriate factor of safety. These are discussed below.

Material: For standard linear static load application and stress analysis, larger factors of safety are used for more brittle materials or materials with an inherently larger spread of material properties, such as composites. For components that are difficult to test, the factor of safety is increased to account for uncertainty in the actual load condition.

Configuration: Two other load configurations are typically analyzed, other than standard linear static loading. These are buckling and gapping/slipping analysis of bolted joints. Each involve analysis of a critical loading threshold, beyond which the component will begin to fail, so each requires their own factor of safety assessment. Note that this analysis is in addition to the material stress analysis, so for a given component there are two sets of factor of safety. See the following section for additional detail on bolted joint analysis.

Use/Application: Factors of safety also vary depending on the criticality of the application. Criticality is defined regarding both the potential for overloading and the impact of a structural failure on camera system safety. Higher factors of safety are incorporated in designs involving pressurized components and support and lift fixtures, where the potential for overload is moderately high and the impact of a failure could be far-reaching. They also are important for parts on a primary structural load path or those that are single point failure items, since a failure would have direct bearing on the ability of a subsystem component to function normally and safely.

Load Case: The final parameter involved in establishing factors of safety are the load cases a component will experience. This parameter is used as an indicator of the conservatism of the loading. For seismic load cases, in particular, the derivation of static-equivalent acceleration values is suitably conservative that large factors of safety are not needed.

Note that these *minimum* factors of safety are intended for the stress analysis and test development of statically loaded hardware only. Hardware that experiences high-amplitude or long-duty-cycle cyclic loading likely requires either dynamic or cyclic loads analysis, or larger factors of safety.

Many of these factors of safety are based on Ref. [6], the NASA standard used for the development of spaceflight hardware. Such systems must be designed with a balance between low mass on the one hand and system safety and reliability on the other. For the LSST camera, mass and reliability are also driving factors in the hardware development, although the camera also includes provision for repair or replacement. Thus, the NASA factors of safety are considered suitably conservative for use in the camera design, with little over-conservatism which would add to the camera weight, but with little gain in safety or reliability.

6.5. Analysis of Bolted Joints and Fasteners

Bolted joints are treated with a different criteria due to the complexity of mechanically-fastened joints. In particular, a factor of safety with respect to joint separation is used, rather than to yield. For all applications, the factor of safety to joint separation must be at least 2. This means that there is sufficient pre-load in the joint under *minimum* pre-load conditions that the joint will not start to separate until the applied load is doubled.

Regarding the fastener, when the joint is pre-loaded to its *maximum* pre-load, the factor of safety of the loaded fastener must be at least 1.4 with respect to the ultimate strength of the fastener material. This factor of safety is calculated using the applied tensile stress in the fastener, and captures both uncertainties in the actual loading as well as other stresses imparted on the hardware due to torquing. If the fastener takes direct shear loads then the factor of safety is calculated using the maximum principal stress in the fastener.

Table 1: Example calculation of Factors of Safety for Analysis of Camera Components (top), with multiplier tables (below) listing multipliers used in developing them

Select Mat'l, Use, and Load Case	Yld	Ult	Test	
1-Ductile: proof test	1.25	1.40	1.20	Material/Configuration (Pick only 1)
D-Pressurized component w/ test[A	1.60	1.71	0.92	Use/Application (Pick only 1)
a-Normal operations: as-installed	1.00	1.00	1.00	Load Case/Configuration (All that apply)
Factors of Safety:	**2.00**	**2.40**	**1.10**	Use these factors for analysis and testing

Multipliers that are used for calculating factors of safety, above					**Ref**
Material/Configuration (Pick only 1)				Includes brittleness, spread of properties, qual process	
1-Ductile: proof test	1.25	1.40	1.20	Metals; tested to proof levels to qual design	[6]
2-Composites: uniform		1.50	1.20	Region w/no geometric or manufac discontinu	[6]
3-Bonds to glass		2.00	1.20	Bonds qualified by test	[6]
4-Composites: discontinuous		2.00	1.20	Region of a composite with geometric discont	[6]
5-Bonds to other materials		2.00	1.50	Bonds qualified by test	[6]
6-Ductile: qual by analysis	2.00	3.00	na	Metals; final config not tested to proof levels	
7-Brittle materials		3.00	1.20	Materials with little capacity for plastic flow	
8-Glass		5.00	2.00	Under pressure or not	[6]
9-Bolted joint		2.00	na	Joint gapping or slipping	
10-Buckling		3.00	1.25	Column or panel buckling	
11-					

Use/Application (Pick only 1)				Component criticality level	
A-Low criticality comp	1.00	1.00	1.00	Multiply-redundant item	
B-Med criticality comp	1.10	1.10	1.10	Secondary struc element, redundant item	
C-High criticality comp	1.20	1.20	1.20	Single-failure point, primary struc element	
D-Pressurized component w/ test[A]	1.60	1.71	0.92	Component forming part of pressure envelope	[4, 6, 10]
E-Lifting device w/ test	1.60	1.71	1.04	Below-the-hook lifting fixture	[7, 8, 9]
F-Fixture, transport container	1.60	1.71	1.04	Floor-mounted, transport fixtures, containers	
G-Pressurized component no test	2.00	2.14	na		[4, 6, 10]
H-					

Load Case/Configuration (All that apply)				
a-Normal operations: as-installed	1.00	1.00	1.00	Gravity + operational loads + pressure
b-Fixture operations: alt mounting	1.00	1.00	1.00	Alt gravity + operational loads + pressure
c-Operational seismic: tel-mounted	0.80	0.80		Ops seismic + operational loads + pressure
d-Survival seismic: tel-mounted		0.71		Surv seismic + operational loads + pressure
e-Base-mounted seismic	0.80	0.80		SLAC/Summit seismic + oper loads + pressure
f-Lifting/handling	1.00	1.00		Handling + any other applicable loads
g-Transportation	1.00	1.00		Transport + any other applicable loads
h-				

[A]: Applies for pneumatic testing; see references for hydraulic testing specifics

6.6. Margins of Safety

The LSST Camera structure is required to have margins of safety greater than or equal to 0.0 relative to the appropriate design factors of safety. Factors of safety are based on risk of failure and introduce conservatism into the design for safety purposes. The margins of safety are calculated thus:

$$MS_y = \frac{\sigma_y}{FS_y \cdot \sigma_{calculated}} - 1 = \frac{\left(\frac{\sigma_y}{FS_y}\right)}{\sigma_{calculated}} - 1$$

$$MS_u = \frac{\sigma_u}{FS_u \cdot \sigma_{calculated}} - 1 = \frac{\left(\frac{\sigma_u}{FS_u}\right)}{\sigma_{calculated}} - 1$$

The calculated stress, $\sigma_{\text{calculated}}$, is analyzed for each load case, and includes provision for the maximum allowable mass of the component and hardware it is supporting, along with any modeling uncertainty factor that is applied. Yield and ultimate stresses, σ_y and σ_u, respectively, are material properties that should be based on industry-standard specifications that are also used in the procurement of the material (see Section 6.2, above). Note that the $\left(\frac{\sigma_y}{FS_y}\right)$ term is often referred to as $\sigma_{\text{allowable}}$, the allowable working stress for the material and load condition. While it may be useful to think of material properties in the context of allowable stresses, it may be misleading since the same material may have different allowable stresses if the factor of safety is not the same for different load cases. Thus, the term "allowable stress" should not be over-used.

