Requirements Management and Functional Requirements for NGAO

KECK ADAPTIVE OPTICS NOTE 573

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ABSTRACT

This note outlines the requirements management process for the NGAO project. It also discusses the interrelationship between the various NGAO requirements documents and the overall design and devolvement process. The text of the functional requirements is contained as an appendix.

1. Overview of NGAO Development

A standard systems engineering tool for visualizing the development process of a project is the V-diagram. The NGAO V-diagram[1] is shown in Figure 1. The diagram shows the progress of the project from initial concept to completion, with the time axis increasing along the bottom of the diagram. Going down the V, the design of the project becomes progressively more and more defined. The design process proceeds down to a level where the subsystems are ready to be fabricated or purchased at the bottom of the V. The design processes starts with high-level requirements and continues through the system architecture definition. This is followed by the subsystem architecture definition. Next, the design process continues with increasing detail through system design, preliminary design, and ends with detailed design.

As subsystems are completed, they are tested to verify performance. Proceeding up the other side of the V, the subsystems are integrated into a full system progressing towards final testing as a complete scientific facility. Results of the performance verification of each succeeding step are documented to verify compliance with the requirements and as a baseline for determining system health throughout is operational lifetime.

In addition to the stages of project design and construction, Figure 1 also contains the associated documentation that captures the NGAO design. These requirements documents are the focus of the next section. Also shown in Figure 1 are the testing plans associated with each level in the NGAO construction. These documents contain the tests used to verify that the required performance is achieved.

2. Hierarchy of Requirements Documents for NGAO

There are three main NGAO requirements documents:

- The Science Case Requirements Document (SCRD): KAON 455 [1].
- The System Requirements Document (SRD): KAON 456 [2].
- The Functional Requirements Document (FRD): KAON 573 and the NGAO requirements database.

There is a fourth requirements document that is referenced by the SRD. This is the Instrument Baseline Requirements Document (IBRD) KAON 572 [3] which contains Keck Observatory constraints and requirements for any new instrument.

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[1] Although the V-diagram is a standard systems engineering tool, ours was greatly influenced by those made for the TMT. See article at: http://www.tmt.org/newsletter/focus-0710.html.

The requirements development process can be described as follows. The initial NGAO scientific concept was used to generate the NGAO Science Case Requirements Document (SCRD). The SCRD delineates the anticipated scientific gains of NGAO and motivates its constructions.

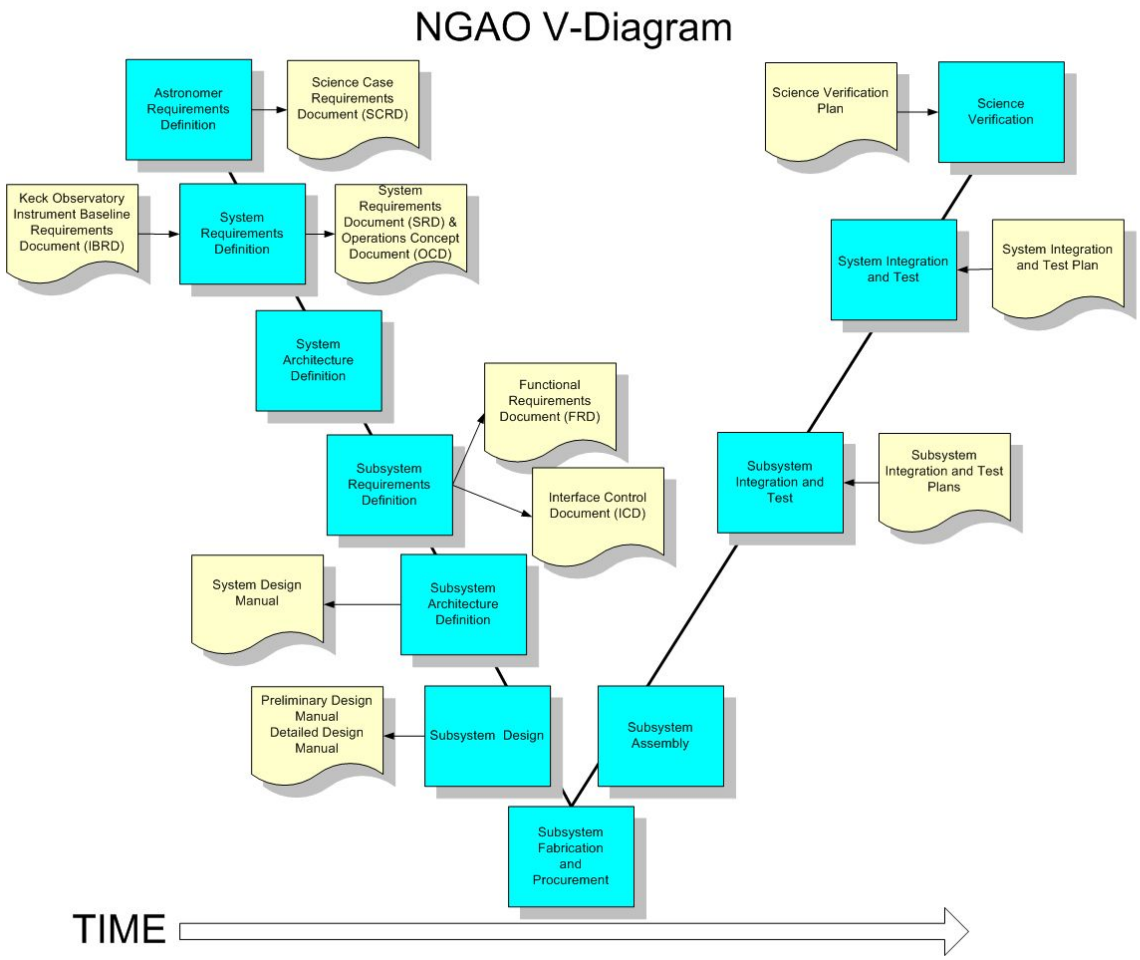

Figure 1: NGAO project V-diagram including the design and development process. Processes are shown in blue and associated documentation in tan.

The implications of these science requirements were then flowed down to requirements on the adaptive optics system and associated instruments. The constraints imposed by the Keck Observatory on new instrumentation are contained in the Instrument Baseline Requirements Document (IBRD). These constraints were also considered along with the science requirements, resulting in the NGAO System Requirements Document (SRD). The science requirements from the SCRD and additional requirements imposed by the Keck Observatory are tabulated in the Overall Requirements section of the System Requirements Document [2]. These overall requirements are then flowed down to discipline-based requirements in the SRD. The requirements document is structured from the common disciplines that make up a typical scientific instrument for observational astronomy.

In the SRD for the NGAO, the disciplines are:

- Optical
- Mechanical
- Electronic/Electrical
- Safety
- Software
- Interface
- Reliability
- Spares
- Service and Maintenance
- Documentation

The SRD, as much as possible, avoids prescribing specific design or implementation solutions as is appropriate before the system architecture is defined.

