Large Synoptic Survey Telescope Technical Note	Document # **LCA-69-D**	Status LSST Camera APPROVED Effective Date: 31 July 2015
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	Subsystem/Office Systems Integration	
Document Title **LSST Camera Environmental Specification Supporting Analyses**		

1. Change History Log

Revision	Effective Date	Description of Change
B	24 Oct 2011	Finalized for CD-1 Review
C	8 Feb 2013	Rev C draft started to incorporate changes from review by SLAC seismic and pressure vessel subject matter experts; Incorporated updated SLAC ground acceleration value from Rev 3 of SLAC seismic spec (Ref [17]); Incorporated updated on-telescope seismic acceleration values from Cerro Pachon and telescope analysis work described in Refs [18] and [19]; Added further detail describing additional risk exposure to seismic loads during transient events Removed section on factors of safety and margin analysis; this is now covered in Ref [10], LCA-280, "Camera Mechanical Standards" Added updated facility temperatures from revised LSE-65 Facility ICD to temp section Added specific derived requirements for subsystems in all sections Added new seismic accelerations from Ref [12] Cam-Tel Mech ICD and Ref [1], Cam Req's; re-wrote derivation section and derived requirements; this was captured in, and approved by, Redline LCN-1033 Updated temperatures in Cryostat to match design changes that combine all electronics into a single board Added section on wind-loading requirements and derivation to static and transient pressures and forces Revised pressure section to include pressures from wind-loading Significantly re-formatted document so each section includes sections defining source requirements, derivation analysis and explanation, and derived requirements to be added to camera and subsystem specifications. Rev C was not released
D	31 July 2015	Rev D draft started since Rev C draft was posted for PDRs, FDRs, and CD-2 Review; Incorporated updated SLAC ground acceleration values from Rev 4 of SLAC seismic spec, 2014 (Ref [17]); Added missing document references for Ref. [18] and [19] Standardized temperature ranges to include "operating," "working," "turn-

		on," and "survival" to encompass all rooms and environmental ranges seen on the summit, during I&T, and during transportation; updated L3 temperatures to reflect interface temperatures to more clearly define boundary conditions Atmospheric pressure: WAS 71.2-78.7 kPa; IS 72.5-77.5 kPa, per revised LSE-59 Cam Reqs document; affects differential pressures, too Pressure and Differentials: removed TBR on 2 kPa camera body over-pressure; modified pressure table with new atmospheric pressures Incorporated LCN-1317 to change CCD and REB survival temperatures for Science and Corner Rafts Released with LCN-1392

2. Contents

3. Scope

This document provides supporting analysis for the derivation of camera and camera subsystem environmental parameters from higher level specifications and operations plans. It includes derivation of all environmental parameters to be used for the design of the LSST Camera and planning Camera operations. This includes all subsystem environments, as well, and should be referenced as the supporting analysis document by subsystem specifications.

4. **Applicable Documents**

The following documents are applicable to the use of this specification

[1] LSE-59, “Camera Subsystem Requirements Document”

[2] LSE-65, “Camera—Telescope Summit Facility Interface”

[3] LCA-40, “Camera Integration and Test Plan”

[4] LSE-64, “Utilities and Services Interface Between the Camera and Telescope”

[5] Rationale for CCD operating temperature

[6] SLAC-I-730-0A21L-006-R001, “SLAC Environment, Safety, and Health Manual, Chapter 14: Pressure Systems;” August 4, 2011.

[7] BNL-81715-2008-IR, “Vacuum System Consensus Guideline for Department of Energy Accelerator Laboratories;” September 9, 2008.

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

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

[10] LCA-280, “Camera Mechanical Standards”

[11] LSE-11, LSST Optical Prescription

[12] LSE-80, “Mechanical, Thermal, and Access Interfaces Between the Camera and Telescope”

[13] “Large Synoptic Survey Telescope Camera Slewing Dynamics;” Doug Neill, July 25, 2008.

[14] MIL-STD-810F, “Environmental Engineering Considerations and Laboratory Tests,” Aeronautical Systems Center, 1 January 2000.

[15]: U.S. Highway Truck Vibration Exposures, MIL-STD-810F, Annex C

[16] Singh, J., S. P. Singh, and E. Joneson. “Measurement and Analysis of U.S. Truck Vibration for Leaf Spring and Air Ride Suspensions and Development of Tests to Simulate these Conditions”. Packaging Technology and Science, Volume 19, Issue 6, Pages 309 –323, 2006.

[17] SLAC-I-720-0A24E-001-R004, “Seismic Design Specification for Buildings, Structures, Equipment, and Systems: 2011,”8 July 2014.

[18] Document-13227, “Seismic Design Accelerations for the LSST Telescope”

[19] Document-13228, “LSST Seismic Design Accelerations Document”

[20] LCA-10734, “Camera I&T Facility Specification”

[21] LSE-30, “Observatory System Specification” (OSS)

[22] LCA-10031, “LSST Camera Mechanical Standards: Factors of Safety”

5. Acronyms

CCD	charge-coupled devices
CCS	Camera Coordinate System
ESD	Electro-Static Discharge
g	acceleration due to gravity
Hz	Hertz (cycles/sec)
ICD	Interface Control Document
I&T	Integration and Test
LSST	Large Synoptic Survey Telescope
MAWP	Maximum Allowed Working Pressure
MOP	Maximum Operating Pressure
QE	quantum efficiency
REB	Raft Electronics Board
REC	Raft Electronics Crate
RSA	Raft Sensor Assembly
RTM	Raft Tower Module
SLAC	SLAC National Accelerator Laboratory
TBD	To Be Determined
TBR	To Be Resolved

6. Definitions

Operating (Op) limits: the range within which a component is expected to operate and meet all performance requirements with positive margins. Note that this is for reference only.

Working limits: the range over which a unit must function normally, within performance specifications with greater than zero margin. This should be used for acceptance testing of the component. For components exposed to or affected by the outside environment, this range corresponds to the “marginal” conditions defined in Ref. [1], LSE-59, “Camera Requirements Document.”

Survival range: the limits at which a component can survive while off without long-term damage, and be able to recover to full performance. At survival limits, components must be capable of being turned on and off and to function, although not within specifications, unless specified otherwise. This is the range over which “Aliveness” tests can be performed. Note that the survival range bounds extremes experienced during off-normal operations or failure scenarios, as well as those experienced during transport and storage.

X, Y, Z: coordinates quoted in the Camera Coordinate System (CCS), as defined in Ref [10]. All coordinates are assumed to refer to the CCS unless explicitly stated otherwise.

7. Environments

7.1. Relative Humidity

7.1.1. Source Requirements

Camera components are exposed to a number of different environments, some of which are directly related to local weather and others set by environmental constraints of the facilities and transportation methods used. The source requirements for these various relative humidity ranges are listed in Table 1. The first set address design ranges for relative humidity of the air, either in and around the dome at the summit, or outside air conditions during transport. These are interpreted to drive requirements for camera components that are normally exposed to outside or dome environments, and NOT to components internal to the camera or equipment used solely in clean rooms or other controlled environments.

Humidity ranges in the summit and integration and test (I&T) clean rooms are set by the operating procedures of the facility. While these could be changed, they are set by interface agreement or plan, then treated as constraints that drive operating requirements of hardware in the facilities.

Table 1: Relative humidity range source requirements

Relative Humidity Requirements		
Source Doc.	**I.D.**	**Requirement Text**
[1]: LSE-59, Camera Reqs	CAM-REQ-0084	The maximum humidity (non-condensing) for normal operations is 90%
[1]: LSE-59, Camera Reqs	CAM-REQ-0086	All equipment on the summit must be capable of surviving a maximum humidity of 100% without damage
[1]: LSE-59, Camera Reqs	CAM-REQ-0087	The relative humidity range (with condensation) for transportation to the summit is 10%-100%
[2]: LSE-65, Cam-Tel Facility ICD	CA-TS-FAC-ICD-0022	Summit facility white room humidity range: 30%-60%
[2]: LSE-65, Cam-Tel Facility ICD	CA-TS-FAC-ICD-0031	Summit facility clean room humidity range: 30%-60%
[20]: LCA-10734, Camera I&T Facility Spec		SLAC Bldg 620 clean room humidity range: 30%-60%

7.1.2. Derivation Analysis

Components in the Cryostat are designed to meet all requirements when under vacuum and cold. There is no need to also meet those requirements in room temperature conditions, so humidities at room temperature are not applicable. However, components in the Cryostat will need to be turned on and checked at room conditions during integration and test and subsequent servicing. Thus, their survival range is defined by the range of humidity that spans all clean rooms where they will be tested.

Components in the camera volume are normally exposed to the controlled environment provided by the purge system. This system must minimize humidity to avoid condensation on the L3 lens outer surface. Given radiative cooling on the L3 lens, the lens outer surface temperature is typically about 20 ^oC below the camera volume air temperature. With the camera temperature range of -3 to 25 ^oC (see Section 7.2.2), this mandates that the maximum allowed dew point for the camera volume air is -23 to +5 ^oC, to ensure that local cooling of the air around L3 will not result in water condensing on the lens.

Table 2 shows the range of air temperatures within the camera volume from the cold end of the operating range to the hot end of the survival temperature. For each temperature, the required maximum dew point is 20 ^oC below that, signifying the temperature of the outer surface of L3. The maximum relative humidity of the air is then the humidity that corresponds to the dew point at that air temperature.

Table 2: Temperature, relative humidity and dew point of the Camera volume purge gas

Camera Volume Relative Humidity		
Air Temp	Req'd Max Dew Point	Max Relative Humidity
-3 ^oC	-23 ^oC	20%
25 ^oC	+5 ^oC	26%
30 ^oC	10 ^oC	29%

This indicates that the maximum humidity of the camera volume should be no greater than 20%, which ensures that L3 will never reach the dew point no matter what the air temperature of the camera volume is. The lower operational humidity limit for the camera volume should be 15%, with the camera purge system required to maintain the purge air at 15-20% relative humidity over the entire working temperature range. This then dictates that all components in the volume be tested to meet all functional and performance requirements at a lower humidity limit of 15%.

TBR: The camera volume may be purged with dry nitrogen gas, which will further dry out the volume and remove oxygen, as well. Thus, components in the camera volume should be capable of operating in a nitrogen environment. This is not yet finalized and will remain at TBR until it is, at which point humidity ranges here and any changes to requirements flowed to subsystems will be assessed as part of that change.