7. Coordinate Systems

The telescope and camera use three coordinate systems to describe the position of elements. These—and the Camera Coordinate System, in particular—should be used whenever possible, and especially for quoting positions and offsets across interfaces within the camera. All other coordinate systems that may be developed are *ad hoc*, and not suitable for use in Interface Control Documents (ICD's) or other documentation or data delivery.

7.1. Observatory Mount Coordinate System

The Observatory Mount Coordinate System (MCS) is fixed with respect to the ground, and is defined as follows:

+Z-axis pointed to zenith, opposite the gravity vector

+X-axis lies in a plane normal to the gravity vector, pointing north

+Y-axis follows the right-hand rule, pointing west

Origin (XYZ = 0, 0, 0) is defined as the intersection of the +Z-axis and the plane defined by the top surface of the azimuth ring, on which the telescope rotates

Azimuth angle (angles around the MCS Z-axis) is based on standard compass angles and does not obey the right-hand rule. 0 degrees azimuth angle is north (along the +X-axis). Azimuth angle increases towards the –Y-axis (east), as do compass bearings.

Elevation angle (angles around the MCS X-axis) and angles around the MCS Y-axis both follow the right-hand rule, with angles increasing from the +Y-axis towards the +Z-axis, and +Z-axis towards the +X-axis.

7.2. Telescope Coordinate System

The telescope parked position is defined as when the M1 mirror is pointing to the zenith, and the centerline of M1 is parallel to the gravity vector and normal to the horizontal plane. The Telescope Coordinate System (TCS) moves with the telescope. In the telescope parked position, the TCS is parallel to the MCS, and is defined as follows:

+Z-axis pointed to zenith

+X-axis lies in a plane normal to the gravity vector, pointing north. This is parallel to the altitude rotation axis of the telescope

+Y-axis lies in a plane normal to the gravity vector, pointing west. The +Y-axis tips upward as the telescope altitude changes and the +Z-axis moves off of zenith, which corresponds to a positive rotation angle around the X-axis.

The origin of the TCS is the theoretical vertex of M1.

7.3. Camera Coordinate System

The parked position of the Camera is with the camera looking down, along the gravity vector.

The Camera Coordinate System (CCS), shown in Figure 1 and Figure 2, is parallel to the TCS, when both the camera and telescope are in their parked positions. The CCS origin is located on the TCS Z-axis at its intersection with the nominal first-surface of the L1 lens. The CCS is fixed to the camera, so it moves and rotates with the camera body. It is defined as-follows, when the camera is in the parked position:

+Z-axis pointed to zenith—this is a vector that points from L1 towards the detector plane and through the camera.

+X-axis lies in a plane normal to the gravity vector, pointing north. This is parallel to the altitude rotation axis of the telescope. As the telescope changes zenith angle, the X-axis remains horizontal.

+Y-axis lies in a plane normal to the gravity vector, pointing west. The +Y-axis tips upward as the telescope zenith angle changes and the +Z-axis moves off of zenith, which corresponds to a positive rotation angle around the X-axis.

The origin of the CCS is at the intersection of the Z-axis and the nominal first-surface of the L1 lens.

Because the CCS origin is on the first surface of L1, almost all of the camera is in the +Z half-space. The camera rotates up to +/- 90 degrees around its Z-axis, centered on its parked position. Thus, the CCS +Y-axis rotates up to +/- 90 degrees, and is aligned parallel to the TCS +X-axis or –X-axis at the extremes of rotation.

When the camera is in its servicing orientation, the +Z-axis is pointed toward the horizon, and the +Y-axis is pointed toward zenith.

7.4. Camera Position and Orientation Naming Conventions

The following conventions should be used in referencing a location, orientation, or position in the camera. Given that the Camera moves and during both I&T and operations can be oriented in a range of attitudes with respect to gravity, these conventions are intended to reduce confusion or miscommunication regardless of camera orientation.

X, Y, Z: translational coordinates in the X-, Y-, and Z-axes of a coordinate system, respectively. If the coordinate system is not referenced, then the assumed coordinate system is the CCS.

RX, RY, RZ: rotations around the X-, Y-, and Z-axes of a coordinate system, respectively, with the CCS being assumed unless explicitly stated otherwise.

Altitude: an angle of rotation around the TCS X-axis, with 0 degrees being zenith-pointed and 90 degrees horizon-pointed.

Azimuth: an angle of rotation around the MCS Z-axis, with 0 degrees azimuth pointing north and increasing clockwise as bearings on a compass (note that this does not agree with the right-hand-rule of coordinate system angles).

Front: the side of the camera or component closest to the first-surface of the L1 lens and incoming light. This is the –Z end of the camera.

Back: the side of the camera or component furthest from the first-surface of the L1 lens and incoming light. This is the +Z end of the camera.

Forward: towards or closer to the front of the camera. In the –Z direction.

Backward: away from or further from the front of the camera. In the +Z direction.

Horizontal: any plane normal to the gravity vector. Also any plane parallel to the MCS XY-plane and the camera XY-plane in its parked position is horizontal.

Vertical: any line parallel to the gravity vector. Also, any line parallel to the MCS Z-axis and the camera Z-axis in its parked position.

To avoid confusion, the terms "Up," "Down," "Left," "Right," "Horizontal," and "Vertical" should not be used, since they refer to orientations relative to gravity and the observer, both of which can change.