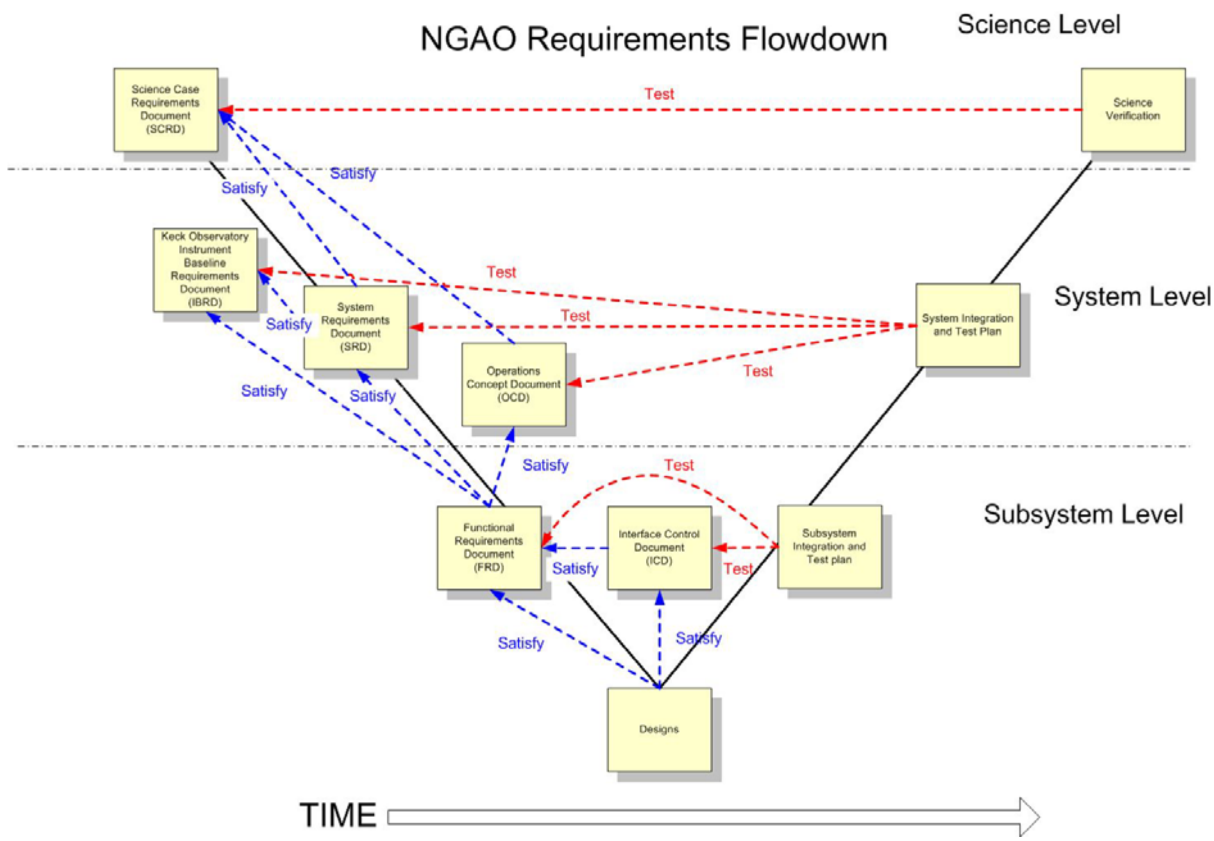

Figure 2: Modified V diagram showing the requirements flowdown and the relationship to testing.

After the system architecture is defined, the Functional Requirements Document is developed. The FRD flows down the requirements from the design-independent SRD to requirements on a few high level subsystems. Note that the flow down of the SRD to the FRD usually entails design choices that could be revisited as the design proceeds. The subsystems were chosen to divide the NGAO system into functions that would be required independent of the selected architecture. These subsystems included the AO system, laser facility, science operations facility and science instruments. The current FRD is consistent with the subdivisions contained in the NGAO System Design phase WBS [4]. For each subsystem there is a breakdown of the requirements by the same engineering disciplines as used in the SRD.

A modified V-diagram is shown in Figure 2; it contains the interrelationship between requirement levels, interface definitions, designs, and the various testing plans. Each requirement must satisfy a higher-level requirement or interface definition, while every test is designed to verify one or more requirements. The FRD provides the criteria against which the subsystems will be evaluated. The SRD provides the criteria against which the NGAO system will be evaluated. The SCRD provides criteria against which the NGAO and its instruments are evaluated.

3. NGAO Requirements Management

The NGAO system design started the configuration management of the SCRD and SRD using word processing tools and the NGAO TWiki page as a means of managing changing versions and traceability between science and system requirements. When the FRD, was started the authors of this KAON came to the realization that the total number of possible requirements and interfaces was likely to be several thousand by the time NGAO and its instruments reached detailed (final) design. Keeping all the levels of systems and subsystem requirements consistent is a large undertaking. One needs to link or relate requirements so that the overall design can be kept logically consistent. Some examples of how the links can be used include:

- Changes in the science (high level) requirements can be traced to effected systems and subsystems (low level) requirements.
- Knowing which low-level requirements satisfy which science requirements can point out over- or under-designed systems.
- Determine how a requirement will be tested.
- Find unassigned or orphaned requirements.

In order to manage the requirements, the authors of this KAON suggested using database software to maintain the requirements. Erik Johansson made a survey of existing requirements management software tools [5] and Contour by Jama Software was selected for a trial evaluation. The results of that trial evaluation are documented in Appendix A: Software Selection for Requirements Management. At present, we continue to use the database to manage the functional requirements. The content of the SCRD and SRD are maintained outside the database but requirements tables from these documents are imported into it.

A short descriptive name and the text of each functional requirement are entered into the database. In addition, the following data is associated with each requirement.

- Why the requirement exists (rationale)
- What requirements are related to it (traceability)
- What reference material supports it (references)How the requirement is checked in the test plan
- Who was the source of the requirement
- Revision history
- Approval status (draft, final, approved, pending, dropped)

4. Status of Requirements

At this time, the Science Case Requirements and System Requirements are fully documented and released [1,2]. They have also been transferred into the database. The first level and lower levels of the Functional Requirements are at various levels of development. The Functional Requirements are being modified to reflect the most recent changes to the NGAO architecture as the design matures in spring 2008. A deliverable of the subsystem design process is revised functional requirements. Checking and modifying the linking of the various requirement levels will follow. The project plans to complete the System Design level functional requirements by May 2008.

A preliminary report of the functional requirements taken from the database is included as Appendix B.

References

1. C. Max, E. McGrath, and P. Wizinowich, “Keck Next Generation Adaptive Optics Science Case Requirements Document,” Keck Adaptive Optics Note 455, release 2.1, version 5, (W. M. Keck Observatory, Kamuela, Hawaii, 2008).
2. D. Gavel, C. Max, E. McGrath, D. Le Mignant, and P. Wizinowich, “Keck Next Generation Adaptive Optics System Requirements Document,” Keck Adaptive Optics Note 456, version 1.17, (W. M. Keck Observatory, Kamuela, Hawaii, 2008).
3. S. Adkins, “Instrument Baseline Requirements Documents”, version 0.1, Keck Adaptive Optics Note 572, (.
4. P. Wizinowich, R. Dekany, D. Gavel, C. Max, S. Adkins, and D. Le Mignant, “Keck Next Generation Adaptive Optics: System Design Phase Systems Engineering Management Plan”, Keck Adaptive Optics Note (KAON) 414, (W. M. Keck Observatory, Kamuela, Hawaii, 2006)
5. E. Johansson, “Requirements Management Software for NGAO”, Keck Adaptive Optics Note 581, (W. M. Keck Observatory, Kamuela, Hawaii, 2008).

Appendix A: Software Selection for Requirements Management

This appendix was originally an NGAO inter-team memo

From: Christopher Neyman
To: NGAO EC and NGAO Team
Date: November 30, 2007

1. Summary and Recommendation

I propose that we purchase a version of Contour starting with the new v2.0 (release date December 2007). We should attempt to use it to the fullest extent possible during the remaining parts of the system design phase of the NGAO project: roughly December 1, 2007- April 1, 2008. As the system design is completed the NGAO team should re-evaluate our requirements management methods as part of planning the next phases of NGAO. At that time, the decision to use Contour should be reevaluated.

2. Current Status of Requirements Management tool Contour by Jama Software:

After evaluation of eight different software tools by Erik Johansson, Contour by Jama Software was selected for installation and a more thorough evaluation by the NGAO team. This evaluation has been ongoing over the past month. The following subset of the NGAO team spent some time reviewing Contour including: Viswa Velur (CIT), Chris Neyman (WMKO), Elizabeth McGrath (UCSC), David Le Mignant (WMKO), and Erik Johansson (WMKO). As far as I am aware other team members were issued accounts but didn’t attempt significant evaluation of the software. Overall, the response to the tool was favorable. It was considered a superior way to collaborate across geographically remote locations as opposed to using MS word and email.

However, we have identified several issues with Contour which include:

- Contour is not compatible with Safari v2.0. Firefox with Mac OS X is a functional work around.
- The glossary can be neither imported nor exported until the Contour 2.0 release (expected December 2007). I created an “NGAO Glossary" report so you can at least output the glossary.
- Two people can edit the same requirement at the same time; there is no check out scheme like other version control software (CVS, Subversion). The software does track all changes and provides an easy

way to view them. However, whoever last saves their edits determine the current document state. This may be fixed in later versions of Contour.

- No provision for version control and multiple links to an attached document, expected to be fixed in early 2008.
- Reports (output from the database) in MS word format generate a Java error, should be fixed in release 2.0 (December 2007). HTML format is a partial work around at the present time.