On the high end, all components in the camera volume need to fully function during normal integration activities in all clean rooms. This sets the working humidity range at 60%.

Components in the Utility Trunk are cooled by air blown in from the cooled top end plenum. This air has unknown de-humidification, so the full operational humidity range of the dome environment needs to be used for these components. Even still, since the air is cooled in the top end, the relative humidity may be even higher than the air in the dome itself, requiring the Utility Trunk blower unit to have a means to dry the air out to a maximum humidity of 90%. On the dry side, the lower humidity level is set by the minimum 30% relative humidity in the clean rooms.

Camera ground units, test equipment, and fixtures must be able to fully function in the relative humidity range of the room where they are located. For units that stay in clean rooms, this range is 30-60%. Note that this includes racks that are ultimately installed in the Control Room on the summit, since they will be located in the clean rooms at SLAC during I&T. For units that operate outside the clean rooms, including the Utility room, anywhere on the telescope or in the dome, and in the SLAC I&T high-bay, a humidity range of 20-90% should bound all of these locations. No environmental conditions for these regions were flowed down from the observatory, so these are expected to be rough values for defining equipment requirements.

7.1.3. Derived Requirements

The following requirements are derived from the high-level humidity environments. Functional requirements define the environments that must be provided inside the camera, while Table 3 shows the derived environments for which subsystem hardware must be designed. Subsystems can expand on this range to match particular environments of facilities at institutions where components are assembled and tested, but they may not reduce the range, since all components will see these ranges during I&T and on-summit operations. On the dry end of the humidity ranges, test conditions assume hands-off testing but survival conditions should be expected to include with personnel around. This may drive electro-static discharge (ESD) requirements or handling precautions for subsystem hardware.

Table 3: Relative humidity requirements for Camera components

Surrounding Environment Relative Humidity Derived Requirements				
Component \ Unit	**Oper %RH**	**Working %RH**	**Survival, Turn-On %RH**	**Comments**
Camera Assembly		30-90	30-100	
L1-L2 Assembly	15-60	15-60	10-60	Outer surfaces test value to 90%
Housing	15-60	15-60	10-60	Outer surfaces test value to 90%
Filter Exchange	15-60	15-60	10-60	In camera volume
Shutter	15-60	15-60	10-60	In camera volume
Cryostat Housing	15-60	15-60	10-60	In camera volume; inner surface in vacuum at 0% humidity
L3 Lens Assembly	15-60	15-60	10-60	In camera volume; inner surface in vacuum at 0% humidity
Cryo Plate	N/A	N/A	30-60	In purged cryostat or lab
Science Raft Tower	N/A	N/A	30-60	In purged cryostat or lab
Corner Raft Tower	N/A	N/A	30-60	In purged cryostat or lab
Cold Plate	N/A	N/A	30-60	In purged cryostat or lab
Utility Trunk	30-90	30-90	30-90	Outer surfaces test value to 100%
Vacuum System	30-90	30-90	30-90	In Utility Trunk volume
System Electronics	30-90	30-90	30-90	In Utility Trunk volume
Optical Transion Module	30-90	30-90	30-90	In Utility Trunk volume
DAQ ground units	30-60	30-60	30-60	Incl other crates in Computer Room
Camera control computer	30-60	30-60	30-60	Incl other crates in Computer Room
Refrig system ground units	20-90	20-90	20-90	All components in Utility Room

The camera purge system shall maintain the purge air at 15-20% relative humidity over the entire working temperature range.

The Utility Trunk blower unit shall dry the incoming air to a maximum relative humidity of 90% and maintain humidity in the Utility Trunk within a range of 30-90%.

For transport, all components must either be able to survive the 10-100% humidity range of possible transport environments, or the shipping containers be able to isolate the hardware.

7.2. Temperatures

7.2.1. Source Requirements

Camera components must operate over a variety of temperatures, some of which are related to local weather and others set by environmental constraints of the facilities and transportation methods used. The source requirements for these various temperature ranges are listed in Table 4. The first set address design ranges for air temperature at the summit or during transport. Temperatures in the summit and I&T clean rooms are set by the operating plans of the facilities, which are set by interface agreement or plan, then treated as constraints that drive operating requirements of hardware in the facilities.

7.2.2. Derivation Analysis

7.2.2.1. Operating Temperatures: Nominally Room-Temperature Components

During normal operation, the nominal air temperature range in the dome is -3 to +19 C. This helps define the operating temperature range for all components directly exposed to the dome environment. This includes all components inside the Camera and Utility Trunk that are exposed to conditioned air that tracks dome-air temperature. On the cold end of the range, the component-level operating temperature is set at -3 C, the minimum dome air temperature.

On the high end of the scale, the peak operating temperature is set by the peak facility air temperature where the camera will be tested. This is 25 C, at the high-bay in Building 620 at SLAC, where the integrated Camera is tested.

Note that operating temperature ranges are for reference only. Working temperature ranges establish the range over which components must meet all requirements.

7.2.2.2. Working Temperatures: Nominally Room-Temperature Components

The working temperature range for components in the Camera and Utility Trunk is set by the “degraded operations” dome air temperature, which is -5 C on the cold end and +30 C on the warm end.

Note that the refrigeration system supply and return refrigerant mixes have an additional requirement to not deviate from the current dome air temperature by more than -15 C to +4 C. Beyond this, insulation in the lines will not be able to moderate the line temperature, which may result in excessive heating or cooling of the dome air.

For support fixtures and test equipment located in the Summit Facility Utility Room or Staging and Test Area, the working temperature range is 0 C on the cold end up to +25 C on the warm end. This includes the refrigeration system base units and any racks in the Utility Room, as well as camera test equipment located in the Staging and Test Area. This range bounds working temperatures of the summit facility Clean Room and White Room, as well as the SLAC Building 620 clean rooms, which have a working temperature range of 19-23 C, and high bay, which has a working temperature range of 10-25 C.

Table 4: Temperature source requirements for the camera

Temperature Requirements		
Source Doc.	**I.D.**	**Requirement Text**
[1]: LSE-59, Camera Reqs	CAM-REQ-0084	The minimum temperature for normal operations at the summit is -3.0 C
[1]: LSE-59, Camera Reqs	CAM-REQ-0084	The maximum temperature for normal operations at the summit is 19.0 C
[1]: LSE-59, Camera Reqs	CAM-REQ-0084	The maximum rate of temperature change for normal operations is 0.7 C/hr
[1]: LSE-59, Camera Reqs	CAM-REQ-0085	The minimum temperature for degraded operations at the summit is -5.0 C
[1]: LSE-59, Camera Reqs	CAM-REQ-0085	The maximum temperature for degraded operations at the summit is 30.0 C
[1]: LSE-59, Camera Reqs	CAM-REQ-0085	The maximum rate of temperature change for degraded operations is 2.0 C/hr
[1]: LSE-59, Camera Reqs	CAM-REQ-0086	All equipment on the summit must be capable of surviving an ambient air temperature of -10 C
[1]: LSE-59, Camera Reqs	CAM-REQ-0087	The ambient temperature range during transportation is -15 C to 40 C
[2]: LSE-65, Cam-Tel Facility ICD	CA-TS-FAC-ICD-0010	Summit facility staging and test area temperature range: 0-20 C
[2]: LSE-65, Cam-Tel Facility ICD	CA-TS-FAC-ICD-0022	Summit facility white room temperature range: 19-23 C
[2]: LSE-65, Cam-Tel Facility ICD	CA-TS-FAC-ICD-0022	Summit facility white room temperature drift: 2 C P-V
[2]: LSE-65, Cam-Tel Facility ICD	CA-TS-FAC-ICD-0031	Summit facility clean room temperature range: 19-23 C
[2]: LSE-65, Cam-Tel Facility ICD	CA-TS-FAC-ICD-0031	Summit facility clean room temperature drift: 2 C P-V
[2]: LSE-65, Cam-Tel Facility ICD	CA-TS-FAC-ICD-0042	Summit facility utility room temperature range: 0-20 C
[2]: LSE-65, Cam-Tel Facility ICD	CA-TS-FAC-ICD-0043	Summit facility utility room chilled water temperature range below night time ambient: -5- -10 C
[2]: LSE-65, Cam-Tel Facility ICD	CA-TS-FAC-ICD-0054	Temperature range of refrigerant exiting Refrig System ground unit relative to dome air ambient: +4- -15C
[5]: LSE-64, Cam-Tel Utilities ICD	CA-TS-UTI-ICD-0008	Temperature range of refrigerant exiting camera Utility Trunk relative to dome air ambient: +4- -15C
[20]: LCA-10734, Camera I&T Facility Spec		SLAC Bldg 620 clean room temperature range: 19-23 C
[20]: LCA-10734, Camera I&T Facility Spec		SLAC Bldg 620 high bay temperature range: 10-25 C

7.2.2.3. Turn-on Temperatures: Nominally Room-Temperature Components

The cold limit for components in the Camera and Utility Trunk is specified as -10 C, with no upper limit. However, an upper limit of 30 C seems prudent, given the uncontrolled temperatures in areas both at SLAC and on the summit. This is defined as the Turn-on Temperature range, over which components must be able to turn on and communicate with the CCS, but not otherwise function.

All fixtures and test equipment must also be able to accommodate this temperature range, as well. During observing, the clean rooms and all maintenance areas of the Summit Facility will not be heated, so all equipment may experience the full temperature range in extreme conditions.

Nominally room-temperature components must be able to survive a sudden +/-15 degC change of air temperature anywhere within its survival temperature extremes shown in Table 5. This applies both when the component is off or on, but it need not meet any performance requirements during this transition. This accounts for moving components between rooms or out of a warm shipping container. This air temperature rate of change is a step function, when a component moves from one room to another, and is defined as a camera specification and not flowed from above. It covers the maximum expected temperature differential between the dome environment and the White or Clean Room when they are at their expected operating temperature.

7.2.2.4. Survival Temperatures

All camera components, including parts in the Cryostat as well as test equipment and fixtures must be able to survive the transportation air temperature range of -15-40 C defined in Ref. [1]. This temperature range must be factored into the design of all components, even if the shipping and storage container is designed to accommodate those external temperatures while keeping components inside within a more moderate range. This sets the survival range for all room temperature components, and the top end of the range for nominally cold components.