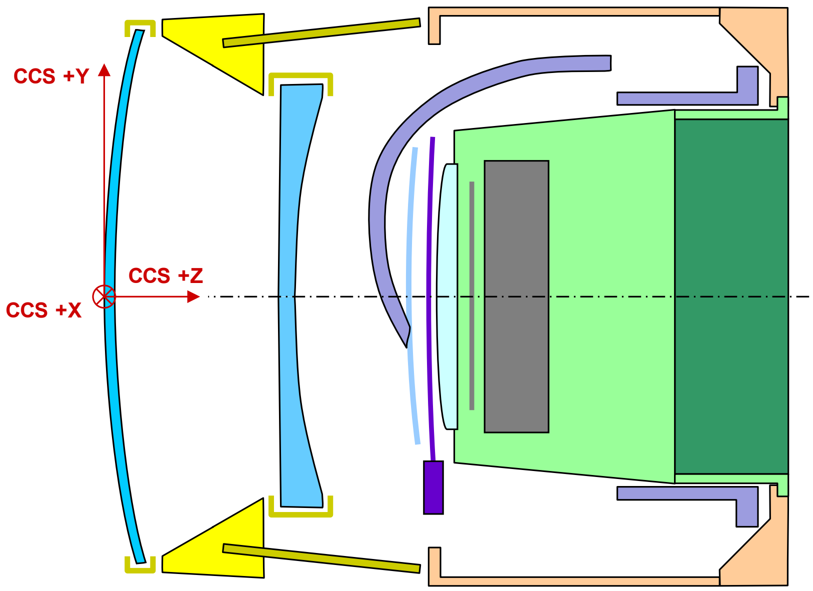

Figure 1: Standard Camera side view showing Camera Coordinate System axes

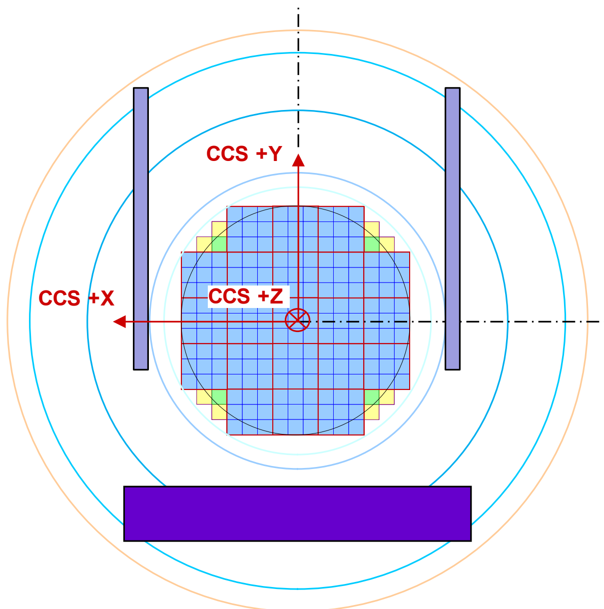

Figure 2: Camera end view looking back in the +Z-direction, with Camera Coordinate System axes

8. Numbering Systems and Configuration Descriptions

The Camera includes components and assemblies that have varying orientations and positions—such as the shutter and filter exchange system, or where there are multiple copies of parts—such as raft towers, shutter blades, or raft electronics boards. To avoid confusion or mis-identification of parts, component locations and/or position should be explicitly referred to, using the configuration and numbering conventions in the sub-sections below. In particular, these conventions should be used for all interface references and for defining command and communication interfaces, including user interfaces. These conventions include both location numbering systems, as well as standardized names for locations, positions, and actions.

Note that formal names for major sub-assemblies—termed entities—are defined in Ref. [11], LCA-10008, "Camera Entities."

8.1. Cryostat Contents

Cryostat numbering is largely centered around the repetitive arrangement of raft towers. Figure 3, Figure 4, Figure 5, and Figure 6 show the numbering conventions for repetitive elements associated with the raft towers and grid layout. This starts with the numbering of the grid bays, as well as definition of the relative orientation of raft towers and flexures in the Cryostat. The orientations shown in the figures are:

Grid bays: oriented orthogonal to X- and Y-axes with matrix numbering with first digit signifying X-position and second digit indentifying Y-position, starting at most negative XY-position; ordinal numbering starts with 00

Grid flexures: 3 arrayed with a single flexure on the –Y side of the Grid; cardinal counting starts at the +X-axis with 1, increasing in the +RZZ direction

CCD's on science raft: matrix numbering with first digit signifying X-position and second digit indentifying Y-position, starting at most negative XY-position; ordinal numbering starts with 00

Science raft/grid interface: 3-point kinematic couplings are arrayed with a single mount on the +X side of the raft and two mounts on the –X side; cardinal counting starts at the +X-axis with 1, increasing in the +RZZ direction

Raft electronics boards on science RTM: boards aligned parallel to the Y-axis; ordinal counting starts with 0 from the most extreme –X-position, so a board position corresponds with the X-position of the CCD's it controls

Science CCD orientation: all CCD's on all science rafts are oriented with serial registers and bond pads aligned on the +X and –X sides of the CCD

CCD segment numbering: CCD's (science, wavefront, and guide) are divided into segments of pixels, each read-out with one serial register and amplifier; segment numbering is matrix numbered with first digit signifying X-location and second digit identifying Y-location, starting at most negative XY-position with 00

Science CCD mount posts: 3-point mount posts are arrayed with a two mounts on the +X side of the raft and one mount on the –X/-Y corner; cardinal counting starts at the +X-axis with 1, increasing in the +RZZ direction

CCD's on corner raft: cardinal numbering starts with 1

Corner raft/grid interface: 3-point kinematic couplings are arrayed with a single mount at each corner of the raft; cardinal counting starts at the square corner near the WFS with 1, increasing in the +RZZ direction

Raft electronic boards on corner RTM: boards aligned on the diagonal with board normals pointing toward the Z-axis; cardinal counting starts at 1 with the board closest to the Z-axis

Corner CCD orientation: for the corner raft in grid bay 44, all CCD's are oriented with serial registers and bond pads aligned on the +X and –X sides of the CCD; for all other rafts, CCD's are oriented the same, relative to the raft, but the raft position in the bay is rotated; see Figure 6

Corner CCD mount posts: for the corner raft in grid bay 44, 3-point mount posts are arrayed with a two mounts on the +X side of the raft and one mount on the –X/-Y corner; cardinal counting starts at the +X-axis with 1, increasing in the +RZZ direction; for all other rafts, CCD mount posts are identical relative to the raft, but the raft position in the bay is rotated