3. Survey of Practices at TMT and JPL

I have made an informal survey of what software the Thirty Meter Telescope and JPL use for requirements management and what their current methods and practices are at this time.

JPL: source Frank Dekens

Software tools: DOORS by Telelogic.

Comments on scope:
JPL does not have a formal project size threshold, but that is probably because flight projects, which are required to use it, are by definition so large that it is needed. On SIM, for example, has 1200 requirements at just the Instrument level (L3) and the requirements run from L1 (mission science requirements) all the way to L6, which are for example optics wave-front-error requirements, etc.

Methods:
JPL has a 1-day course that teaches people how to use DOORS in the morning, and teaches standards so that the requirements are consistent in the afternoon. When a new project is started templates are made by the people that teach the class, so that makes it easy and standardized. Because of that, the overhead of using DOORS is made smaller. Without the JPL support, Frank had no basis of estimating when the overhead of a software tool like DOORS would become worth the effort.

TMT: sources Mark Sirota and Scott Roberts

Software tools: DOOR by Telelogic.
The TMT project started out using Word for requirements, but in the last couple of months has been using DOORS and finds it very helpful. The major issues that prompted converting to dedicated requirements software are tracking changes to requirements and developing traceability. DOORS is a very useful tool for both of these issues. It is set up to allow you to easily track changes to individual requirements and allows you to baseline a set of requirements at a particular time in the project so that you can always see what the requirements were at a certain milestone in the project. It also includes a relational database and good tools that allow you to add attributes to requirements and to relate them to each other. DOORS is also very good at reading requirements from and outputting to Word and Excel.

Comments on Scope:
TMT has been working hard on requirements for the project for the last year. They have a top level science requirements document which flows down into 3 foundation engineering documents: the Operations Concept Document, the Observatory Requirements Document, and the Observatory Architecture Document. These in turn flow down into subsystem requirement documents, of which they will have about 20, and into approximately 100 interface control documents. In addition to this, they will have test plan documents for each of the subsystems and the integrated system. One of the things that they have been asked to do by their external advisory panel is to show the traceability of requirements from the top level science requirements down to the engineering requirements. By doing this they will be able to show which lower level requirements are related to the top level and visa versa. They believe it will be helpful for engineers, managers, and reviewers to trace through this tree to understand why and how the requirements are related, and to understand the key drivers as to why the requirements are what they are.

Methods:

TMT project current approach with DOORS is to keep it internal to the systems engineering group and to maintain the project requirements in Word. DOORS can also create traceability reports and html pages to allow project staff to view the structure of the requirements. TMT believes that implementing DOORS for the entire staff might be useful, but it would require significant training etc.

Both Scott and Mark commented that DOORS is not a silver bullet. To quote Scott, "it is a good tool if you decide to approach requirements from a formal systems engineering approach. I think this is the crux of the issue, in that a project has to define an approach to requirements before you can proceed with any sort of implementation. In TMT it took a significant amount of effort to define our approach to requirements, and required compromise and understanding of the various viewpoints before we could make progress. Requirements engineering is not an insignificant amount of work to undertake and the approach can result in different amounts of effort being invested. Your project as a whole will need to buy into an approach for it to be successful."

4. Recommendations:

Both surveyed groups (TMT and JPL) are using DOORS by Telelogic and find it to be useful for projects the size of TMT and SIM. All people surveyed mentioned the importance of adopting a team wide process and trying to use as much standardization as possible.

Although DOORS appears to be a superior product to Contour, I do not think we have time learn to use it during the next 3 months of the NGAO project, even if it was purchased today. Therefore, our available choices are using MS word or using Contour for the next 3 months of NGAO requirements management.

In comparison to MS word, the cons for the Contour software are:

- Putting requirements in database requires extra work that was not and is not in NGAO plan
- Support costs at host site for installation and maintenance
- Team is not fully trained to use the tool; this will result in some inefficiency
- Contour is a small company, may not be around in a year
- Several issues with current software; these may be fixed during the next release, but no firm commitment from Jama Software at this time
- Export of requirements with available tools in Contour will likely require additional formatting by a person to produce acceptable final requirements documents for the NGAO system design review

The pros for Contour software are:

- Web based: remote access is essentially instantaneous
- Easier to track change than MS Word
- Links for traceability between requirements
- Useful for checking design against requirements
- Seeing impacts of changes, compliance matrices, test matrices
- Costs compared to other software choices are reasonable for NGAO project
- Support is currently very fast and friendly

I proposed to continue with Contour and then re-evaluate requirements management practices and tools as part of planning for NGAO system design management plan in March of 2008.

Appendix B: Functional Requirements

The following pages list the, data base ID number, WBS number, short name and the description NGAO functional requirements. The query to the database represents the working copy of the NGAO functional requirements database on March 28, 2008. The database will continue to be updated as the project progresses. The other meta-data from the database, such as traceability, was not part of this data query. The ID number is just a unique ID number in the database and is not in numerical order in the report, instead the requirement are organized by functional blocks base on the original system design works breakdown structure (WBS).

AO System Overall

ID	WBS	NAME	DESCRIPTION
FR-1	3.2	Location	The AO system is located on the left Nasmyth platform.
FR-2	3.2	Motion control	For devices that must track paralactic angle changes, the rate of compensation will be consistent with the zenith "dead zone" of the telescope. The Keck telescope's maximum tracking rate in azimuth sets the size of the 'dead zone".
FR-3	3.2	Power consumption	The entire NGAO facility must not exceed a total electrical power requirement of 30 kW
FR-4	3.2	Azimuth cable wrap	Electrical connections between the NGAO systems on the Nasmyth platform to other location in the observatory will be through the azimuth cable wrap.
FR-5	3.2	Downtime	NGAO shall be designed to minimize downtime. The current SRD requires <= 5% of observing time lost to problems and the median time between faults during observing time should be >= 3 hrs
FR-6	3.2	Diagnostics	NGAO will provide built-in diagnostics and be fully operable and maintainable by observatory staff
FR-7	3.2	Operational readiness	The system shall be designed for operation on a TBD basis. The system shall be designed to be deployed at night with TBD hours of preparation for setup and calibration, so that it can support both classical and semi queue scheduled modes. Setup and preparation times: Daytime prep time TBD

			Nighttime setup time TBD Object setup TBD
FR-8	3.2	Spares	TBD pending results of a failure analysis of system.
FR-9	3.2	Maintenance	TBD pending results of a failure analysis of system.
FR-10	3.2	Documentation	Standard documentation provided including: Mechanical drawings, Electrical schematics, Optical design prescription and Optical alignment plan. See full requirements reference in Traceability section
FR-21	3.2	Vibration	AO enclosure, AO relay, and associated system must be consistent with observatory vibration standards. Additional standards for NGAO are TBD
FR-1398	3.2	Non-operating Environment	The Instrument shall meet all of the performance specifications without repair or realignment after being subjected to any number of cycles of any of the non-operating environment conditions defined in Table 5. These represent environments associated with normal non-operating telescope activities including but not limited to storage and handling within the facility and installation and removal from the telescope.

Non-Operating Environment

Parameter	Min.	Typ.	Max.	Units	Notes
Altitude	0	-	4300	m	
Temperature					
Range	-10	0	30	ºC	1
Rate of change	-0.8	-	0.8	ºC/h	
Humidity	0	-	90	%	2
Gravity orientation	-	-1	-	g	3
Vibration	-	-	8.0×10^{-4}	g^2/Hz	4
Shock	-	-	15	g	5
Acceleration					
Due to handling	-	-	-	g	6
Due to seismic activity	-	-	2	g	7

Notes:
1. Typical value is the average annual temperature.
2. Relative, non-condensing.

3. Normal to the earth's surface.
4. 20 Hz to 1000 Hz, 6db/oct drop- off to 2000 Hz.
5. 0.015 second half-sine, all axes.
6. 2 g vertical, 1 g fore/aft, 0.5 g lateral
7. 0.5 Hz to 100Hz, all axes.

FR-1399	3.2	Transporting and Shipping requirement	The Instrument shall continue to meet all of the performance requirements without repair after a single shipment to the delivery location by any combination of air or surface transportation. For information, the expected conditions to be encountered during shipping are given below.