7.2.2.5. Cold Components Inside the Cryostat

Temperatures for components in the cryostat are set by two values: the target operating temperature for charge-coupled devices (CCD's) on the detector plane, and the minimum working temperature for electronics using standard hardware. Ref. [5] discusses trade-offs in choosing the CCD operating temperature, concluding that a target temperature of -100 C serves to balance the competing trends of improved quantum efficiency (QE) with increasing temperature, and decreasing defects and hot columns with reduced temperature. Given the temperature uniformity requirements of the CCD, a suitable working temperature range for the CCD's on the Raft Sensor Assemblies (RSA's) is -105— -95 C. This establishes the range over which the CCD's must meet all requirements, but also defines derived requirements for conductivity and uniformity of components along the heat conduction path.

Working temperature ranges for components along the conduction path are set based on the expected temperature gradient backward from the CCD to the Cryo Plate heat sink. The gradient through the RSA is expected to be small, so the working temperature range of the RSA interface to its heat sink (the thermal straps) bounds that of the sensors, from -110 to -95 C. Again, the Raft Electronics Crate (REC) sidewall temperatures are colder and broadened. This reflects both their position closer to the Cryo Plate heat sink and the added uncertainties associated with the heat load and the thermal resistances. A working temperature range of -130 C to -115 C at the REC interface to the Cryo Plate supports the CCD ranges while accounting for the larger uncertainties. The expected operating temperature at this interface should be closer to -130 C to -125 C. Note that these ranges are at the interface to the component's heat sink, so temperatures on the component will be warmer.

The Cryo Plate itself is expected to operate somewhere between -127 and -120 C, depending on the temperature gradients in the Raft Tower Module (RTM). Bounding the operating range, the working temperature range of -130 to -115 C ensures that the system can function normally beyond its expected operating range.

The low end of the survival and turn-on temperature ranges for the Cryo Plate, REC and RSA is set by the coldest no-load temperature achievable by the refrigeration system. This is expected to be around -135 C, and could be achieved if all electronics is turned off with the refrigeration system running. Components need to be able to both survive this soak temperature and turn-on to read temperatures and warm up. Given the IR heat loading on the CCDs, it is not possible to reach this cold limit, so the CCD survival and turn-on limit is set at -130 C. On the warm end, the Cryo Plate, RTM, RSA, and CCD's all need to turn on and provide basic aliveness functionality at the maximum clean room temperature, which is 23 C, as defined in Ref. [2] and [3]. However, this is an operating temperature, and does not account for non-operating conditions, or off-normal cases in the facilities where components may be stored. To guard against possible loss of power in the summer or other failure conditions, it is prudent to set the high-end of the survival range at 30 C, covering just component survival while off, with no turn-on functionality.

For the raft electronics boards (REB's) mounted to the Cold Plate, to reduce outgassing from the electronics the working temperature is set as low as practical for conventional electronics. For industrial-grade electronics components, this is -40 C. This sets the bottom of the working temperature range at the interface of the REB to the Cold Plate. On the warm end of the range, -25 C provides adequate margin for design and operational uncertainties in the Cold Plate and REB design. The expected interface temperature during operation should be at the cold end of this range, likely on the order of -40 to -35 C at the interface to the Cold Plate, with a considerable temperature gradient along the board to its front end.

The cold turn-on temperature for the REB is established by the no-load temperature floor of the Cold Plate refrigeration system, which is expected to be around -50 C. Thus, a turn-on temperature of -55 C provides some margin. This also defines a functional requirement on the Cold Plate refrigeration system to have a no-load temperature floor of no less than -50 C. Although the REB is surrounded by REC sidewalls cooled by the Cryo Plate, the cold survival temperature is set by the component spec survival temperature of -55 C. At the floor of the Cryo Plate operating range, the REB could slowly drift down in temperature due to radiative cooling to the sidewalls, thus the Cold Plate refrigeration system must include interlocks to turn off the Cryo Plate refrigeration system if it is shut down.

On the high end of the survival range, the transportation temperature extreme defines the survival temperature of +40 C and applies to all components mounted to the Cold Plate, as well as the Cryo Plate. The hot-end turn-on temperature is likewise set by the top end of the clean room temperature range, which is 23 C. This allows for aliveness testing at the high end temperature of any room.

These working and turn-on temperatures apply at the interface of the part with its heat sink, while survival soak temperatures apply to the entire component since it is assumed to be nearly isothermal.

Components in the cryostat must also be able to survive a +/-30 C/hr temperature rate-of-change during warm-up/cool-down, when off or on. This is faster than the fastest expected rate of change of the Cryo Plate and Cold Plate. From this, a functional and operational requirement is set on the maximum ramp rate of the Cryo and Cold Plates at +/-25 C/hr

For L3, the working temperature is defined at the interface of the L3 assembly with the cryostat, and thus is set at the cryostat working temperature range of -5 C to +30 C. Over this range, the convection boundary to camera air should use the air temperature at -5 C to +30 C, as well. The radiation boundary condition should use CCD temperatures in its working range of -105 C to -95 C. These three boundary conditions can be used by pairing each set of extremes to define a “cold-case” and “hot-case” working boundary.

For L3, the extreme operational conditions over which the lens assembly must survive while in use corresponds with the turn-on temperature for other subsystems. This is defined at the interface of the L3 assembly with the cryostat, and thus is set at the cryostat turn-on temperature range of -10 C to +30 C. Over this range, the convection boundary to camera air should use the air temperature at -10 C to +30 C, as well. The radiation boundary condition should use CCD temperature in the range of -130 C to +23 C.

The L3 survival soak temperature is set by the transportation temperature range of -15 C to +40 C. The entire L3 assembly is soaked at this temperature.

7.2.2.6. Thermal Systems Requirements

The camera includes four primary thermal control zones: Cryo Plate, Cold Plate, Camera body, and Utility Trunk. Each is independently controlled, so the functional requirements for them are independent of the others. For each, their temperature control functional requirements are to ensure that the system maintains the sink temperature within the various temperature ranges for the components that are thermally sinked to it.

7.2.3. Derived Requirements

A table summarizing derived temperature environments is shown in Table 5. As discussed above, these temperature environments are controlled by one of four thermal control systems within the camera. Thus, these temperature environment requirements also establish functional requirements for the thermal control systems.

Transportation temperature: all camera components, including parts in the Cryostat as well as test equipment and fixtures must be able to handle the transportation air temperature range of -15 to +40 C

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 glycol temperature range of -5 to -10 C below ambient temperature.

During normal operations, the camera purge system shall fully function over the entire working temperature range of -5 to + 30 C, maintain the camera volume purge gas temperature within this range, and shall provide alarms if the purge gas exceeds this range.

During normal operations, the Utility Trunk cooling system shall fully function over the entire working range of -5 to +30 C, maintain the Utility Trunk volume air temperature within this range, and shall provide alarms if the air exceeds this range.

During normal operations, the Cryo Plate control system shall fully function over the entire working range of -130 to -115 C, maintain the Cryo Plate temperature within this range, and shall provide alarms if the Cryo Plate exceeds this range.

The extreme no-load temperature of the Cryo Plate shall be no lower than -135 C, or under-temperature protection elements shall be used.

The Cryo Plate and its control system shall not ramp its temperature faster than +/- 25 C/hr.

During normal operations, the Cold Plate control system shall fully function over the entire operating range of -40 to -25C, maintain the Cold Plate temperature within this range, and shall provide alarms if the Cold Plate exceeds this range.

The extreme no-load temperature of the Cold Plate shall be no lower than -50 C, or under-temperature protection elements shall be used.

The Cold Plate and its control system shall not ramp its temperature faster than +/- 25 C/hr.

Table 5: Component temperature range derived requirements

Component Temperature Derived Requirements										
	Survival Soak (when off)									
		Turn-On								
			Working							
				(Operating)					Survival (on or off)	
Component \ Unit	**°C**	**°C**	**°C**	**°C**	**°C**	**°C**	**°C**	**°C**	**Rate of Change**	
Camera Assembly	-15	-10	-5	-3	+25	+30	+30	+40	+/-15	up/down step
L1-L2 Assembly	-15	-10	-5	-3	+25	+30	+30	+40	+/-15	up/down step
Housing	-15	-10	-5	-3	+25	+30	+30	+40	+/-15	up/down step
Filter Exchange	-15	-10	-5	-3	+25	+30	+30	+40	+/-15	up/down step
Shutter	-15	-10	-5	-3	+25	+30	+30	+40	+/-15	up/down step
Cryostat Housing	-15	-10	-5	-3	+25	+30	+30	+40	+/-15	up/down step
L3 Lens Assembly	-15	-10	-5	-3	+25	+30	+30	+40	+/-15	up/down step
Cryo Plate	-135	-135	-130	-127	-120	-115	+23	+40	+/-30	C/hour ramp
Cold Plate	-50	-50	-40	-40	-35	-25	+23	+40	+/-30	C/hour ramp
Science Raft Tower										
CCD's	-130	-130	-105	-100	-100	-95	+23	+40	+/-30	C/hour ramp
Raft Sensor Ass'y	-135	-135	-110	-100	-100	-95	+23	+40	+/-30	C/hour ramp
Raft Elec Crate walls	-135	-135	-130	-130	-125	-115	+23	+40	+/-30	C/hour ramp
Raft Electronics Board	-55	-55	-40	-40	-35	-25	+23	+40	+/-30	C/hour ramp
Corner Raft Tower										
CCD's	-130	-130	-105	-100	-100	-95	+23	+40	+/-30	C/hour ramp
Raft Sensor Ass'y	-135	-135	-110	-100	-100	-95	+23	+40	+/-30	C/hour ramp
Raft Elec Crate walls	-135	-135	-130	-130	-125	-115	+23	+40	+/-30	C/hour ramp
Raft Electronics Board	-55	-55	-40	-40	-35	-25	+23	+40	+/-30	C/hour ramp
Utility Trunk	-15	-10	-5	-3	+25	+30	+30	+40	+/-15	up/down step
System Electronics	-15	-10	-5	-3	+25	+30	+30	+40	+/-15	up/down step
Optical Transition Module	-15	-10	-5	-3	+25	+30	+30	+40	+/-15	up/down step
DAQ ground units	-15	-10	+19			+23	+30	+40	+/-15	up/down step
Camera control computer	-15	-10	+19			+23	+30	+40	+/-15	up/down step
Refrig system ground units	-15	-10	+0			+25	+30	+40	+/-15	up/down step
Clean room equipment	-15	-10	+19			+23	+30	+40	+/-15	up/down step
Other fixtures, equipment	-15	-10	+0			+25	+30	+40	+/-15	up/down step

Notes:

All temperatures are in degrees C; see acronym list for an explanation of acronyms

Temperatures shown are for the interface of the component to its sink, unless otherwise noted

7.3. Atmospheric Pressures

7.3.1. Source Requirements

Camera components are exposed to a range of atmospheric pressures since they are operated over a range of altitudes from sea level to 2700 meters. Furthermore, camera components are transported by air, which sets additional survival pressure requirements. These source requirements are listed in Table 6, below.