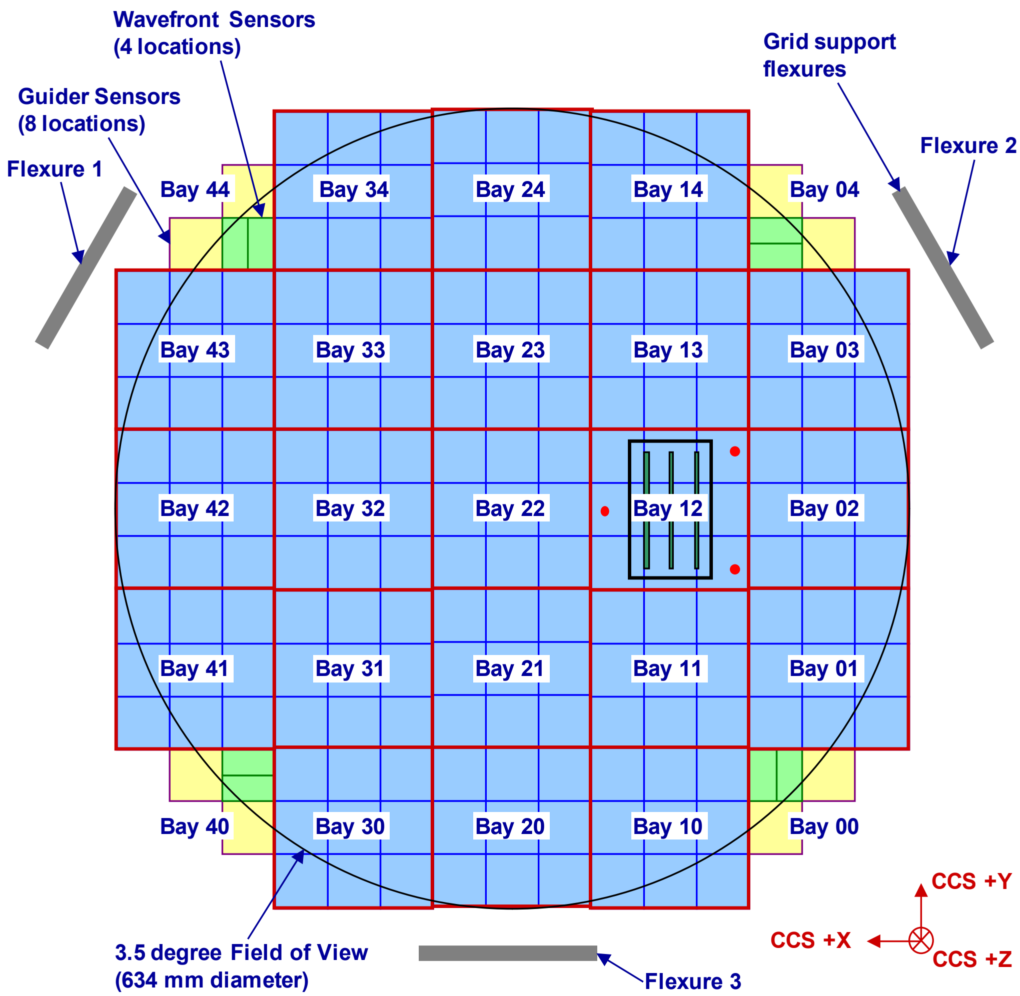

Figure 3: Cryostat bay numbering system and orientation of key components

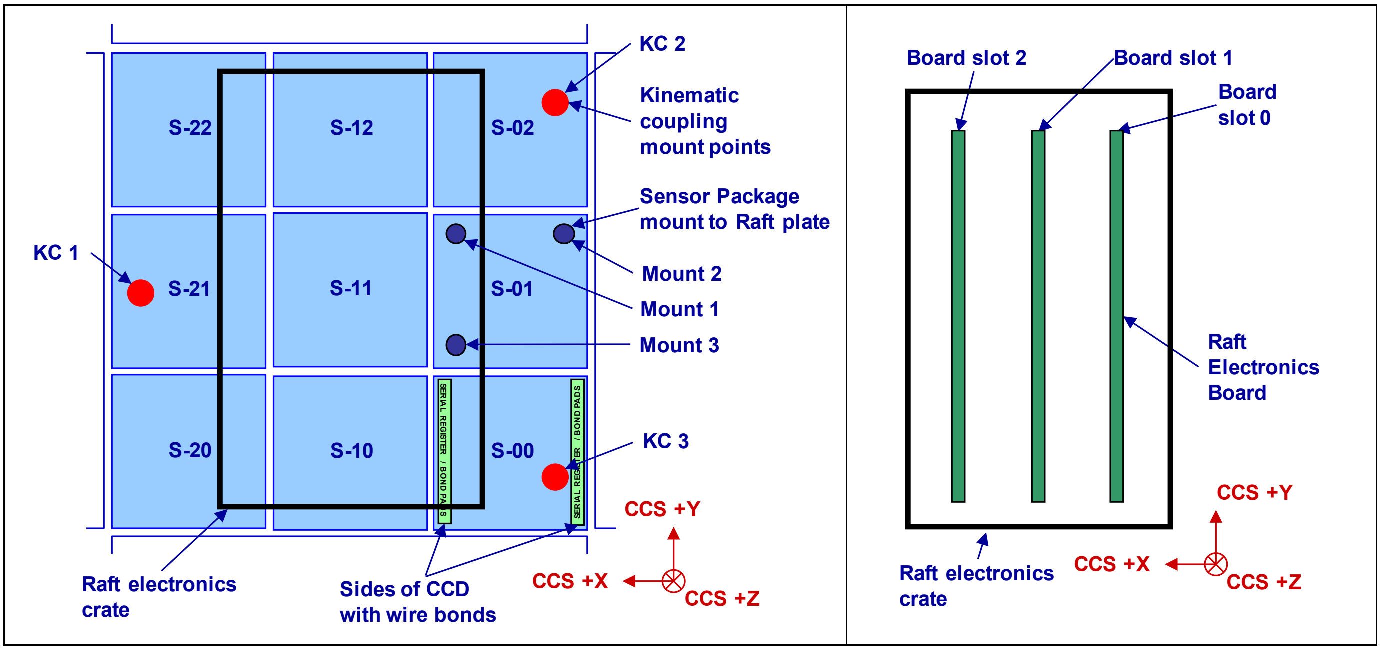

Figure 4: Orientation and number of science raft-centric components in the Cryostat