Parameter	Min.	Typ.	Max.	Units	Notes
Altitude	0	-	4,572	m	1
Temperature	-33	-	71	ºC	2, 3
Temperature shock	-54	-	70	ºC	4
Humidity	0	-	100	%	5
Gravity orientation	-	-	-	NA	6
Vibration	-	-	0.015	g^2/Hz	7, 8
Shock	-	-	15	g	9
Acceleration					
Due to transport	-	-	4	g	10
Due to seismic activity	-	-	2	g	11

Notes:
1. See MIL-STD-810F Method 500 §2.3.1.
2. Maximum is for induced conditions, see MIL-STD-810F Method 501 Table 501.4-I.
3. Minimum is for induced conditions, see MIL-STD-810F Method 502 Table 502.4-II.
4. See MIL-STD-810F Method 503.
5. Relative, condensing.
6. Packaged equipment may be subjected to all possible gravity orientations during transportation and shipping.
7. 10 Hz to 40 Hz, -6dB/oct. drop-off to 500 Hz, all axes.
8. See MIL-STD-810F Method 514.
9. 0.015 second half-sine, all axes.
10. All axes.
11. 0.5 Hz to 100Hz, all axes

AO Enclosure

ID	WBS	NAME	DESCRIPTION
FR-14	3.2.2	Cooling	The optical components are enclosed and cooled to -20° C. If needed, parts of the system, such as electronics that do not require a direct interface to the optical path, might be located in nearby housing and kept at a warmer temperature.
FR-15	3.2.2	Input window	There shall be a set of two input windows to the cooled enclosure of the NGAO adaptive optics system.
FR-16	3.2.2	Output window	There shall be an output window to the cooled enclosure. Need for this requirement is TBD. The NGAO reference design has open ports for instruments. Instruments are mounted with gaskets against these ports, and the instrument entrance windows seal NGAO.
FR-17	3.2.2	Size	AO enclosure will be located within the boundary of the already existing Nasmyth platform and will not extend above the roof line of the current AO enclosure.
FR-18	3.2.2	Weight	AO enclosure, AO facility, instruments, and support equipment will not exceed the weight limit of the Keck I and II left Nasmyth platforms.
FR-20	3.2.2	Cooling and waste heat removal	The AO system must not dissipate more than 50 watts of heat into the telescope dome ambient environment. All heat generated by the Instrument in excess of this amount must be carried away by a glycol based cooling system.
FR-22	3.2.2	Instrument handling	The AO enclosure will be equipped with a suitable mechanism for the installation and replacement of instruments. This mechanism could be a crane, cart, or other device.
FR-19	3.2.2	Access requirements	The enclosure and its associated mechanism and optics shall be situated on the Nasmyth platform in such a way so as to not preclude access for routine maintenance of the elevation bearing, elevation wrap, bent Cassegrain platform and mirror cell stairwell.
FR-23	3.2.2	Diagnostics and monitors	The AO enclosure will provide diagnostics and sensors for vibration. (Accelerometers)
FR-24	3.2.2	Diagnostics and monitors	The AO enclosure will provide diagnostics for cooling system flow rate. (Glycol flow)

FR-25	3.2.2	Diagnostics and monitors	The AO enclosure will provide temperature sensors.
FR-26	3.2.2	Diagnostics and monitors	The AO enclosure will provide humidity sensors.
FR-27	3.2.2	Diagnostics and monitors	The AO enclosure will provide particle count monitors and control the cleanliness of the AO environment.
FR-28	3.2.2	Diagnostics and monitors	The AO enclosure will provide video cameras for remote monitoring of the AO enclosure from the summit control rooms and by remote observers (Hawaii and mainland United States).
FR-29	3.2.2	Diagnostics and monitors	The AO enclosure will be able to monitor the background light levels in and around the AO bench.
FR-30	3.2.2	Background light and stray light	Interior: Whenever possible encoders and other electronics will have no visible or IR light sources such as LEDs or optical encoders, etc. inside the optical path of the AO system and instruments. If used optical switches or shaft encoders must be optically baffled or enclosed so that no stray visible or infrared light is emitted into the adaptive optics system and telescope optical path or dome environment. Exterior: NGAO should not produce stray light from LED or lamp indicators, optical switches or optical shaft encoders. LED or lamp indicators should not be used on the exterior of the NGAO enclosure. Any indicators required for service should be concealed behind a cover or access door. Optical switches or shaft encoders must be optically baffled or enclosed so that no stray visible or infrared light is emitted into the telescope optical path or dome environment.

AO Optical-Mechanical, Field Rotation

ID	WBS	NAME	DESCRIPTION
FR-31	3.2.3.1	Input K-mirror	The AO system will have a derotator at the front end of the optical train. It must be located optically upstream of the science instruments, wavefront sensors, and tip/tilt sensors. It is envisioned that this can be accomplished by a K-mirror arrangement.

AO Optical-Mechanical, AO Relay

ID	WBS	NAME	DESCRIPTION
FR-34	3.2.3.2	LOWFS optical interface	A wide field output from the first relay provides an interface for up to 3 NGS low order wavefront sensors (LOWFS)
FR-35	3.2.3.2	Deployable Integral field spectrograph interface	A wide field output from the main relay also directs light into the optical inputs of multiple deployable integral field spectrographs
FR-36	3.2.3.2	High Strehl science instrument interface	A narrow field output from the second relay directs light into one of five instrument stations. The direction of the light into any one of these instrument stations shall not require physically moving any of the instruments.
FR-37	3.2.3.2	Acquisition Camera Interface	The need for and location of an acquisition camera is TBD
FR-38	3.2.3.2	Calibration (Truth) wavefront sensor interface	Location of this sensor is TBD
FR-39	3.2.3.2	NGS wavefront sensor interface	Location of this sensor is behind both optical relays
FR-1362	3.2.3.2	Uplink tip tilt corrector location	Each beacon has its own tip tilt (or a dedicated TT in front of the HOWFS for each beacon?).
FR-1363	3.2.3.2	Uplink AO	Baseline design has no higher order uplink correction.
FR-1366	3.2.3.2	turntable	The LGS WFS module with 9 LGS WFS's shall be mounted on a turn-table.
FR-1510	3.2.3.2	Telescope pupil image tilt, first relay	Pupil tilt, woofer mirror, first relay, shall be less than 25 mm at edge of 100 mm DM
FR-1511	3.2.3.2	Telescope pupil image tilt, second relay	Pupil tilt, tweeter mirror, second relay, shall be less than 6 mm at the edge of 25 mm DM

FR-40	3.2.3.2	First relay field of view	First relay field of view: The first stage of the optical relay will pass a circular unvignetted field of view of 150 arc seconds diameter, without vignetting beams coming from point sources at 80 km altitude. (These fields are referenced to the sky).
FR-41	3.2.3.2	Second relay field of view	The second stage of the relay will pass a circular unvignetted field of view of 20 arc seconds diameter with a goal of 40 arc seconds. (These fields are referenced to the sky)
FR-42	3.2.3.2	Static optical quality of first relay	Static optical quality of first relay: The static optical quality of the first AO relay should be as high as possible over the entire field of view of the AO system. Uncorrectable static aberrations of the AO relay should be no more than 30nm, including chromatic focal shift.
FR-43	3.2.3.2	Static optical quality of second relay	The static optical quality of the second AO relay should be as high as possible over the entire field of view of the AO system. Uncorrectable static aberrations of the AO first and second relays shall be no more than 30 nm, including chromatic focal shift.
FR-46	3.2.3.2	Curvature of output focal plane, first relay	Sufficient to implement deployable integral field spectrograph and low order wave front sensor object selection mechanisms.
FR-47	3.2.3.2	Curvature of output focal plane, second relay	Curvature of output focal plane of the second relay will be known, so that instruments fed by the second relay will compensate, if necessary.
FR-56	3.2.3.2	Pupil image size internal to the first relay	The pupil image size within the first relay will be 100 mm
FR-57	3.2.3.2	Pupil image size internal to the second relay	The pupil image size of the second relay will be 25 mm.
FR-58	3.2.3.2	Output pupil distortion, first relay	The allowable pupil distortions will less than 0.1 %
FR-59	3.2.3.2	Output pupil distortion, entire relay	The combined first and second relay shall provide less than TBD% pupil distortion in the output beam.
FR-61	3.2.3.2	Athermalization, performance at operating temperature	The optical relay shall be able to satisfy its optical requirements at the operating temperature specified for the cooled enclosure, allowing for a variation of plus or minus xxx C. See requirement Cooling(row 9 this spread sheet) for the operating temperature
FR-62	3.2.3.2	Athermalization, performance at dome ambient temperature	Both cooled (-20° C) and ambient temperatures (0° C).
FR-63	3.2.3.2	Alignment	As a goal the alignment of the optical relay should be maintained whenever possible by accurate machining of static fixtures.
FR-64	3.2.3.2	LGS background light in other sensors	Filters, baffles, and selection of dichroics shall be made so as to limit the background light from laser guide stars from entering into other detectors. The background shall be less than TBD mag/arcsec2 at the LOWFS and less than TBD mag/arcsec2 at the visible science instruments.