Table 6: Atmospheric pressure source requirements for the camera

Atmospheric Pressure Requirements		
Source Doc.	**I.D.**	**Requirement Text**
[1]: LSE-59, Camera Reqs	CAM-REQ-0084	The mean barometric pressure for normal operations is 75 kPa
[1]: LSE-59, Camera Reqs	CAM-REQ-0084	The maximum barometric pressure for normal operations is 77.5 kPa
[1]: LSE-59, Camera Reqs	CAM-REQ-0084	The minimum barometric pressure for normal operations is 72.5 kPa
[1]: LSE-59, Camera Reqs	CAM-REQ-0087	Pressure change during transportation is 100-75 kPa

7.3.2. Derivation Analysis

The minimum atmospheric pressure for all components is set by the 2700 m elevation of the observatory, where the pressure range is 72.5-77.5 kPa. However, since the camera is integrated and tested at sea level at SLAC, the operating atmospheric pressure range must extend to include the expected pressure at sea level. The nominal sea level air pressure is 101.6 kPa, so a maximum working pressure of 102 kPa is defined. The maximum recorded pressure near SLAC is 103.7 kPa, so a reasonable survival pressure is 104 kPa.

During transport of components and the completed camera, all hardware and shipping containers should be designed to travel by airplane in a partially-pressurized cargo hold. Here, the minimum expected atmospheric pressure that components must be able to survive is the pressure at 2500 m (8000 feet), which is the expected minimum allowed pressure on passenger and cargo planes. This corresponds to 76 kPa. Given that this is already bounded by the atmospheric pressure on the summit, this does not add any further constraint.

Transportation by air also establishes a maximum expected rate of change of air pressure, due to changes in pressure in the cargo hold during ascent and descent at the maximum expected rate of climb. Approximate design values for the pressure rate of change is +120 / -60 kPa/hr (+1.2 / -0.6 atmospheres/hr), corresponding to a 30 minute ascent and 15 minute descent with the corresponding linear change of pressure over time. These rates of change may impact the degree of air-tightness of a component or enclosure.

7.3.3. Derived Requirements

Table 7 summarizes the bounding atmospheric pressures that all camera components and assemblies must be designed to handle. The following section uses these values to derive the pressure differentials across pressurized components. Note that subsystem specifications show the minimum atmospheric pressure as slightly less than what is shown in the table, owing to more conservative values being used earlier in the project. We have elected to preserve the more conservative value, but could use the one shown in the following table if preferred by the subsystem.

Table 7: Atmospheric pressure derived requirements

Atmospheric Pressure Derived Requirements				
Component \ Unit	**Units**	**Min**	**Max**	**Comments**
Working pressure for all camera components	kPa	72.5	102	Max set by nominal air pressure at sea level
Survival pressure for all camera components	kPa	72.5	104	Max is set by max recorded air pressure near SLAC
Survival pressure rate of change	kPa/hr	-60	120	Rough rates of change for air transport

7.4. Pressures and Differentials

7.4.1. Source Requirements

Both the Camera and Cryostat volumes are vessels that operate under controlled pressure/vacuum and are sealed to the outside. Thus, components in each of these vessels see larger variations in pressure than just those due to changes in atmospheric pressure. The camera and cryostat housings must be designed to carry these pressure differentials, while components inside each vessel must be capable of normal operation while exposed to the pressure and vacuum extremes.

Requirements on pressure differentials within the camera volume come from two sources. First, atmospheric pressure ranges have been derived in the previous section. This establishes the range of outside pressures that the vessels in the camera must be able to accommodate. Second, nominal pressures within the cryostat and camera body are determined by their designs. Since the cryostat is a vacuum vessel, its minimum pressure is a vacuum. The camera body is over-pressurized by a very small amount, just enough to provide adequate air flow for purging the camera volume. This operating pressure is designed to not exceed 0.3 psi or 2.0 kPa +1.0 / -0.5 kPa. This is based on preliminary design work, but is levied on the purge system design, since it impacts pressure environments for other subsystem equipment.

Also, maximum pressures in the camera body and cryostat are set by the selection of the relief valves/burst disk for the two vessels. For the camera body, and relief pressure of 3.0 kPa is being used, while for the cryostat, a relief pressure of 80 kPa overpressure is used. There is no under-pressure relief for the cryostat, since pressures in excess of atmospheric pressure are controlled by the relief valve in the camera body.

Note that there are also local pressure differentials on the outer wall of the camera body due to wind blowing over the camera. These values are derived from higher-level requirements in Section 8. The Camera Body and L1 lens must accommodate these pressure differentials, where the change in the pressure differential due to changes in wind speed must be accommodated by the performance of the lens. This is factored into the derivation analysis and derived requirements in this section.

7.4.2. Derivation Analysis

Table 8 lists all possible combinations of internal and external pressures for the two vessels, including over- and under-pressure cases both during I&T at SLAC and on the summit. This sets the pressure differentials for which the two vessels must be designed, as well as the pressure extremes for components in the vessels. Since these extremes may well occur at any time, components must be designed to withstand these pressures while applied simultaneously with all inertial load cases described in Section 9.3, except seismic load cases. Furthermore, since the camera body and cryostat vessels are operated independent of each other, all combinations of pressures of both vessels must be evaluated to ensure that the extreme conditions are captured, regardless of operational state of either vessel. Note that this also includes all lenses.

The permutations of pressure differentials are established by combining pressures for:

(Nom) Nominal operating condition: pressurized camera body, evacuated cryostat

(Maint) Maintenance condition: pressurized camera body, vented cryostat

(Ext) Extreme condition set by relief valves: overpressurized camera body, overpressurized cryostat

The combinations of pressure differentials shown in Table 8 list all possible combinations of pressures for these conditions. Note that the nominal operating pressures for both vessels are single values and do not include a range of operating pressures. For both, the nominal operating pressure marks the limit of the nominal range, and anything more benign than this is acceptable from the perspective of safety.

The final step in establishing subsystem pressure specifications is to pick out from the table of permutations the most extreme pressures in each vessel and the most extreme differentials across the vessel walls. These extremes establish two types of pressure specification. First, the Maximum Operating Pressure (MOP) defines the pressure range—or range of pressure differential—over which a component is expected to operate. This is for reference only. Next, the Maximum Allowable Working Pressure (MAWP) establishes the peak pressures—or differentials—the component will ever experience and still function normally and meet all performance and functional requirements.

The MAWP is used for establishing the Test pressure to be used for component pressure testing. Components must be able to survive the test pressure with no residual damage, but are not required to meet performance requirements. For pneumatic testing, Test pressures are typically set at 10% above the MAWP, per Ref [6], SLAC-I-730-0A21L-006-R001, "SLAC Environment, Safety, and Health Manual, Chapter 14: Pressure Systems" and its supporting documents, Ref.'s [7, 8, and 9].

Note that the MAWP and MOP pressures listed in the table account for static pressure differentials only. These values need to be modified to add in extremes of the time-varying pressures. These come from wind loading and from variations in the internal pressure of the camera. Pressure changes due to wind loading are derived in the following section. Variations in the internal pressure of the camera are defined above, and these values are then set as functional requirements on the camera purge system.

Table 8 also shows the pressure differentials across pressure-relief devices in both the cryostat and camera body. Relief valves or burst disks are needed to ensure that the MAWP is never exceeded and, indeed, the MAWP is established by the selection of the overpressure rating for the relief device.

Table 8: Pressure state combinations for the camera body and cryostat housing (does not include time-varying pressures due to wind loading)

Camera State	Cryostat State	Loc.	Outside Air Abs Press	dP	Camera Volume Abs Press	dP	Cryostat Volume Abs Press
Nom: pressurized	Nom: evacuated	SLAC	+104.0	+2.0	+106.0	-106.0	+0.0
Nom: pressurized	Maint: vented	SLAC	+104.0	+2.0	+106.0	-2.0	+104.0
Nom: pressurized	Ext: overpressurized	SLAC	+104.0	+2.0	+106.0	+80.0	+186.0
Ext: overpressurized	Nom: evacuated	SLAC	+104.0	+3.0	+107.0	-107.0	+0.0
Ext: overpressurized	Maint: vented	SLAC	+104.0	+3.0	+107.0	-3.0	+104.0
Ext: overpressurized	Ext: overpressurized	SLAC	+104.0	+3.0	+107.0	+80.0	+187.0
Ext: underpressurized	Nom: evacuated	SLAC	+104.0	-3.0	+101.0	-101.0	+0.0
Ext: underpressurized	Maint: vented	SLAC	+104.0	-3.0	+101.0	+3.0	+104.0
Ext: underpressurized	Ext: overpressurized	SLAC	+104.0	-3.0	+101.0	+80.0	+181.0
Nom: pressurized	Nom: evacuated	Summit	+72.5	+2.0	+74.5	-74.5	+0.0
Nom: pressurized	Maint: vented	Summit	+72.5	+2.0	+74.5	-2.0	+72.5
Nom: pressurized	Ext: overpressurized	Summit	+72.5	+2.0	+74.5	+80.0	+154.5
Ext: overpressurized	Nom: evacuated	Summit	+72.5	+3.0	+75.5	-75.5	+0.0
Ext: overpressurized	Maint: vented	Summit	+72.5	+3.0	+75.5	-3.0	+72.5
Ext: overpressurized	Ext: overpressurized	Summit	+72.5	+3.0	+75.5	+80.0	+155.5
Ext: underpressurized	Nom: evacuated	Summit	+72.5	-3.0	+69.5	-69.5	+0.0
Ext: underpressurized	Maint: vented	Summit	+72.5	-3.0	+69.5	+3.0	+72.5
Ext: underpressurized	Ext: overpressurized	Summit	+72.5	-3.0	+69.5	+80.0	+149.5

Notes:

All pressures in kPa

Nom: Nominal operating pressure
Ext: Extreme pressure condition
Maint: Maintenance condition

		Camera		Cryostat	
		dP	Absolute Press	dP	Absolute Press
Max / Internal	Test	+3.3	+107.3	+88.0	+195.0
	MAWP	+3.0	+107.0	+80.0	+187.0
	MOP	+2.0	+106.0	-2.0	+104.0
Min / External	MOP	+0.0	+74.5	-106.0	+0.0
	MAWP	-3.0	+69.5	-107.0	+0.0
	Test	-3.3	+69.2	-117.7	+0.0

Over-test diff.	10%
Sea level, max (kPa)	104
2650 m, min (kPa)	72.5

Relief Valve Settings

	Camera	Cryostat
Overpress. Relief	+3	+80
Nominal Working	+2	
Underpress. Relief	-3	--

7.4.3. Derived Requirements

The following requirements flow out of the pressure and pressure differentials shown in Table 8:

Camera body surfaces carrying a pressure differential shall be capable of meeting all performance requirements when subject to a Maximum Operating Pressure differential of 0 to +2 kPa

Camera body surfaces carrying a pressure differential shall be capable of meeting all performance requirements when subject to a time-varying pressure differential of -1 to +1 kPa from wind loading, in addition to its MOP range.