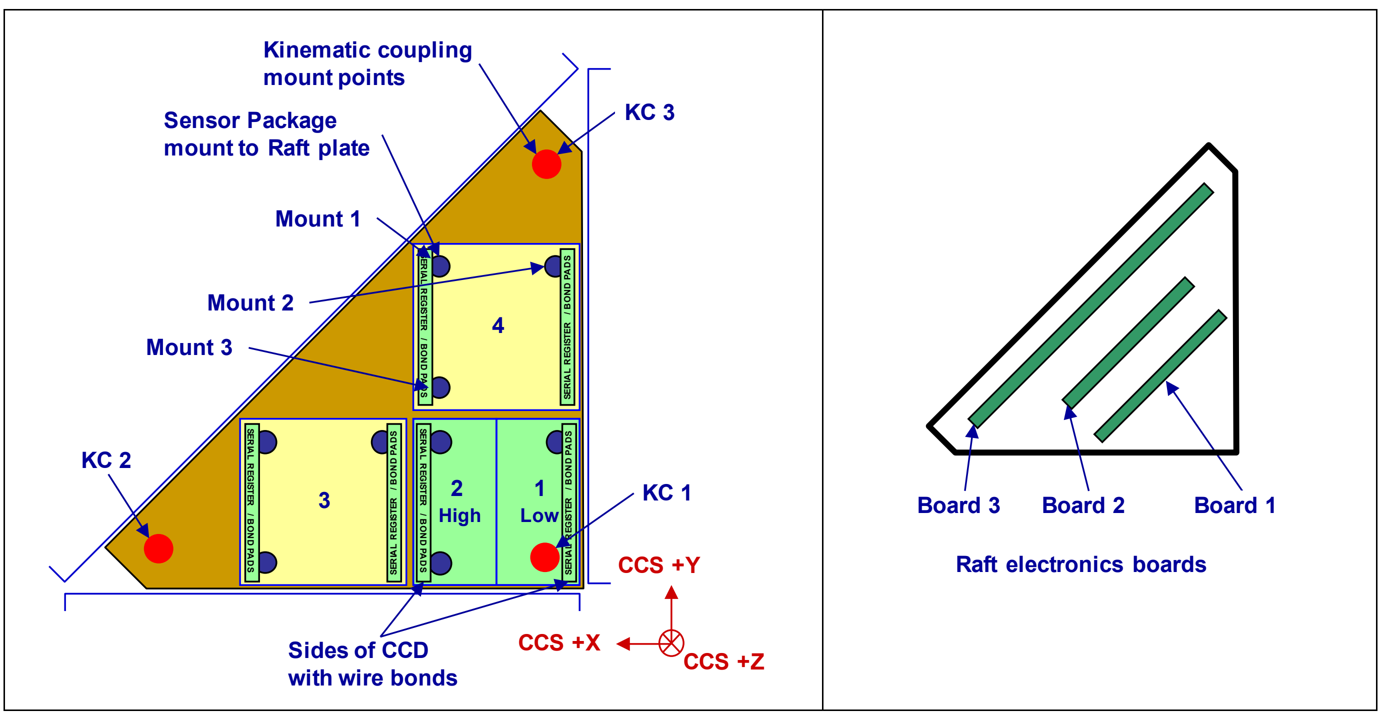

Figure 5: Orientation and number of corner raft-centric components in the Cryostat

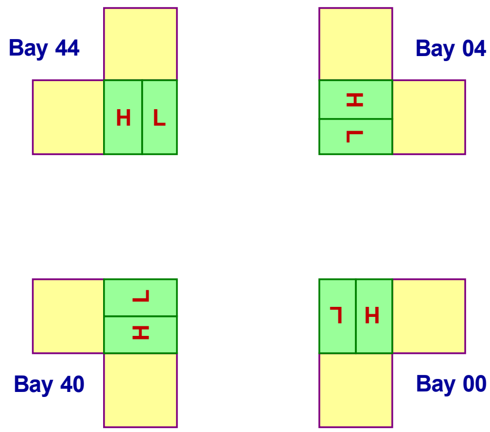

Figure 6: Rotation of corner rafts on the Grid

8.2. Filters and Exchange System

Conventions for orientations and positions of filter exchange system components are shown in Figure 7. This includes conventions for the position names of the elements of the system that move and have more than one standard position. This also lists common verbs and adverbs to be used in describing the actions taken by exchange system mechanisms. These conventions are used to avoid confusion as to the exact nature of the action.

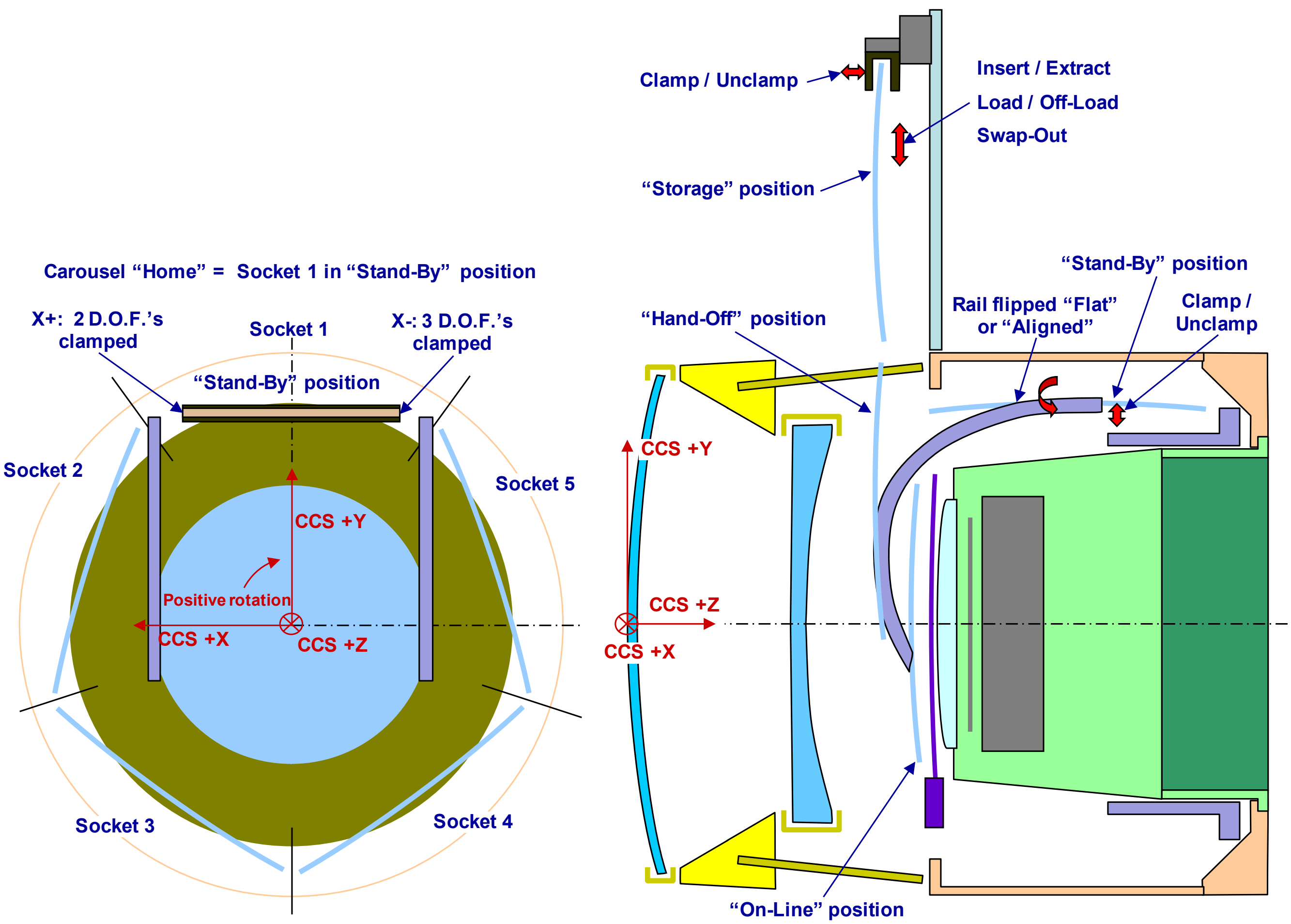

Figure 7: Orientation and position naming for the exchange system

8.3. Shutter

The shutter is comprised of two separate stacks of blades, each of which is independently controlled. Names, numbering and configuration definitions for the shutter are shown in Figure 8. When blades are stacked atop each other, this is termed the "parked" or "home" position for the stack. They are "deployed" when they cover the field of view. Note that the terms "opened" and "closed" are not used to describe the position of the blades. This is to avoid confusion between the slight difference in position between the "parked" position and the blade location when the leading-edge starts to occlude the first pixel on the detector plane. Technically, the latter is the position at which the shutter is actually "opened."