FR-1490	3.2.3.2	Lateral color, first relay	Lateral color shall be no more than 30 milli arc sec (TBD) for the first relay.
FR-1491	3.2.3.2	Lateral color, second relay	Lateral color shall be no more than (30 milli arc sec) TBD for the second relay.
FR-1495	3.2.3.2	Field distortion, first relay	Field distortion, first relay: The optical distortion shall be calibratable across the field of the first relay
FR-1496	3.2.3.2	Field distortion, second relay	Field distortion, second relay: The optical distortion shall be calibratable across the field of the second relay when used in combination with the first relay.
FR-1497	3.2.3.2	Transmission, first relay	Transmission, first relay: Transmission in the wavelength range XXXnm to YYYnm [IR Science wavebands] will be TBD %. Transmission in the wavelength range XXXnm to YYYnm [Visible Science wavebands] will be TBD % Transmission at the sodium D2 line (~589nm) will be TBD% Transmission in the wavelength range XXXnm to YYYnm [NGS wfs sensing bands] will be TBD %
FR-1498	3.2.3.2	Transmission, second relay	Transmission, second relay: Transmission in the wavelength range XXXnm to YYYnm [IR Science wavebands] will be TBD %. Transmission in the wavelength range XXXnm to YYYnm [Visible Science wavebands] will be TBD %
FR-1499	3.2.3.2	Output focal ratio, first relay	Output focal ratio, first relay: The output focal ratio of the first relay shall be made compatible with the input to the second relay, the inputs to the LOWFS, and the inputs to the units
FR-1500	3.2.3.2	Output focal ratio, second relay	The output focal ratio of the second relay will be > f/40
FR-1501	3.2.3.2	Exit pupil location, entire relay	The output of the AO optical relays will be a telecentric beam (pupil at infinity)
FR-1502	3.2.3.2	Exit pupil location, first relay	The output pupil location of the first relay will be at infinity (i.e. telecentric)
FR-1505	3.2.3.2	Telescope pupil image grid distortion, first relay	Pupil grid distortion on woofer first relay, <0.5%
FR-1506	3.2.3.2	Telescope pupil image grid distortion, second relay	Pupil grid distortion on tweeter, second relay <0.2 %
FR-1507	3.2.3.2	Telescope pupil image aberrations, first relay	Pupil aberration, woofer mirror, first relay: <10% of a subaperture on DM
FR-1508	3.2.3.2	Telescope pupil image aberrations, second relay	Pupil aberration, tweeter mirror, second relay <10% of a subaperture on DM

FR-1509	3.2.3.2	Output pupil distortion, entire relay	Output pupil distortion, entire relay: The combined first and second relay shall provide less than 10% pupil distortion in the output beam.
FR-1512	3.2.3.2	Telescope pupil image tilt, combined relay	Output pupil tilt, entire relay:
FR-32	3.2.3.2	First stage relay	The NGAO AO system shall have a main relay that contains a deformable mirror at an optical conjugate to the telescope pupil
FR-33	3.2.3.2	Second stage relay	A second stage relay with a second deformable mirror located at an optical conjugate to the ground layer. The position of the second stage in the optical train is in series, after the first stage
FR-65	3.2.3.2	No mechanism vignetting of optical beam	Mechanical systems inside and around the AO enclosure will not obscure the optical beam from a 202 arc second transferred field of view from the first relay and a 40 arc second transferred field from the second relay.
FR-1368	3.2.3.2	vibration working	The laser facility shall work through vibration environment up to 1X10^(-5) g^2/Hz
FR-1369	3.2.3.2	vibration maximum	The laser facility shall survive vibration environment up to 8X10^(-4) g^2/Hz
FR-1370	3.2.3.2	impact tolerant	The laser facility shall survive 15g shock environment

AO Optical-Mechanical, Optical Switchyard

ID	WBS	NAME	DESCRIPTION
FR-66	3.2.3.3	Optical interface to multi-object deployable near-IR IFU and LOWFS	There shall be an optically flat dichroic splitter that feeds appropriate bands of infrared light to multi-object deployable near-IR IFU and the LOWFS. Dichroic choices are: Mirror (sends all light to multi-object deployable near-IR IFU and LOWFS) J band only H band only Both J and H bands The dichroic shall maintain optical quality in order to meet wavefront specifications (this spread sheet) along both paths, transmitted and reflected.
FR-67	3.2.3.3	Optical interface to LGS wavefront sensors	There shall be a sodium D2a line reflecting dichroic that sends LGS light to the wavefront sensors. The dichroic shall maintain optical quality in order to meet wavefront specifications 7.2.2.3 along both paths, transmitted and reflected. The dichroic shall pass wavelength range 0.6 to 2.2 microns.
FR-68	3.2.3.3	Optical interface to acquisition camera	Optical interface to acquisition camera is TBD
FR-69	3.2.3.3	Optical interface to truth wavefront sensor	Optical interface to truth wavefront sensor is TBD
FR-70	3.2.3.3	Optical interface to narrow field science instruments	An optically flat mirror shall be used to select the instrument into which the light from the second optical relay shall be directed. The flat shall maintain optical quality in order to meet wavefront specifications 7.2.2.4.
FR-71	3.2.3.3	Motion control	1.The input K mirror must provide image or pupil rotation compensation, which is selectable by the AO control software. 2. A moving optical element will select between the five instruments located at the output of the second stage relay. 3. The atmospheric dispersion compensator will be removable from the second relay. 4. The atmospheric dispersion compensator will be driven based on the telescope elevation and the direction of the Keck zenith on the AO bench. 5. The LGS dichroic will be removable. 6. The LOWFS and multi-object deployable near-IR IFU pickoff will be selectable between one of several optical elements in order to optimize LOWFS performance and scientific instrument throughput.

FR-72	3.2.3.3	Mechanism motions	Speed of mechanism motions is TBD Accuracy of the mechanism motions is TBD

AO Optical-Mechanical, Wavefront Sensor, LGS HO Wavefront Sensors

ID	WBS	NAME	DESCRIPTION
FR-507	3.2.3.5.1	Purpose	The laser guide star (LGS) wavefront sensor (LGSWFS) shall be able to measurement the wavefront using several sodium laser guide stars as reference sources.
FR-508	3.2.3.5.1	LGS configuration	The laser guider star wavefront sensors shall operate in a configuration with one wavefront sensor channel per laser guide star.
FR-509	3.2.3.5.1	Multiple laser guider star operation	The LGS WFS shall support up to 9 laser guide stars. The current NGAO architecture assumes six lasers arranged in a regular pattern or constellation on the sky. Of these lasers, one is located at the center of the field of view and the other five are arranged in a regular pentagon around the central star. The remaining 3 guide stars can be positioned at random around the field of view for AO correction of natural guide stars used in sensing the tip tilt and other low spatial order aberrations.
FR-510	3.2.3.5.1	LGS Wavefront sensor performance	The exact performance level of the LGS wavefront sensor system is TBD
FR-511	3.2.3.5.1	Location	The LGS WFS wavefront sensor will be located at a dedicated output port of the first stage optical relay. The 589 nm light will be separated from the other output ports of the cascaded relay by a dedicated dichroic beamsplitter that reflects 589 nm light
FR-512	3.2.3.5.1	Cooling	The optical components of the LGS wavefront sensor shall be capable of operation at -20° C or must be located on the other side of the optical window that isolates the cooled area of the AO enclosure. If needed, parts of the LGS WFS, such as electronics that do not require a direct interface to the optical path, might be located in nearby housing and kept at a warmer temperature
FR-513	3.2.3.5.1	Laser guide star range related focus correction mechanism	The laser guide star wavefront sensor shall provide a means to focus its sensors on the sodium layer. This mechanism must compensate for slow range changes in the sodium layer distance.
FR-514	3.2.3.5.1	Laser guide star range related focus correction control	This mechanism will be driven by commands from the Calibration WFS and Low order WFS that have been processed by the AO real time control
FR-515	3.2.3.5.1	LGS range related higher order aberration mitigation	The LGSWFS will provide a means (calibration or correction) for range dependent aberrations created by the LGS traveling through the telescope and first stage optical relay at the incorrect optical conjugate (i.e. defocused).
FR-516	3.2.3.5.1	LGS on rotator stage	The laser guide star wavefront sensor will be mounted on a rotating stage in order to track the motion of the LGS spots on the sky.