Camera body surfaces carrying a pressure differential shall be capable of surviving a Maximum Allowable Working Pressure differential of -4.7 to +4.7 kPa, and be tested at a differential of -5 to +5 kPa. These include a +/- 1.7 kPa suction/pressure from wind loading.

The camera body shall include a relief device to prevent pressure extremes beyond allowable working pressures. The relief device shall be sized for a nominal operating pressure differential of +2 kPa, and a relief pressure of +3 kPa internal pressure and -3 kPa external pressure.

The camera body relief device shall be sized to vent the camera volume fast enough to ensure that the relief pressure is never exceeded for all possible sources of over-/under-pressure condition.

The L1-L2 Assembly and its supports shall be capable of meeting all performance requirements when subject to a Maximum Operating Pressure differential of +2 kPa between the camera volume and outside environment.

The L1-L2 Assembly and its supports shall be capable of meeting all performance requirements when subject to a time-varying pressure differential of -0.5 to +1 kPa internal pressure (i.e.: external suction) from wind loading and variations in internal working pressure, in addition to its MOP range.

The L1-L2 Assembly and its supports shall be capable of surviving a Maximum Allowable Working Pressure differential of -3 to +4.7 kPa, and be tested to a differential of -3.3 to +5 kPa between the camera volume and outside environment. These include a +1.7 kPa MAWP and 2 kPa Test max internal pressure (i.e.: external suction) from wind loading.

Components in the camera body shall be designed to meet all specifications while subject to an absolute working pressure range of 73—106 kPa. [Note that this is slightly less conservative than the value shown in Table 8, but is consistent with specification value].

Components in the camera body shall be designed to survive without damage a MAWP pressure range of 72.5—107 kPa. [Note that subsystem specifications may list 68 kPa as the minimum. This is based on earlier, more conservative atmospheric pressure values. This value shown can be used if the earlier value is deemed to not be tenable].

Components in the camera body shall be designed to survive a maximum rate of change of pressure of -60 kPa/hr and +120 kPa/hr.

Cryostat housing surfaces carrying a pressure differential shall be designed for a Maximum Operating Pressure differential of -106—+0 kPa, a Maximum Allowable Working Pressure differential of -107—+80 kPa, and be tested at a differential of -118—+88 kPa.

The L3 lens assembly shall be capable of meeting all performance requirements when subject to a Maximum Operating Pressure differential of -106 to -73 kPa.

The L3 lens assembly shall be capable of surviving a Maximum Allowable Working Pressure differential of -107 to +80 kPa, and be tested to a differential of -118 to +88 kPa.

The cryostat housing shall include a relief device to prevent pressure extremes beyond allowable working pressures. The relief device shall be sized for a nominal operating pressure differential of -108 kPa, and a relief overpressure of +80 kPa internal pressure.

The cryostat housing relief device shall be sized to vent the cryostat volume fast enough to ensure that the relief pressure is never exceeded for all possible sources of over-/under-pressure condition.

Components in the cryostat shall be designed to survive without damage an absolute working pressure range of 0—184 kPa.

Components in the cryostat shall be designed to survive a maximum rate of change of pressure of -60 kPa/hr and +120 kPa/hr.

8. Wind Loading

8.1. Source Requirements

Requirements on the wind speeds that the Camera must endure originate in the Camera Requirements document and are shown in Table 9 for reference. The requirements are being interpreted here to apply to the Camera as it is mounted to the telescope in the dome and not anywhere in the rest of the summit facility. Furthermore, they are assumed to apply to the Camera directly, with no assumption about attenuation or reduction of wind speed due to shielding from the dome or telescope.

Table 9: Wind loading source requirements

Wind Loading Source Requirements		
Source Doc.	**I.D.**	**Requirement Text**
[1]: LSE-59, Camera Reqs	CAM-REQ-0084	The maximum wind speed for normal operations is 12 m/sec
[1]: LSE-59, Camera Reqs	CAM-REQ-0085	The maximum free air wind speed for degraded operations at the summit is 20 m/sec
[1]: LSE-59, Camera Reqs	CAM-REQ-0086	Equipment in the interior of the Summit Facility must be capable of surviving a constant wind speed of 20 m/sec
[1]: LSE-59, Camera Reqs	CAM-REQ-0086	Equipment in the interior of the Summit Facility must be capable of surviving an exterior 10-second wind gust speed of 25 m/sec
[1]: LSE-59, Camera Reqs	CAM-REQ-0087	The Camera and shipping container shall be deigned to withstand a maximum wind speed of 45 m/sec

8.2. Derivation Analysis

Winds are assumed to impinge onto the Camera side. This is not particularly realistic, given that the Camera will be pointed away from the opening in the dome, and the dome louvers are planned to be set to allow for a maximum crosswind velocity of 5 m/sec. However, this orientation provides worst-case loading, and can be easily analyzed using simple fluid mechanics models of turbulent flow of air around a cylinder. There are three effects of wind loading on the Camera. First, the cylindrical body produces a drag force that the Camera mounts and external components need to be able to handle.

Drag force on a cylindrical body is: $F_D = \frac{1}{2} * \rho * V^2 * A * C_D$,

where

A = cross-sectional area = Length*Diameter = (1.9 m) * (1.6 m)
V = 12 m/sec (operational), 20 m/sec (marginal), 25 m/sec (survival)
ρ = density of air = 1.23 kg/m^3
C_D = drag coefficient = 0.35 for Reynolds numbers ~ 10^6

The resultant drag is 94 N (operational), 262 N (working), and 410 N (survival). Loads imparted on the L1-L2 Assembly are half of these loads, since it is roughly half the length of the overall Camera.

The second effect of wind loading is that flow around the Camera produces changes in pressure that components on the wetted surfaces need to be able to withstand. For turbulent flow, local pressure as a function of angle, θ, of the incoming wind direction is: $(p_\theta - p_\infty) = \frac{1}{2} * \rho * V^2 * (1 - 4 * \sin^2 \theta)$

This results in a peak local pressure of 0.27 kPa (operational), 0.7 kPa (working), and 1.2 kPa (survival). The peak pressure loading produces a suction 90^o to the air stream, but to be conservative we will assume that this is a reversible pressure and can occur anywhere around the Camera. For the L1 lens, this will only be a suction pressure, since it cannot be pointed directly into the wind.

The third effect of wind loading is that wind gusts can produce dynamic buffeting due to cyclic changes to wind speed producing dynamic loads on the Camera, as well as vortex shedding off the back of the Camera. These dynamic effects require an understanding of the expected power spectral density of the wind gusts, which is not described in the requirements. Thus, this effect is not accounted for.

8.3. Derived Requirements

Requirements imparted on the Camera and subsystem components are listed in Table 10. These include a modeling uncertainty factor multiplied to the results discussed above, to cover uncertainties in the analysis.

Pressure loading due to variable wind speed has been added as requirements in Section 7.4.3, for the L1 lens and Camera Body.

The L1-L2 Assembly and its supports shall be capable of meeting all performance requirements when subject to a transverse (radially-applied) time-varying drag force of 200 N applied uniformly from any direction from wind loading. Note that this is in addition to inertial loads.

The L1-L2 Assembly and its supports shall be capable of surviving a transverse (radially-applied), time-varying drag force of 310 N applied uniformly from any direction from wind loading. Note that this is in addition to inertial loads.

The Camera Body and its supports shall be capable of meeting all performance requirements when subject to a transverse (radially-applied), time-varying drag force of 400 N applied uniformly from any direction from wind loading. Note that this is in addition to inertial loads.

The Camera Body and its supports shall be capable of surviving a transverse (radially-applied), time-varying drag force of 615 N applied uniformly from any direction from wind loading. Note that this is in addition to inertial loads.

Table 10: Wind loading derived requirements

9.

Requirements Derived from Wind Speed (with M.U.F., rounded)				
Load Case	**Operational**	**Working**	**Survival**	**Units**
Drag force on Camera	140	400	615	N
Drag force on L1-L2 Ass'y	70	200	310	N
Local pressure on external surfaces of the Camera (+/-)	0.4	1.1	1.7	kPa
Local pressure on the first surface of the L1 lens (+ = suction pressure only)	0.4	1.1	1.7	kPa
Modeling uncertainty factor	1.5	1.5	1.5	

Loads and Accelerations

9.1. Overview

The Camera and its constituent components are subject to five classes of inertial accelerations: static, dynamic re-pointing, integration and handling, transportation, and seismic. For each class of loads, the camera and its components must be able to survive the resultant stresses and deflections, while for the operational load cases, they must also fully function or perform to specification. The following sub-sections describe the five classes of loads and the requirements placed on the camera when subject to those accelerations.

These load classes are defined as mutually-exclusive load sets. Furthermore, a number of load cases are defined for each class of loading. These, also, are mutually exclusive. Thus, load cases should not be added together or in any way combined, but a component should be analyzed for each load case individually.

Note that gravity is already included for each load class and that all loads orientations are in the Camera Coordinate System (CCS), as defined in Ref. [10], LCA-280, "Camera Mechanical Standards," unless specifically defined otherwise.

9.2. Simplified Analysis

Given the location and use of the camera, it sees many types of operational and survival-state loads and accelerations which influence the design of many components. These operating states are described in the sections below.