The verbs "open" and "close" can be used to describe the action of the blade stacks, as long as it refers to which stack is moving.

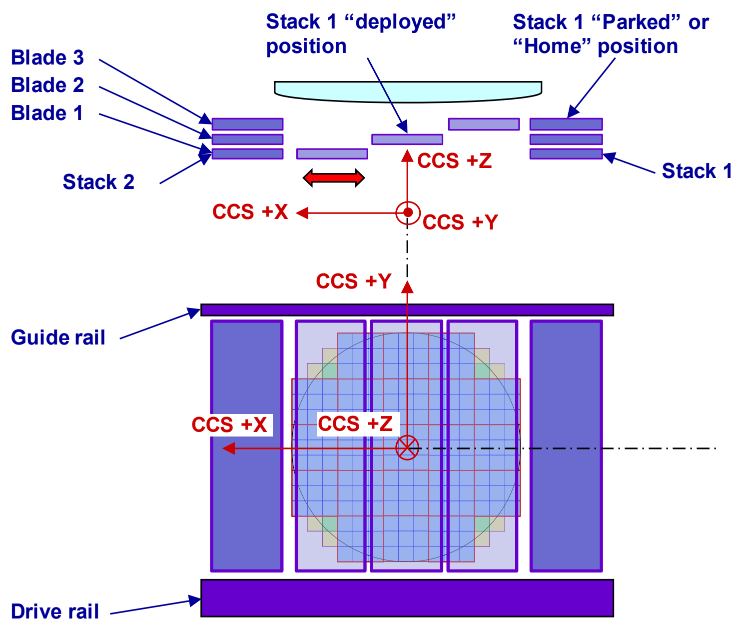

Figure 8: Position and component naming and numbering for the shutter

8.4. Lenses and Optical Path

Optical elements and their constituent parts, along with their naming and numbering conventions, are shown in Figure 9. Lens numbers and surfaces follow standard practice for optical system design, while the strut numbering increases clockwise from the +X-axis. The A-struts support the L1-L2 assembly off of the camera outer housing, while the B-struts hold the L2 lens cell off of the L1-L2 support ring. Struts are labeled and numbered to clarify the position of serialized strut assemblies and clarify adjustment instructions during survey and alignment processes.

Locations for sphere-mounted retroreflectors around the perimeter of the L1 lens are numbered starting near the +X-axis and increasing clockwise. The 13th location is the only non-uniform location.

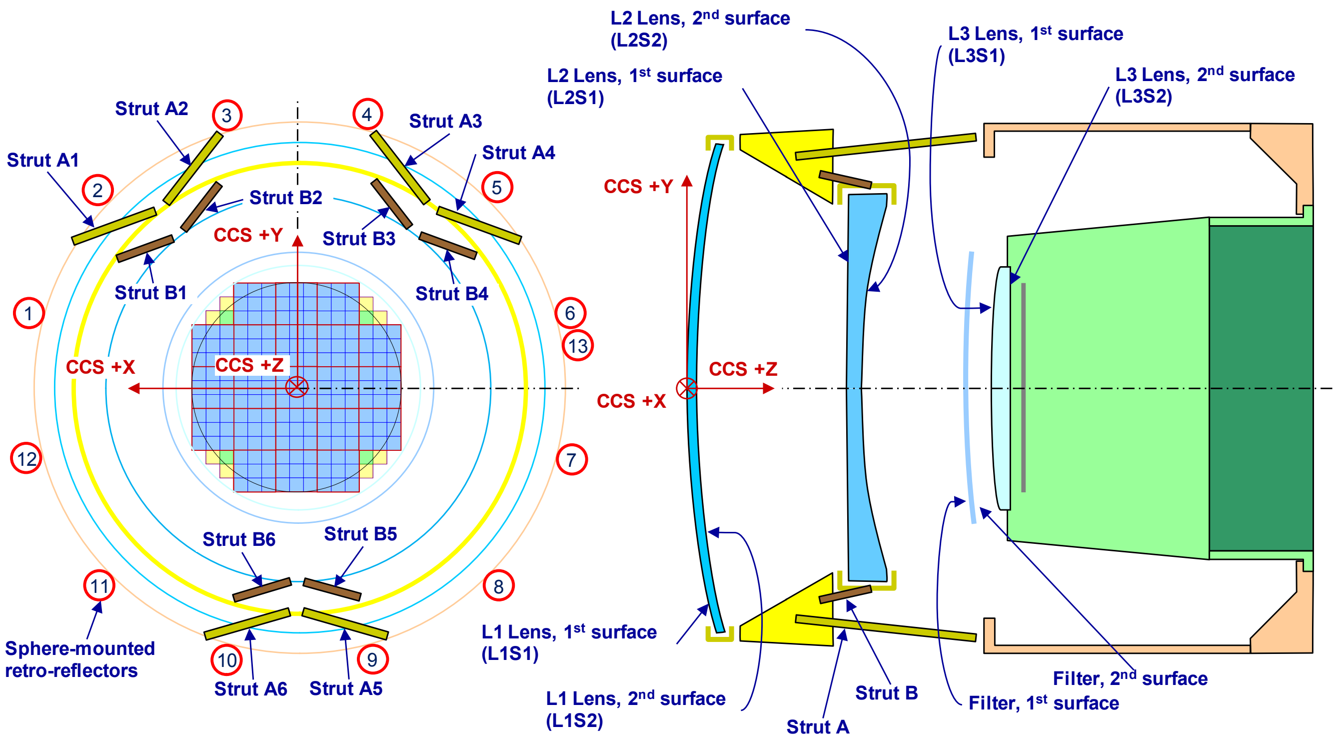

Figure 9: Optical element position and component naming and numbering

9. Policy on Use of Metric and English Systems

9.1. Design and Parts Selection

The metric system should be used wherever possible, unless its use causes significant increase in cost or compatibility concerns. In general, this refers to dimensions of millimeters or meters.

In particular, metric dimensions should be used as the default whenever there is a dimension that results from altering stock material in some way (machining, sheet metal bending, etc.).

Imperial units may be used for standard U.S. tube/pipe, plate material, or where the stock dimension will not be altered. Inch units are also appropriate for purchased components that are procured using inch units. Double dimensioning is appropriate to use with the Imperial dimension as primary and the metric dimension as secondary when parts or stock material meet these criteria.

Otherwise, as a rule, double dimensioning should not be used.