FR-517	3.2.3.5.1	Type of wavefront sensor and geometry	The LGSWFS will be composed of nine wavefront sensors of a Shack-Hartmann configuration, utilizing square lenslets in a rectangular array.
FR-518	3.2.3.5.1	Pupil sampling	The pupil sampling for the LGS NGS wavefront will have one mode that has 64 subapertures across the Keck (10.949 m) pupil. The pupil sampling for the LGS NGS wavefront will have one mode that has 128 subapertures across the Keck (10.949 m) pupil. Options for other pupil sampling values is a goal, exact values are TBD, but might include 48, 32, and 20 subapertures across the Keck telescope pupil.
FR-519	3.2.3.5.1	Deployable about the field of view	The LGSWFS will be able to make measurements on any LGS that is in the field of view passed by the first stage of the Cascaded Relay.
FR-520	3.2.3.5.1	Elevation distance	The LGSWFS will meet its performance goals at elevations of 30 degrees and higher. Requirement for differential atmospheric refraction compensation (DAR) is TBD.
FR-521	3.2.3.5.1	LGS uplink tip tilt compensation	The LGS wavefront sensor must provide a measurement of the LGS full aperture tilt for driving the LGS tip tilt control loop. This is often referred to as uplink tip tilt compensation.
FR-522	3.2.3.5.1	Natural guide star mode	As a goal, the channels of the LGSWFS will be able to sense light from natural guide stars for testing purposes. There is no requirement on minimum NGS brightness. There is no requirement on measurements from multiple natural guide stars simultaneously.
FR-542	3.2.3.5.1	Mechanism controller	As determined from the optical design, the LGS WFS will provide a means of controlling all mechanisms inside the WFS subsystem. This controller may or may not be common to the rest of the NGAO system.
FR-543	3.2.3.5.1	CCD requirements	The exact requirements on CCD pixel size, dark current, read noise, and quantum efficiency are TBD at this time.
FR-1526	3.2.3.5.1	Acquisition accuracy	Acquisition accuracy of the LGS WFS shall be better than a 100 mili arc seconds
FR-1527	3.2.3.5.1	Dither accuracy	The LGS asterism must be counter dithered when the laser follows the source to 100 mili arc seconds accuracy (To Be Confirmed)
FR-523	3.2.3.5.1	Wavelength of operation	The LGSWFS will be optimized to work with light from the sodium D2a line.
FR-524	3.2.3.5.1	Transmission	The LGS wavefront sensor transmission should be optimized for the D2a line as much as possible. See overall transmission requirements
FR-525	3.2.3.5.1	Focus	The LGSWFS optics must reimage the DM onto the LGSWFS lenslets to an accuracy of TBD mm in focus.
FR-526	3.2.3.5.1	Registration	The LGSWFS optics must register the DM actuators onto the LGSWFS lenslets to an accuracy of TBD % of a subaperture.

FR-527	3.2.3.5.1	Lenslet size	The LGSWFS shall have lenslets corresponding to 0.171 m on the telescope primary mirror.
FR-528	3.2.3.5.1	Lenslet size	The LGSWFS shall have lenslets corresponding to 0.0855 m on the telescope primary mirror.
FR-529	3.2.3.5.1	Plate scale	The LGSWFS shall provide a plate scale of TBD arc sec/pixel.
FR-530	3.2.3.5.1	Pixels per subaperture	The LGSWFS shall provide TBD pixels per subaperture.
FR-531	3.2.3.5.1	Field stops	The LGSWFS shall provide spatial filtering with field stops.
FR-532	3.2.3.5.1	Input focal ratio	The optical input to the Laser guider star wavefront sensor will be from the first stage of the Cascaded Relay.
FR-533	3.2.3.5.1	Static calibration errors	The static wavefront calibration errors are TBD
FR-534	3.2.3.5.1	Pupil distortion	The level of pupil distortion on the lenslet array is TBD.
FR-535	3.2.3.5.1	WFS dynamic range	The dynamic range of the wavefront sensor is TBD.
FR-536	3.2.3.5.1	Athermalization	The optical relay shall be able to satisfy its optical requirements at both cooled (-20° C) and ambient temperatures (0° C).
FR-537	3.2.3.5.1	CCD window	Flatness, wedge and AR coating requirements.
FR-538	3.2.3.5.1	Packaging	The optics, mechanisms, and electronics of the LGS WFS will be compatible with the AO enclosure and main optical relays
FR-539	3.2.3.5.1	Mechanisms	The LGSWFS will have mechanisms for the exchange of optics for the purpose of configuring the pupil sampling and dynamic range (plate scale). Control of these mechanisms will under direction of the AO non-real time control software.
FR-540	3.2.3.5.1	Mechanism motions	Number and type of mechanisms is TBD. Speed of mechanism motions is TBD. Accuracy of the mechanism motions is TBD. Focus tracking accuracy is TBD.

FR-541	3.2.3.5.1	No mechanism vignetting of optical beam	Mechanical systems inside and around the AO enclosure will not obscure the optical beam from a 202 arc second transferred field of view from the first relay and a 40 arc second transferred field of view from the second relay.
FR-544	3.2.3.5.1	Mechanism control software	The mechanism control software for the LGS WFS will be part of AO non real-time control system
FR-545	3.2.3.5.1	Real time control	The focal plane arrays that are part of the LGS WFS will have a means to be externally controlled and send pixel data streams to the AO system RTC
FR-546	3.2.3.5.1	Interface to AO non real-time control	The mechanism control and other status information (temperate, humidity, etc.) will be reported to the AO non real-time control system. The input optical pickoff will be controlled by the AO non real-time control system.
FR-547	3.2.3.5.1	Interface to AO acquisition system	The LGSWFS will interface to the AO acquisition system, the subsystem of the AO control software that is responsible for coordinating this task between AO subsystems, and the telescopes.
FR-548	3.2.3.5.1	Interface to AO real-time control system	The LGS WFS will be interfaced to the AO real-time control system. The AO RTC will be able to set the readout rate and other parameters of the detector focal plane. The pixel data from the focal plane will be interface to the RTC for the purpose of reconstruction the wavefront. The mechanism and optics for LGS focus and higher order aberration correction will interface with the AO RTC for control commands.

AO Optical-Mechanical, Wavefront Sensor, NGS HO Wavefront Sensors

ID	WBS	NAME	DESCRIPTION
FR-126	3.2.3.5.2	Cooling	The optical components of the NGS wavefront sensor are located inside the AO enclosure, which will be cooled to -20 C (see KAON 501). If needed, parts of the NGS WFS, such as electronics that do not require a direct interface to the optical path, might be located in nearby housing and kept at a warmer temperature.
FR-127	3.2.3.5.2	Deployable about the field of view	The NGS WFS will be able to make measurements on any star that is the field of view passed by the second stage of the Cascaded Relay.
FR-128	3.2.3.5.2	Elevation distance	The NGS WFS will meet its performance goals at elevations of 30 degrees and higher. Requirement for atmospheric dispersion compensation (ADC) and differential atmospheric refraction are TBD.
FR-130	3.2.3.5.2	Pupil sampling	The pupil sampling for the NGS wavefront will have one mode that has 64 subapertures across the Keck (10.949 m) pupil. Options for other pupil sampling values is a goal, exact values are TBD, but might include 32 and 20 subapertures across the Keck telescope pupil.