However, many parts and components in the camera are compact and relatively small, and are designed more for stiffness, heat transfer, or other non-structural considerations and are expected to easily meet all load cases with margin. To simplify the analysis process for these components, a simplified loads analysis is proffered. This is applicable to relatively "compact" components with natural frequencies above 40 Hz, since those with lower frequencies or more distributed geometries may see different loadings that need special attention. Furthermore, all such compact structures should have load-bearing members made entirely from ductile metals, with no brittle materials or load geometries susceptible to buckling.

Stiff, compact components may be designed to be capable of surviving a 5 g acceleration in any orientation, when powered on or off over its entire operating temperature range as defined in Table 5. This is in lieu of all other loading requirements, and is intended to bound the worst-case accelerations of the many load cases described below.

9.3. Operational Load Cases and Camera Orientations

9.3.1. Source Requirements

Camera orientations during normal operation and maintenance are not fully described by higher-level requirements, partly because the standard orientations are self-evident. The optical prescription for the observatory is described in Ref. [11], LSE-11, "LSST Optical Prescription," which obliquely defines the nominally "downward pointing" attitude of the camera. Table 11 defines the explicit requirements listed in higher-level documents, defining the maximum rotation angle of the camera around its boresight axis and the X-axis horizontal attitude of the camera during a filter change.

Table 11: Source requirements defining camera orientations

Operational Load Case and Camera Orientation Source Requirements		
Source Doc.	**I.D.**	**Requirement Text**
[21]: LSE-30, Observatory System Spec	OSS-REQ-0300	The LSST shall be capable of maintaining rotation tracking the duration of a standard visit over a range of angles 90 on either side of a nominal reference with respect to the optical bore sight.
[21]: LSE-30, Observatory System Spec	OSS-REQ-0304	The LSST telescope shall maintain tracking over elevation angles from 15.0 to 86.5 elevation off the horizon

9.3.2. Derivation Analysis

Load cases are derived from the allowed on-telescope orientations of the camera, to include all possible orientations of the camera with respect to gravity. Note that many of these are reproduced during system-level testing, but during handling and at lesser levels of assembly, the camera may be exposed to other loads and orientations, as described in Section 9.5.

To simplify analysis the elevation angle range is extended from 15.0—86.5 degrees to 0.0—90.0 degrees elevation off the horizon, since the small differences in angle have little to no effect on structural loads and deflection. For analysis and assessment of margins, static-pointing 1g accelerations are assumed to be applied in all viable combinations along all three cardinal axes of the camera, as shown in Figure 1. This defines a conservative limit that ensures worst-case stresses and deflections are captured. This captures allowance for the very low level accelerations caused by tracking motion of the telescope, possible residual vibrations from slewing, and low-level accelerations from wind buffeting.

In reality, camera orientations are defined by a uniform 1g gravity vector that is swept over a quarter-sphere phase space. However, there are infinite combinations of angular orientations around the three cardinal axes, and it is often difficult to assess which combination produces the worst-case deflection or stress. Thus, the circumscribed box shown in Figure 1 ensures that the maximum loads are captured—albeit in a conservative enveloping of gravity loads. If this is deemed too conservative for the design of a component, alternate load cases may be developed, using a 1 g vector swept at regular angular intervals through the entire quarter-sphere domain.

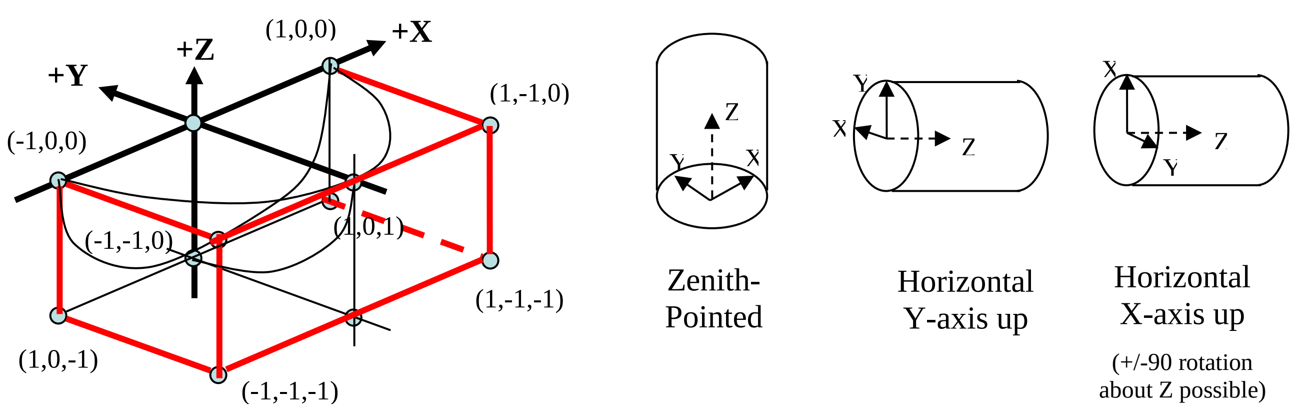

Figure 1: Maximum envelope of operational loads and camera positions

9.3.3. Derived Requirements

Table 12 lists all viable combinations of 1 g accelerations along the camera cardinal axes. The camera and its constituent components must meet all performance requirements when exposed to these static pointing load cases.

Note that the Filter Exchange system must also be able to support a filter while exposed to any combination of loads listed in Table 12 with a filter either in the on-line position or stored in the Carousel. However, the system need only operate while subject to the final four load cases.

Table 12: Camera and subsystem component operational loads worst-case envelope

Operational Load Cases															
Load Case	Camera and Subsystems											Auto Changer, Carousel			Filter Loader
	Op-1	Op-2	Op-3	Op-4	Op-5	Op-6	Op-7	Op-8	Op-9	Op-10	Op-11	Op-12	Op-13	Op-14	Op-15
X	+1.00	+1.00	+1.00	+1.00	+0.00	+0.00	+0.00	-1.00	-1.00	-1.00	-1.00	+0.00	+0.00	+0.00	+0.00
Y	+0.00	+0.00	-1.00	-1.00	+0.00	-1.00	-1.00	+0.00	+0.00	-1.00	-1.00	+0.00	-1.00	-1.00	-1.00
Z	+0.00	-1.00	+0.00	-1.00	-1.00	+0.00	-1.00	+0.00	-1.00	+0.00	-1.00	-1.00	+0.00	-1.00	+0.00

Values are in g's, where 1 g = 9.81 m/sec^2 Orientations are with respect to the Camera Coordinate Systems (CCS)

9.4. Re-Pointing Load Cases

9.4.1. Source Requirements

Camera re-pointing loads are shown in Table 13. These flow to the camera from Ref [12], the Camera-Telescope Mechanical Interface Control Document (ICD). Since the telescope slews to re-point the camera, it is responsible for meeting higher-level visit timing and operations cadence requirements. To do that, it is designed to slew at certain maximum accelerations and speeds, which the camera must be able to tolerate.

Table 13: Source requirements for re-pointing load cases

Re-Pointing Load Case Source Requirements		
Source Doc.	**I.D.**	**Requirement Text**
[12]: LSE-80, Cam-Tel ICD	CA-TS-MEC-ICD-0007	The Camera filter exchange system must be able to fully operate while exposed to the slewing accelerations defined in requirement CA-TS-MEC-ICD-0009
[12]: LSE-80, Cam-Tel ICD	CA-TS-MEC-ICD-0009	The camera shall be able to function normally while the telescope is slewing (including during filter change). The maximum telescope azimuth ac-/de-celeration is 10.5 deg/s^2 and velocity 10.5 deg/s; the maximum telescope elevation ac-/de-celeration is 5.25 deg/s^2 and velocity 5.25 deg/s

9.4.2. Derivation Analysis

Dynamic linear accelerations in the camera can be derived by bounding the slewing and tilting angular motions of the telescope and rotations of the camera. These angular velocities and accelerations translate into linear accelerations in the camera which vary as a function of telescope azimuth angle and location from the center of rotation. Analysis in Ref [13] describes linear accelerations of the camera at various radii and altitude angles for the camera. The phase space of motion, accelerations, and radii is fairly large, then gravity must be included as well. Ref [13] includes all variations, then simplifies the results down to bounding linear accelerations for the camera, most of which turn out to be less than 0.1 g.

Given the relatively small magnitude of these accelerations and to simplify camera structural analyses, the re-pointing accelerations have been boiled down to combinations of this 0.1 g bounding acceleration for different attitudes of the camera with respect to gravity. Furthermore, the angular component of these accelerations around camera axes have been ignored, since their magnitudes are sufficiently small as to be inconsequential.

9.4.3. Derived Requirements

The camera and all its subsystem components must be able to fully function, but not necessarily meet all performance requirements when subjected to the re-pointing loads listed in Table 14. This encompasses the worst-case load envelope due to changes in both the gravity vector and accelerations due to angular velocities and accelerations of the telescope during re-points. The Filter Exchange system mechanisms must also be capable of fully functioning over the full range of motion while subject to these combined accelerations, but only while in an X-axis horizontal orientation, as the load cases define.

Table 14: Combined static and dynamic re-pointing loads

Re-Pointing Load Cases														
	Camera and Subsystems											Exchange System		
Load Case	Repoint-1	Repoint-2	Repoint-3	Repoint-4	Repoint-5	Repoint-6	Repoint-7	Repoint-8	Repoint-9	Repoint-10	Repoint-11	Repoint-12	Repoint-13	Repoint-14
X	+1.10	+1.00	+1.10	+1.10	+0.00	+0.00	+0.00	-1.10	-1.10	-1.10	-1.10	+0.10	+0.10	-0.10
Y	+0.00	+0.00	-1.10	-1.10	+0.00	-1.10	-1.10	+0.00	+0.00	-1.10	-1.10	+0.10	-1.10	-1.10
Z	+0.00	-1.10	+0.00	-1.10	-1.10	+0.00	-1.10	+0.00	-1.10	+0.00	-1.10	-1.10	+0.10	-0.10

Values are in g's, w here 1 g = 9.81 m/sec^2 Orientations are w ith respect to the Camera Coordinate Systems (CCS)

As with the static load cases, if these load combinations are deemed too conservative for the design of a component, alternate load cases may be developed, using a 1.1 g vector swept at regular angular intervals through the entire quarter-sphere domain.