9.2. Analysis

Analyses should use metric units wherever possible, with a few exceptions. In general, the following units should be used:

Distance, area, volume: millimeters, meters, liters (avoid cc)

Angles: decimal degrees (use milli-radians sparingly; avoid arc-minute and arc-seconds)

Mass: kg

Force: N, kN (avoid kgf)

Pressures over atmospheric pressure: Pa, kPa, MPa

Vacuum pressures: Pa, Torr

Temperature: Celsius

Power: Watts

10. Drawing Standards

10.1. Standard Drawing Content

10.1.1. Title Block Minimum Content

Drawing title blocks must contain a minimum set of information to fully identify the drawing and specify standards used to generate and interpret the drawing. Table 2 lists the content needed in the title block of each sheet of a drawing. Note that much of this is collected as meta-data when the drawing is imported in the document management system, so the information should be consistent with standard project names.

Table 2: Title Block minimum content

Title Block Minimum Content		
Content	**Description**	**Comments/Options/Examples**
Drawing number	LCA- number	LCA-12345
Revision	Revision letter	A, B, C, …
Title Line 1	Entity name associated with drawing	"LSST Camera Exch System"
Title Line 2	Next assembly name	
Title Line 3	Drawing name	Avoid generic titles and be specific
Drawing size	Size of drawing sheet	A, B, C, D, E, R; B (11"x17") and D (34"x44") preferred
Number of sheets	Sheet number and total count	"Sheet 1 of <N>"
Institutional drawing number	Number from institution's drawing numbering system, if required	
Next assembly	LCA- number of next assembly (-ies)	Do not use an institutional number for next assembly
Engineer	Engineer of record	Same as author in document meta-data in Docushare
Drafter/Designer	Individual who generated drawing	
Approval block	Space for PDF approval stamp with LCN number and date	Min space: XX mm wide x YY mm high
Scale	Predominant scale used on the sheet; may be different for each sheet	1:1, 1:2, 1:5, 1:10, 1:20, 1:50 preferred (metric scales)
Tolerance block	List of standard tolerances used	Specify either by decimal point or distance range
Units	Units for linear and angular dimensions	mm and decimal degrees are standard
Projection method	Method of orthographic projection	Third-angle (US) or first-angle (Fr) projection
Standards used	Drawing standards	
"Do Not Scale" note	Note to warn against scaling drawing	
CAD program used	Program used to generate drawing	"Solid Edge v. 27"
Institution name	Institution where drawing is generated	
Institutional info	Institutionally-required information	DOE contract number, etc.

10.1.2. Revision Block Minimum Content

Revision blocks must contain information adequate to track revision information for all past revisions. This is done by referring to the “LCN-” number of the revision, to allow looking it up in the document management system. The content is described in Table 3. Note that this content is required for every revision of the drawing, not just the most recent one.

Table 3: Revision Block minimum content

Revision Block Minimum Content		
Content	**Description**	**Comments/Options/Examples**
Revision	List of letters for all revisions made (not just the most recent)	A, B, C, …
Revision LCN #	Number of LCN document describing the changes	"Revisions described in LCN-12345"
Engineer	Initials of engineer handling revision	
Drafter/Designer	Initial of designer handling revision	
NO approval block		This will be in title block

10.1.3. Parts List/Bill of Materials

The parts list may be on the face of the first sheet of an assembly drawing, shown stand-alone on a separate sheet of the drawing, or referenced and listed on a separate companion document, depending on institutional standards. In any case, parts lists must contain the minimum content shown in Table 4.

Note that the part number should be uniquely specified. For purchased parts, this should refer to a specification used to procure a part, such as a screw or bolt, or a manufacturer's part number. This should be adequate to re-order the part. Thus, "generic" parts call-outs such as "M6 cap screw" or a distributor number which does not uniquely identify the part should be avoided.

The part description should also uniquely define the part. For references to other drawings, this description should be identical to the third line of the drawing title for the component. For purchased hardware, the description should include the specific material and temper, hardware size (including length), and any surface treatments.

Table 4: Parts List minimum content

Parts List / Bill of Materials Minimum Content		
Content	**Description**	**Comments/Options/Examples**
Call-out	Call-out number on face of drawing	1, 2, 3, …
Part number	LCA- number, company and part number, or spec number for each part	LCA-12345, Varian AG-987-65-A; do NOT use institutional drawing number
Part Description	Description of part	Specific description of component
Quantity	Quantity of item used in the assembly	Total count for all sheets

10.1.4. Materials List

Materials list minimum content is listed in Table 5.

For component manufacturing drawings, the materials list should be used to identify all constituent materials used in the fabrication of the component. These should all be identified with call-outs on the face of the drawing. Materials should be specified uniquely by specification used to procure it. This includes referring to any options in the spec to fully define the material.

The materials list must also identify all materials used in the joining of parts that make up the component or final processing. This includes weld filler metals, braze alloys, marking inks, paints, and any other materials that ultimately form a part of the finished product. Note that drawings of welded and brazed parts are generally considered part drawings and not assembly drawings.

For assembly drawings, materials should be folded into the parts list. Here the parts list must also identify all materials used in the completion of the full assembly. This includes constituents of topical cleaners, adhesives, lubricants, tapes, marking inks, and any other materials that ultimately form a part of the finished product.

Table 5: Materials List minimum content

Materials List Minimum Content		
Content	**Description**	**Comments/Options/Examples**
Call-out	Call-out number on face of drawing	1, 2, 3, …
Material spec	Specification number for material, including any options	AMS-QQ-1234-2008, Type 4
Material type	Material and further information on form, temper, or special conditions	Alum, 6061-T651 plate; if spec identifies the form of the material (plate, cold-forged bar, …), write it down

10.1.5. Stamps

Stamps signifying the following class of parts should be clearly shown on the first sheet of every drawing. If a stamp is not shown, then the presumption is that the component or assembly is not part of the final camera.

“Cryostat Volume Part:” component is used in, or in contact with the cryostat vacuum

“Camera Volume Part:” component is used in, or in contact with the camera volume outside the cryostat

“UT Volume Part:” component resides within, or form part of the Utility Trunk

In all cases, this is used to better classify the expected handling and cleanliness requirements for the component, so for components that are in contact with more than one of these volumes, the more restrictive of the two applies.

Additional stamps/labes should be used where appropriate to raise attention to special precautions or hazards that are addressed in the notes. These are:

WARNING: ESD-Sensitive Part; Handling Precautions Req’d

WARNING: Clean Part; Handling and Environmental Controls Req’d

10.2. Drafting Conventions and Standards

10.2.1. Title Naming Conventions

The drawing title records the name by which the part or assembly being depicted is known. For part and sub-assembly drawings, the title also records the next assembly on which the item is used.

Drawing titles shall be as brief and simple as possible, shall describe the facility, system, assembly or part, and shall distinguish between similar items. The maximum length of a line in the title is 30 characters, including spaces and punctuation.

Titles must be three lines long, as follows:

First line: lists the overall project title and entity (e.g.: LSST Camera Science Raft Tower; LSST Camera Exchange System); these should comply with the entity names defined in Ref. [11].