FR-131	3.2.3.5.2	Solar system objects	The NGS wavefront sensor shall be capable of wavefront correction on solar system objects that are 4" in diameter or less. Correction on these large objects is at a TBD level.
FR-132	3.2.3.5.2	Single NGS mode	The NGS wavefront sensor shall provide the capability to perform "classical" single natural guide star AO observations
FR-133	3.2.3.5.2	Type of sensor and geometry	The NGS WFS will be of a Shack-Hartmann configuration, utilizing square lenslets in a rectangular array.
FR-134	3.2.3.5.2	Wavefront sensor performance	The exact performance level of the NGS wavefront sensor system is TBD.
FR-149	3.2.3.5.2	CCD requirements	The exact requirements on CCD pixel size, dark current, read noise, and quantum efficiency are TBD at this time.
FR-150	3.2.3.5.2	Focal plane array control	The basic readout function the NGS WFS focal plane will be controlled by a set of dedicated electronics. These electronics will interface to the AO RTC system.
FR-151	3.2.3.5.2	Mechanism controller	As determined from the optical design, the NGS WFS will provide a means of controlling all mechanisms inside the WFS subsystem. This controller may or may not be common to the rest of the NGAO system.
FR-129	3.2.3.5.2	Location	The NGS wavefront sensor will be located at the back of the high Strehl relay (OAP4), before the narrow field science instruments.
FR-135	3.2.3.5.2	Athermalization	The optical relay shall be able to satisfy its optical requirements at both cooled (-20 C) and ambient temperatures (0 C).
FR-136	3.2.3.5.2	Input focal ratio	The optical input to the NGS wavefront sensor will be from the second stage of the cascaded relay.
FR-137	3.2.3.5.2	Pupil distortion	The level of pupil distortion on the lenslet array is TBD.
FR-138	3.2.3.5.2	Static calibration errors	The static wavefront calibration errors are TBD.
FR-139	3.2.3.5.2	Transmission	The transmission is TBD %.
FR-140	3.2.3.5.2	Wavelength of operation	The exact wavelength range of operation is TBD. At present the architecture assumes that it is from 0.6 microns to 1.0 micron (the wavelength range between the sodium line and the response cutoff of silicon charge coupled devices).

FR-141	3.2.3.5.2	WFS dynamic range	The dynamic range of the wavefront sensor is TBD.
FR-142	3.2.3.5.2	Mechanism motions	a) Number and type of mechanisms is TBD. b) Speed of mechanism motions is TBD. c) Accuracy of the mechanism motions is TBD.
FR-143	3.2.3.5.2	Mechanisms	As needed the NGS WFS will have mechanisms for the exchange of optics to enable configuration of pupil sampling and dynamic range (plate scale). The AO non real-time control software will be used to control these mechanisms.
FR-144	3.2.3.5.2	Motion control	Requirements on motion control aspects of the NGS WFS are dependent on the detailed optical design of the wavefront sensor that is not completed at this time.
FR-145	3.2.3.5.2	No mechanism vignetting of optical beam	Mechanical systems inside and around the AO enclosure will not obscure the optical beam from a 202 arc second transferred field of view from the first relay and a 40 arc second transferred field from the second relay.
FR-146	3.2.3.5.2	Packaging	The optics, mechanisms, and electronics of the NGS WFS will be compatible with the AO enclosure and main optical relays
FR-147	3.2.3.5.2	Thermal	The NGS WFS shall have a method for removal of waste heat from its mechanisms and electronics located inside the AO enclosure. This should be part of an overall cooling design for the AO enclosure.
FR-148	3.2.3.5.2	Vibration	The NGS WFS, its mechanisms, and associated system must be consistent with observatory vibration standards. Additional standards for NGSO are TBD.
FR-152	3.2.3.5.2	Mechanism control software	The mechanism control software for the NGS WFS will be part of AO non real-time control system.
FR-153	3.2.3.5.2	Real-time control	The focal plane arrays that are part of the NGS WFS will have a means to be externally controlled and send pixel data streams to the AO real-time control system
FR-154	3.2.3.5.2	Interface to AO acquisition system	The NGS WFS will interface to the AO acquisition system, the subsystem of the AO non real-time control software that is responsible for coordinating this task between AO subsystems, and the telescopes.
FR-155	3.2.3.5.2	Interface to AO non real-time control	The mechanism control and other status information (temperate, humidity etc.) will be reported to the AO non real-time control system. The input optical pickoff will be controlled by the AO non real-time control system.
FR-156	3.2.3.5.2	Interface to AO real-time control system	The NGS WFS will be interfaced to the AO real-time control system. The AO RTC will be able to set the readout rate and other parameters of the detector focal plane. The pixel data from the focal plane will interface to the RTC for the purpose of reconstructing the wavefront.

AO Optical-Mechanical, Wavefront Sensor, NGS Low Order Wavefront Sensors

ID	WBS	NAME	DESCRIPTION
FR-157	3.2.3.5.3	Cooling	1. The LOWFS assembly shall work in an ambient temperature of -20 C. 2. The temperature of the region after the cold stop shall be -xx C
FR-158	3.2.3.5.3	Cooling of LOWFS detectors	The detector shall be maintained at -xxx C by means of active cooling
FR-159	3.2.3.5.3	Deployable about the field of view	1. Each of the three LOWFS channel shall have the ability to pick off stars anywhere in the field. 2. The minimum separation between two stars that the channels (LOWFS or PSF cam) inside the LOWFS assembly shall be x arc seconds.
FR-160	3.2.3.5.3	Elevation distance	The LOWFS will meet its performance goals at elevations of greater than 30 degrees. Requirement for atmospheric dispersion compensation (ADC) is TBD.
FR-161	3.2.3.5.3	Functionality	The low order wavefront sensor will provide the ability to measure tip tilt and other low order aberrations from natural guide stars.
FR-163	3.2.3.5.3	MOAO correction	1. Each LOWFS channel shall have a MEMS DM on a TT stage. 2. The Low-order WFS channels shall support MOAO (and MCAO?) operations.
FR-164	3.2.3.5.3	Modes of operation	The low order wavefront sensor will be capable of working with the LGS and NGS modes of NGAO
FR-165	3.2.3.5.3	Number of NGS guide stars	1. There LOWFS assembly shall be able to pick off 3 NGSs for wavefront sensing. 2. Each LOWFS channel shall be able to pick off any star in the FoR; provided they are separated by xx arc seconds.
FR-166	3.2.3.5.3	Pupil sampling	LOWFS tracking (tip-tilt) channels will have one subaperture. The TTFA sensor will have 2 x 2 subapertures in a rectangular array.
FR-167	3.2.3.5.3	Tracking and wavefront sensor performance	The exact performance level of the LOWFS system is TBD.

FR-168	3.2.3.5.3	Tracking on extended objects	1. The LOWFS channels shall be able to guide on partially resolved objects. 2. The LOWFS shall be able to guide on extended objects off size less than 100" (TBC)
FR-169	3.2.3.5.3	Type of sensor and geometry	1. The TT channels are quad-cell in nature. 2. The TTFA is a 2x2 Shack-Hartmann WFS.
FR-184	3.2.3.5.3	Detector requirements	The exact requirements on detector, type, number of pixels, pixel size, dark current, read noise, and quantum efficiency are TBD at this time. The exact wavelength range of operation is TBD. At present, the architecture assumes that it is the J and H near infrared bands. These filter bands roughly cover the atmospheric transmission windows between 1.0 microns to 1.8 micron. The design should not preclude tracking in the K band (2.0-2.5 microns) at reduced performance caused by the higher background.
FR-185	3.2.3.5.3	Focal plane array control	The basic readout functions of the LOWFS detectors will be controlled by a set of dedicated electronics. These electronics will interface to the AO real-time control system
FR-186	3.2.3.5.3	Mechanism controller	As determined from the optical design, the LOWFS will provide a means of controlling all mechanism inside the LOWFS subsystem. This controller may or may not be common to the rest of the NGAO system.
FR-1528	3.2.3.5.3	Acquisition accuracy	LOWFS acquisition accuracy shall be 70 mas (TBC) .
FR-1529	3.2.3.5.3	Dithering (on-chip)	LOWFS on-chip dither requirement: max. dither shall be 3 arcsecs with an accuracy of 0.5 lambda/D.
FR-1530	3.2.3.5.3	Dithering (off-chip)	LOWFS requirement for off-chip dithering: max. dither shall be 15" (TBC).
FR-1531	3.2.3.5.3	Position knowledge	The LOWFS channel shall have position knowledge of 0.1 lambda/D (TBC) or better.
FR-1532	3.2.3.5.3	Dither overhead	Any dither shall be performed in less than 3 seconds.
FR-1533	3.2.3.5.3	Non-sidereal tracking	The LOWFS shall be able to track non-sidereal sources
FR-1535	3.2.3.5.3	Description	There shall be 2 TT and 1 TTFA sensors that comprise the LOWFS WFS for NGAO.
FR-162	3.2.3.5.3	Location	The LOWFS shall be fed by the beam from the first AO relay with a 150" FoV.