9.5. Integration and Handling Load Cases

9.5.1. Source Requirements

There are no source requirements that drive integration and handling load case requirements. These have been generated based on general handling experiences and the understanding that incidental loading occurs for a variety of reasons and it is prudent to plan for them in the design of components. Such loads could include: crane lift and travel accelerations, small seismic loads, loads from vibrations while moving components, or shock loads from small drops or jarring handling.

9.5.2. Derivation Analysis

A 0.25 g acceleration is intended to bracket all possible loads seen during integration and handling operations. Actual loads are expected to be lower than this, but this provides a worst-case boundary for loads that encompass normal handling as well as unexpected events and accidents like collisions, short drops, and fast stops. The 0.25 g is not based on any empirical or historical experience, and may be reduced if needed. However, any such reduction needs to be accompanied with special handling procedures to ensure that any sensitive parts are suitably isolated from any potentially damaging loading during integration and handling.

9.5.3. Derived Requirements

Table 15 lists the load cases to be used for the design of all camera components and assemblies, as well as lifting and handling fixturing and storage and transport containers. For all components in the cryostat and the full cryostat assembly, all systems must be able to survive the handling loads while the cryostat is evacuated and cold, as well as at room temperature.

Table 15: Camera and component integration and handling load cases

Integration and Handling Load Cases				
Load Case	Handling-1	Handling-2	Handling-3	Handling-4
Transverse	+0.00	+0.00	+0.25	-0.25
Gravity Direction	-1.25	-1.25	-1.25	-1.25
Direction of Motion	+0.25	-0.25	+0.00	+0.00

Values are in g's, where 1 g = 9.81 m/sec^2 Orientations are with respect to the Camera Coordinate Systems (CCS)

Furthermore, subsystems should also identify any additional loading other than these inertial loads that may be applied to their hardware during integration. These include forces and moments due to bolt torquing, forces applied as part of the assembly process, and any temporary forces.

Orientations: note that during integration and handling, subsystem components and assemblies may be oriented in alternate orientations and be exposed to gravity and inertial accelerations not included in Table 15. Subsystems are responsible to identify and analyze any such handling orientations that may define a maximum loading for a component.

Support configurations: note that during integration and handling, both the camera assembly and subsystem components may be supported in configurations with load paths that are not standard for normal camera operations. Subsystems and I&T groups are responsible to identify all such configurations and analyze hardware responses to the load cases defined in Table 15 for each applicable support configuration.

Partial states of integration: note that during camera and component integration, assemblies may be subject to the load cases in Table 15, but in partial states of assembly, or while mounted to assembly fixturing. Subsystem and I&T groups are responsible to identify all such states of partial assembly and analyze the response of both camera hardware and fixturing to the load cases listed.

9.6. Transportation

9.6.1. Source Requirements

There are no source requirements that drive transportation load case requirements. These have been generated based on industry information and military specifications and reports, and are intended to bound worst-case accelerations and shock loads from standard transportation by air and ground.

9.6.2. Derivation Analysis

The static-equivalent acceleration load cases are intended to bound the worst-case dynamic accelerations seen during transport. These are derived from Refs. [14],[15], and [16] which include measured power spectral densities for truck transport on U.S. highways using various military transport vehicles. The acceleration captures 3-sigma events up to 500 Hz, which includes most structure-borne shocks and accelerations. Chilean roads are assumed to be similar to U.S. roads. Air transport loads are enveloped by truck loads. For some military transport aircraft, there is additional high-frequency acoustic energy that is not captured in the static-equivalent acceleration. This is not expected to be an issue with modern, commercial cargo aircraft. If conventional transport loads given in Refs. [14] and [15] are too severe, some relief can be found by transporting equipment on trucks with “Air-Ride” suspensions (see Ref. [16]). These loads are also specified in Table 16.

9.6.3. Derived Requirements

Static-equivalent acceleration load cases shown in Table 16 should be used in developing plans for shipping the camera and its subassemblies. They should be used as the input load for the design of any isolation system, or for analyzing the hardware to be shipped in containers without any shock isolation. Components and shipping containers should be designed to carry this acceleration in any orientation.

Table 16: Camera and component transportation load cases

Transportation Load Cases								
Load Case	Transport-1	Transport-2	Transport-3	Transport-4	Transport-5	Transport-6	Transport-7	Transport-8
Conventional Transport [15]								
Transverse	+0.00	+0.00	+0.61	-0.61	+0.00	+0.00	+0.61	-0.61
Gravity Direction	-4.12	-4.12	-4.12	-4.12	+2.12	+2.12	+2.12	+2.12
Direction of Travel	+2.22	-2.22	+0.00	+0.00	+2.22	-2.22	+0.00	+0.00
Air-Ride Truck Transport Option [16]								
Transverse	+0.00	+0.00	+0.61	-0.61	+0.00	+0.00	+0.61	-0.61
Gravity Direction	-2.00	-2.00	-2.00	-2.00	+0.10	+0.10	+0.10	+0.10
Direction of Travel	+2.22	-2.22	+0.00	+0.00	+2.22	-2.22	+0.00	+0.00

Values are in g's, where 1 g = 9.81 m/sec² Orientations are with respect to the Camera Coordinate Systems (CCS)

[Ref 15]: U.S. Highway Truck Vibration Exposures, MIL-STD-810F, Annex C

[Ref 16]: Singh, J., S. P. Singh, and E. Joneson. “Measurement and Analysis of U.S. Truck Vibration for Leaf Spring and Air Ride Suspensions and Development of Tests to Simulate these Conditions”. Packaging Technology and Science, Volume 19, Issue 6, Pages 309 –323, 2006.

9.7. Seismic

9.7.1. Source Requirements

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. Camera hardware may be exposed to seismic accelerations while in five configurations and locations:

Fixture-mounted at SLAC: completely or partially integrated camera, supported off of integration and test fixtures in the I&T facility at SLAC

Off-telescope hardware base-mounted at SLAC: most support equipment is mounted directly to the facility floor in the I&T facility at SLAC

Telescope-mounted on Cerro Pachon: on-telescope camera hardware in its operational configuration, mounted to the telescope top end assembly

Fixture-mounted on Cerro Pachon: completely or partially integrated camera, supported off of fixtures on the third floor of the summit maintenance facility on Cerro Pachon

Off-telescope hardware on Cerro Pachon: support equipment installed on the second (racks), third (racks and test equipment), or fifth (refrigeration system) floor of the summit maintenance facility on Cerro Pachon

For all camera equipment installed in the I&T facility at SLAC—both that mounted to a fixture and support hardware directly mounted to the foundation—loads are by static-equivalent accelerations, defined in Ref. [17], SLAC-I-720-0A24E-001-R004, “Seismic Design Specification for Buildings, Structures, Equipment, and Systems: 2014,” for a return period of 500 years—equivalent to a 10% probability over 50 years. They include the power spectral density of the peak ground accelerations as well as factoring in the structural response as a function of natural frequency. This bounds the worst-case accelerations for most standard engineering structures with first mode natural frequencies of 5-25 Hz. According to Ref. [17], “inverted-pendulum” structures such as the camera and its sub-assemblies mounted in support fixtures must be designed to survive 0.85 g horizontal ground accelerations simultaneous with 0.5 g and 1.6 g vertical accelerations. The vertical accelerations include gravity—they are equivalent to gravity plus 0.5 g partial down-thrust or 0.6 g up-thrust. All on-camera hardware and base-mounted support equipment should use the values listed in the table, below, unless there is a justifiable and compelling reason to use the lower value.

For all telescope-mounted camera equipment on Cerro Pachon, “Operable,” “Recoverable,” and “Survival” level seismic events are defined in Ref. [1], flowing down from observatory-level requirements for telescope systems. These define the allowed damage level and criteria, while Ref [12], the “Camera—Telescope Mechanical ICD” establishes the seismic loads imparted on the camera for each of these levels of seismic event. Since the camera is mounted to the telescope, seismic loads on the camera are fully defined by the response of the telescope and, thus, are part of the mechanical ICD with the telescope. The derivation of these numbers was done through investigation of site- and region-specific ground acceleration criteria as well as observatory-level dynamic and modal analysis to characterize the magnification of ground accelerations at the telescope top end interface to the camera. This analysis is summarized in Refs. [18] and [19].

For camera components mounted in summit facility rooms either permanently or during servicing, no seismic design accelerations have been flowed to the camera. For these components, then, SLAC seismic design criteria also apply to their installation in the summit facility.

Table 17: Seismic load case source requirements

Source Doc.	I.D.	Requirement Text
[1]: LSE-59, Camera Req's	CAM-REQ-0106	When mounted to the telescope, the Camera shall be designed to operate without any significant damage following an operable-level seismic event, with accelerations as defined in LSE-80, the Camera-Telescope Mechanical ICD, req CA-TS-MEC-ICD-0010. "Significant damage" is defined as any yielding, structural failure, or loss of function that requires more than 40 hours (TBR) to repair after access and initial inspection.
[1]: LSE-59, Camera Req's	CAM-REQ-0107	When mounted to the telescope, the Camera shall be designed to operate without any permanent damage following a recoverable-level seismic event, with accelerations as defined in LSE-80, the Camera-Telescope Mechanical ICD, req CA-TS-MEC-ICD-0028. "Permanent damage" is defined as any damage to optical elements, damage where repair costs are in excess of $4M (TBR), or where repair times are longer than 6 months after access, initial inspection, and damage assessment.
[1]: LSE-59, Camera Req's	CAM-REQ-0108	When mounted to the telescope, the Camera shall be designed to withstand a survival-level seismic event without catastrophic failure, with accelerations as defined in LSE-80, the Camera-Telescope Mech ICD, req CA-TS-MEC-ICD-0029. "Catastrophic failure" is defined as fracture or rupture that allows a significant element to separate and fall, or significantly increases the risk of personnel injury.
[12]: LSE-80, Cam-Tel ICD	CA-TS-MEC-ICD-0010	When mounted to the telescope rotator, the camera shall be designed to withstand without significant damage the seismic operational accelerations of 2.42 g transverse, 0.61 g along the +Z-axis, and 1.44 g along the -Z-axis. These loads are analyzed individually with no additional safety factors
[12]: LSE-80, Cam-Tel ICD	CA-TS-MEC-ICD-0028	When mounted to the telescope rotator, the camera shall be designed to withstand without permanent damage the seismic recoverable accelerations of 3.7 g transverse, 1.17 g along the +Z-axis, and 1.83 g along the -Z-axis. These loads are analyzed individually with no additional safety factors
[12]: LSE-80, Cam-Tel ICD	CA-TS-MEC-ICD-0029	When mounted to the telescope rotator, the camera shall be designed to withstand without catastrophic failure the seismic survival accelerations of 5.7 g transverse, 2.04 g along the +Z-axis, and 2.45 g along the -Z-axis. These loads are analyzed individually with no additional safety factors

9.7.2. Derivation Analysis

Derivation of camera-level seismic design requirements involves combining the damage-tolerance requirements from Ref. [1], the Camera Requirements Document, with the accelerations listed in Ref. [12], the Camera-Telescope Mechanical ICD, then putting them in the context of Camera mechanical design standards and factors of safety as laid out in Ref. [10], LCA-280 "Camera Mechanical Standards."