Second line: identifies the next assembly of the part being detailed. For consistency and clarity, titles for each assembly should be set by the design team

Third line: specifies the part name; by default, this is used as the "name" of the part and title of the document in Docushare, so identical third-line names should be avoided; titles of non-part drawings, such as schematics or diagrams, should include the drawing type in the third line of the title (e.g.: "Cryostat Thermal Control System Schematic")

Multiple-sheet drawings shall have the same title, number, and revision number on each sheet. Titles of sub-assembly and part drawings shall be consistent with the titles of the next assembly drawing, except where the interchangeability of the parts between assemblies makes consistency impractical, or when such use limits application.

10.2.2. Process for Double-Numbering

Standardized drawing formats need to include provision for adding a second number.

When a drawing is produced by a University or Lab that requires the use of internal drawing numbers, the second number field is used for the institutional number and revision, while the LSST Camera "LCA-" number is shown in the number field.

When a set of drawings uses LCA- and institutional numbers, the LCA- number must be used for all references to the drawing. This is essential to ensure that drawings and parts can be identified and traced during operations and maintenance, when only the LCA- number references are available. References where LCA numbers are required include the following:

Next assembly lists: LCA- numbers are used to refer to the next assembly(ies) on which the part is used.

Part lists/Bills of Material: parts lists on assembly drawings must refer to the LCA- numbers of components that are used in the assembly. If institutional numbers are required, then they may be added outside the normal field of the parts list.

Notes: notes on the face of the drawing referring to manufacturing, assembly, or inspection details for a part need to refer to the part's LCA- number.

External procedures: more complicated component and assembly fabrication relies on stand-alone procedures; these procedures must refer to the LCA- number of the part(s) to ensure traceability between the procedure and drawings.

When a drawing depicts a part supplied by a vendor, the second number field can be used to record the vendor name and vendor's part number, as a cross reference. Note that this is only done if the part number does not show up in the parts list, as would be typical.

10.2.3. Drawing Standards

10.2.3.1. Drawing Sizes and Scales

Drawing sizes are chosen in accordance with Ref. [12], ASME Y14.1 “Drawing Sheet Size and Format.” Standard drawing sizes are B, C, D, E, and R, with preferred sizes being B (11” x 17”) or D (34” x 44”).

For drawings not originating in the U.S., European sheet sizes may be used, according to ISO TBD.

Drawings should be drawn to scale, using the preferred drawing scales listed below. Multi-sheet drawings may have a different predominant scale for each sheet. Views, details, and sections with scales different than the sheet scale must list the scale with the title of the view.

Preferred scales:

Metric drawings: 10:1, 5:1, 2:1, 1:1, 1:2, 1:5, 1:10, 1:20

Inch drawings: 8:1, 4:1, 2:1, 1:1, 1:2, 1:4, 1:8, 1:20

10.2.3.2. Call-outs, Dimensioning and Tolerancing

Dimensioning and tolerancing should conform to Ref. [13], ASME Y14.5M “Dimensioning and Tolerancing” and Ref. [14], ASME Y14.5.1M “Mathematical Definition of Dimensioning and Tolerancing Principles.”

Part features on the drawing should be represented and called out according to one of the following specifications, as appropriate:

Ref. [15]: ASME Y14.6, “Screw Thread Representation”

Ref. [16]: ASME Y14.6M, “Screw Thread Representation (Metric Supplement)”

Ref. [17]: ANSI/AWS-A2.4, “Standard Welding Symbols”

Ref. [18]: ANSI B46.1, “Surface Finish”

Alternate standards may be used when needed—such as for drawings originating in France—but the standards used should be called out on the drawing.

10.1. Drawing Notes

Drawing notes should be used to specify fabrication processes and clarify the intent of any call-out on the drawing. In particular, notes should address any of the topics listed below that are applicable. It is important to use notes to define what is exactly required or prohibited regarding steps in the manufacturing or assembly process, or the final product. Given that the drawing is essentially a manufacturing specification, the notes complete the definition of requirements defining the manufacturing processes.

Standardized notes should be used wherever possible, to ensure uniformity of direction and provide consistency among the instructions on all camera drawings. Standardized notes are available in Ref. [19] for many common processes and practices. This document also includes instructions regarding the applicability of many standard processes and in cases where they have been pre-qualified (e.g.: cleaning processes for various materials).

Drawing notes should address the following topics in this approximate order:

Material special treatment: any processing of the parent material or finished part that affects its bulk or surface behavior, such as heat treatment, ball peening, etc.

Allowed lubricant/coolants for machining: list the allowed coolants or refer to another document; this applies specifically for vacuum components

Constraints or instructions for special fabrication processes: allowed or prohibited processes (e.g.: electrostatic discharge machining, stamping)

Heat treatment: includes case-hardening, stress-relieving, annealing, tempering; refer to a process specification for this, or detail all aspects of the method including furnace atmosphere, temperature profile and ramp rate

Part marking: painting, ink marking, stamping or upset tooling (e.g.: vibro-etching); specify ink to be used in the parts/materials list, whether upset stamping is allowed, and where part should be marked; identify the location for the marking with a dashed box on the part

Serial number marking: serial numbers are not required, but may be needed for multiple-quantity parts where each will carry their own pedigree, or for critical parts.

Part marking for weight and handling: components and assemblies weighing more than 25 kg should have their weight marked in a conspicuous location adjacent to the part; any special handling provision, like stay-clear or lift points should also be marked

Inspection requirements: call out required inspection steps, including non-destructive testing, leak checking and dimensional inspection; for more involved lot, destructive, and/or coupon testing refer to a test procedure document; for partial dimensional inspection, an additional drawing sheet may be warranted, to identify dimensions to be inspected; signify whether dimensions apply before or after any surface treatments

Surface treatments: plating, passivation, coating, painting, anodizing, other surface conversion coatings; specify industry standards for surface treatments, or call out specific cleaning, priming, and painting/coating procedures including specific cleaning agents and coatings

Cleaning processes: cleaning notes should show up on the component to be cleaned and not at the next assembly. This may warrant special language in procurement documents defining whether the component is supplied “dirty” or “clean.” Cleaning methods may include dunking, washing, ultrasonic cleaning, vacuum baking, hot-air baking. For “generic” cleaning processes, refer to a separate procedure.

Assembly procedure and process call-outs: refer to separate procedure and traveler documents for assembly processes

Welding or brazing method: define specific welding or brazing process; define weld gas/furnace atmosphere as well as type and configuration of filler metals; weld rod or braze eutectic alloys should be called out in the bill of materials, as well

Special handling and storing: handling precautions (static-discharge sensitivity, clean handling), wrapping, storage environment; specify method for protecting the component for storage and shipment both to keep clean and to protect it

Reference to other documents: reference to detailed assembly or process procedure document, reference to electrical drawings

11. Manufacturing Standards

Recommended manufacturing standards are listed in Ref. [19]. These should be used when possible, but their use is not required

Custom manufacturing processes may be called out, but detailed notes or a separate specification should be used to ensure that all aspects of the process are clarified. This goes for internal manufacturing or for procurement specifications.