For on-telescope hardware, all components need to be designed to withstand the operable-level accelerations with no yielding of ductile materials and no structural failure, with a goal of returning to normal operation after short re-verification runs of subsystems. This means that factors of safety for operational seismic conditions should be used, as defined in Ref. [10] and the companion tables in Ref. [22], LCA-10031, "LSST Camera Mechanical Standards: Factors of Safety." These define a scaling of factors of safety depending on the criticality of the component and materials and uses involved, so they apply design conservatism as needed to ensure that recovery after an operational-level earthquake is relatively straightforward.

Components internal to the camera need to be designed to survive and recover from the recoverable-level accelerations with no permanent or large-scale damage. To ensure this, survival-level factors of safety from Ref's [10], and [22] should be used in component design. This ensures that components are designed to ultimate strength or failure point, but with conservatism included to scale for the criticality of the component and uncertainty in material properties or load condition.

While components forming the structural envelope of the camera need to handle the "Recoverable" level of acceleration, they also need to survive the "Survival" level. These much higher levels define the worst-case loading for these elements, with the damage threshold being no fracture, rupture, or separation of components from the integrated camera. Here, survival-level factors of safety are also used, per Ref's [10] and [22], to ensure that key camera structures will not rupture or fail, even though significant yielding or other damage may be incurred.

As discussed in the previous section, components that are not part of the on-telescope assembly must be able to withstand base accelerations equivalent to the SLAC site-specific peak accelerations. This is for both permanently installed equipment as well as temporary installations and configurations of components during I&T at SLAC as well as during maintenance and testing on the summit.

9.7.3. Derived Requirements

The Camera and all subsystem components that form part of the on-telescope camera assembly shall be designed to withstand the "Operable" seismic load cases described in Table 18 with no yielding, structural failure or other damage or loss of function. Loads are to be analyzed individually and not combined. Analysis of these load cases should use the operational-seismic factors of safety described in LCA-280, Mechanical Standards, and LCA-10031, Factors of Safety.

All components internal to the on-telescope camera structural envelope shall be designed to survive the "Recoverable" load cases described in Table 18 with no ultimate or structural failure, damage to optical elements or detector plane integrity, or damage requiring a full subsystem re-build. Loads are to be analyzed individually and not combined. Analysis of these load cases should use the survival-seismic factors of safety described in LCA-280, Mechanical Standards, and LCA-10031, Factors of Safety.

All components that form part of the structural envelope of the on-telescope camera shall be designed to survive the "Survival" load cases described in Table 18 with no ultimate failure, rupture, fracture, or separation of components from the integrated camera. Loads are to be analyzed individually and not combined. Analysis of these load cases should use the survival-seismic factors of safety described in LCA-280, Mechanical Standards, and LCA-10031, Factors of Safety.

During all stages of integration and test and in all standard off-telescope orientations, the Camera, it's sub-assembly components, and all loaded integration and test fixtures shall be designed to withstand the "Off-Telescope" seismic load cases described in Table 18 with no yielding or other damage. Loads are to be applied in the combinations listed, for all expected orientations of the component. Analysis of these load cases should use the operational-seismic factors of safety described in LCA-280, Mechanical Standards, and LCA-10031, Factors of Safety.

All off-telescope camera support hardware, including electronics racks, camera cable runs, and refrigeration system and utilities installations, shall be designed to withstand the "Off-Telescope" seismic load cases described in Table 18 with no yielding or other damage. Loads are to be applied in the combinations listed. Analysis of these load cases should use the operational-seismic factors of safety described in LCA-280, Mechanical Standards, and LCA-10031, Factors of Safety.

Table 18: Camera and component seismic load cases

Load Case	**On-Telescope**			**Off-Telescope**		
	Operable	Recoverable	Survival		Seismic-1	Seismic-2
Transverse	+2.42	+3.70	+5.70	**Transverse**	+0.85	+0.85
+Z-direction	+0.61	+1.17	+2.04	**Vertical**	+1.60	+0.50
-Z-direction	-1.44	-1.83	-2.45			
Referenced to Camera Coordinate System (CCS)				Referenced to gravity and mounting orientation		

Values are in g's, where 1 g = 9.81 m/sec^2

9.8. Limited-Time Seismic Risk Exposure

9.8.1. During Operation and Maintenance

The only exception to using the above seismic load cases is that configurations and orientations of the camera that are transient or temporary need not be designed to these seismic load cases. This includes when hardware is being handled during crane lifts, fixture re-orientation, hardware moving or rolling, and during integration and servicing steps. It also includes the repetitive transient operations of exchanging a filter and swapping out a filter. Note that all other repetitive transient operations must be inherently seismically safe, including opening and closing the shutter, servicing the cryostat, and running the refrigeration system.

Specifically, the analysis below specifies four exceptions to the seismic design criteria listed above:

Filter exchange system hardware does not need to be safe against seismic loads during operation

Camera components may be in a configuration not safe to seismic loading for at most 1 hour during routine maintenance of the Camera.

Camera components may be in a configuration not safe to seismic loading for at most 6 hours during integration or during a standard yearly servicing operation of the Camera.

Planned maintenance activities of the Camera that put it in a seismically unsafe configuration for more than 6 hours must be reviewed and approved.

These values are derived from an initial assumption that such configurations should not add to the probability of damage from an earthquake by more than 20% of the probability during normal operations. As discussed above, the probability of recurrence for the design seismic accelerations is 10% over 50 years. Thus, an additional probability of 2% over 50 years is allowed due to seismically-unsafe integration or maintenance activities.

For purposes of establishing the amount of time the camera can be in seismically unsafe configurations, we first need to define what constitutes an unsafe condition. For reference, all components are designed to be safe under gravity load and all can absorb some minimal level of lateral load with no ill effect—specified as negative margins on any stresses. Handling load cases incorporate a 0.25g lateral load due to incidental handling and bumping, but this seems too large for establishing the definition of a seismically unsafe configuration. Likewise, 0.05g seems too small a value—any configuration should remain stable when exposed to such a small lateral load. Thus, 0.15g seems to be a good compromise for establishing the threshold for the definition of a seismically safe configurations. Graphs of the probability of exceedence at the Cerro Pachon site indicate that the probability of an earthquake with peak ground acceleration (PGA) of 0.15 g is 50% in 50 years. Given our definition of a seismically unsafe configuration, this ground acceleration is the lateral acceleration at which damage may begin to occur for seismically unsafe configurations. Since we have established that we will only accept an incremental increase in risk of 2% over 50 years, then the Camera and its components can only be in an unsafe configuration for 2/50 = 4% of the time. In other words:

Total probability = 12% over 50 years = (10% over 50 years for the camera when in a seismically safe configuration corresponding to the values in Table 18) + (4% of the time)(50% over 50 years for the camera when in a seismically unsafe configuration with respect to a 0.15g lateral acceleration).

This 4% value establishes the total amount of time per annum that the camera can be in a seismically unsafe configuration, which corresponds to 15 days per year.

In summary, during normal operations and maintenance the camera may only be in seismically unsafe configurations for 15 days per year. Filter exchange operations are expected to take a total of 10 days (240 hours) per year, given the design operations plans, so the sum total of all other activities that are seismically unsafe must have a duration of no more than 5 days per year.

To set the scale on the allowed risk exposure time per event, some estimate on the number of operations per year is needed. Classify three durations and frequencies that total to 5 days of total exposure, plus the filter exchange and swap-out durations:

Filter exchange: 90 sec x 14 change / day + 3 hr x 4 swaps / month = 10 days

Short-term: 1 hr duration x 6 times / month = 72 hours = 3 days

Medium-term: 6 hr duration x 4 times / year = 24 hours = 1 day

Long-term: 12 hr duration x 2 time / year = 24 hours = 1 day

This allows for three classes of exposure during operations, maintenance, and more significant work

Routine maintenance: 1 hour max duration

Yearly servicing: 6 hours max duration

Large-scale project: 12 hours max duration

9.8.2. During Integration, Test, and Off-Telescope Servicing

During integration and test and off-telescope servicing, the same 15 days per year holds. However, here the filter exchange system is not operated on its normal cadence. For purposes of scaling the work, we can similarly divide up integration and test activities based on duration:

Short-term: 2 hr duration x 6 times / month = 144 hours = 6 days (e.g.: crane lift, re-configuration of fixture, raft tower insertion)

Medium-term: 8 hr duration x 2 times / month = 192 hours = 8 days (e.g.: re-alignment, moving camera, setting up test configurations)

Long-term: 48 hr duration x 1 time / year = 48 hours = 2 days (e.g.: positioning camera for final testing, final crating of the camera)

Clearly, these are scoping estimates only, but provide some insight into requirements to control our additional risk exposure to seismic hazards during the integration and test process.

9.8.3. Derived Requirements

During routine operations and maintenance (excluding filter changes and swap-outs), the Camera shall not be in a seismically unsafe state for longer than 1 hour without prior approval of the procedure by the operations manager.

During on-telescope troubleshooting and repair, the Camera shall not be in a seismically unsafe state for longer than 6 hours without prior approval of the procedure by the operations manager and camera personnel.

During the integration and test process, components shall not be in a seismically unsafe state for longer than 2 hours without prior approval of the procedure by the I&T manager.

During the integration and test process, Camera components and subassemblies shall be braced against full seismic loads in all steady-state configurations and orientations, defined as a state lasting longer than 8 hours.

During the integration and test process, sub-assemblies and assemblies shall not be in a seismically unsafe state for longer than an 8 hour shift or while unattended without prior approval of the procedure by the Camera Systems Integration Manager or Project Manager.

During the integration and test process, camera assemblies shall not be in a seismically unsafe state for longer than 48 hours.