FR-170	3.2.3.5.3	Athermalization	The optical relay shall be able to satisfy its optical requirements at both cooled (-20 C) and ambient temperatures (0 C).
FR-171	3.2.3.5.3	Input focal ratio	The input f# to the the LOWFS assembly shall be 13.66
FR-172	3.2.3.5.3	Pupil distortion	The level of pupil distortion on the lenslet array is TBD.
FR-173	3.2.3.5.3	Static calibration errors	The static wavefront calibration errors are TBD.
FR-174	3.2.3.5.3	Transmission	The transmission will be TBD %.
FR-175	3.2.3.5.3	Wavelength of operation	1. The LOWFS WFS shall work in J and H bands (1.16-1.77 um) - to be confirmed. 2. The LOWFS WFS design shall not preclude K band operation.
FR-176	3.2.3.5.3	WFS dynamic range	The dynamic range of the wavefront sensor is TBD.
FR-1534	3.2.3.5.3	Atmospheric dispersion	The residual atmospheric dispersion between the science image and the TT(FA) sensors should be compensated by the LOWFS to better than TBD mili arc seconds.
FR-178	3.2.3.5.3	Mechanisms	As needed the LO WFS will have mechanisms for the exchange of optics that enable configuration of pupil sampling and dynamic range (plate scale). AO non-real time control software will direct these mechanisms.
FR-179	3.2.3.5.3	Motion control	Requirements on motion control aspects of the low order WFS are dependent on the detailed optical design of the wavefront sensor which is not completed at this time.
FR-180	3.2.3.5.3	No mechanism vignetting of optical beam	Mechanical systems inside and around the AO enclosure will not obscure the optical beam from a 180 arc second transferred field of view from the first relay and a 40 arc second transferred field of view from the second relay.
FR-181	3.2.3.5.3	Packaging	The optics, mechanisms, and electronics of the LOWFS will be compatible with the AO enclosure and main optical relays (see section 7.2).
FR-182	3.2.3.5.3	Thermal	The LOWFS shall have a method for removal of waste heat from its mechanisms and electronics located inside the AO enclosure. This should be part of an overall cooling design for the AO enclosure.
FR-183	3.2.3.5.3	Vibration	LOWFS, its mechanisms, and associated system must be consistent with observatory vibration standards. Additional standards for NGAO are TBD.

FR-187	3.2.3.5.3	Mechanism control software	The mechanism control software for the LOWFS will be part of AO non real-time control system
FR-188	3.2.3.5.3	Real-time control	The detectors that are part of the LOWFS will have a means to be externally controlled by the AO RTC. The LOWFS detectors will send pixel data streams to the AO RTC.
FR-189	3.2.3.5.3	Interface to AO acquisition system	The LOWFS will interface to the AO acquisition system, the subsystem of the AO control software that is responsible for coordinating this task between AO subsystems, and the telescopes.
FR-190	3.2.3.5.3	Interface to AO non real-time control	The mechanism control and other status information (temperate, humidity, etc.) will be reported to the AO non real-time control system. Tracking of the input optical pickoffs will be controlled by the AO non real-time control system.
FR-191	3.2.3.5.3	Interface to AO real-time control system	The LOWFS will be interfaced to the AO real-time control system. The AO RTC will be able to set the readout rate and other parameters of the detector focal plane. The pixel data from the focal plane will be interfaced to the RTC for the purpose of reconstruction of the wavefront. The position of the LOWFS will be communicated to the RTC for purposes of calculating the LOWFS wavefront correction. The LOWFS deformable mirror will interface to the AO RTC.

AO Optical-Mechanical, Wavefront Sensors, Calibration or Truth Wavefront Sensors

ID	WBS	NAME	DESCRIPTION
FR-192	3.2.3.5.4	Cooling	The optical components of the NGS wavefront sensor are located inside the AO enclosure, which will be cooled to -20 C (see KAON 501). If needed, parts of the TWFS, such as electronics that do not require a direct interface to the optical path, might be located in nearby housing and kept at a warmer temperature.
FR-193	3.2.3.5.4	Deployable about the field of view	The TWFS will be able to make measurement on any start that is the field of view passed by the first stage of the Cascade Relay.
FR-195	3.2.3.5.4	Pupil sampling	The pupil sampling for the TWFS wavefront will have one mode that has five subapertures across the Keck (10.949 m) pupil. Options for other pupil sampling values are a goal. Exact values are TBD, but might include 10 and 20 subapertures across the Keck telescope pupil.
FR-196	3.2.3.5.4	Functionality	The truth wave front sensor is used to calibrate biases that arise when using LGS in an adaptive optics system. The biases are principally caused by the elongated nature of the LGS when views by subapertures of the laser guide star wavefront sensor and the changing sodium layer density profile. The TWFS measures these biases by sensing the wavefront from a natural star located in the large field of the first optical relay. These biases are slowly varying and of low spatial order. As such a natural guide star WFS using long exposures and only measuring the lowest spatial wavefront error is sufficient
FR-197	3.2.3.5.4	Type of sensor and geometry	The TWFS will be of a Shack-Hartmann configuration, utilizing square lenslets in a rectangular array.
FR-198	3.2.3.5.4	Wavefront sensor performance	The exact performance level of the NGS wavefront sensor system is TBD.
FR-212	3.2.3.5.4	Detector requirements	The exact requirements on detector, type, number of pixels, pixel size, dark current, read noise, and quantum efficiency are TBD at this time. The exact wavelength range of operation is TBD. At present the architecture assumes that it is in the range of 0.6-1.0 microns.
FR-213	3.2.3.5.4	Focal plane array control	The basic readout functions of the TWFS detector will be controlled by a set of dedicated electronics. These electronics will interface to the AO RTC system
FR-214	3.2.3.5.4	Mechanism controller	As determined from the optical design, the TWFS will provide a means of controlling all mechanisms inside the TWFS subsystem. This controller may or may not be common to the rest of the NGAO system.

FR-194	3.2.3.5.4	Location	The TWFS wavefront sensor will be located after the first stage optical relay. The exact pickoff mechanism is TBD.
FR-199	3.2.3.5.4	Athermalization	The optical relay shall be able to satisfy its optical requirements at both cooled (-20 C) and ambient temperatures (0 C).
FR-200	3.2.3.5.4	Input focal ratio	The optical input to the truth wavefront sensor will be from the first stage of the cascaded relay.
FR-201	3.2.3.5.4	Pupil distortion	The level of pupil distortion on the lenslet array is TBD.
FR-202	3.2.3.5.4	Static calibration errors	The static wavefront calibration errors are TBD.
FR-203	3.2.3.5.4	Transmission	The transmission will be TBD %
FR-204	3.2.3.5.4	Wavelength of operation	The exact wavelength range of operation is TBD. At present, the architecture assumes that it is from 0.6 microns to 1.0 micron (the wavelength range between the sodium line and the response cutoff of silicon charge coupled devices).
FR-205	3.2.3.5.4	WFS dynamic range	The dynamic range of the wavefront sensor is TBD.
FR-206	3.2.3.5.4	Mechanism motions	a) Number and type of mechanisms are TBD. b) Speed of mechanism motions is TBD. c) Accuracy of the mechanism motions is TBD.
FR-207	3.2.3.5.4	Motion control	Requirements on other motion control aspects of the TWFS are dependent on the detailed optical design of the wavefront sensor which is not completed at this time.
FR-208	3.2.3.5.4	No mechanism vignetting of optical beam	Mechanical systems inside and around the AO enclosure will not obscure the optical beam from a 180 arc second transferred field of view from the first relay and a 40 arc second transferred field of view from the second relay.
FR-209	3.2.3.5.4	Packaging	The optics, mechanisms, and electronics of the TWFS will be compatible with the AO enclosure and main optical relays.
FR-210	3.2.3.5.4	Thermal	The TWFS shall have a method for removal of waste heat from its mechanisms and electronics located inside the AO enclosure. This should be part of an overall cooling design for the AO enclosure.
FR-211	3.2.3.5.4	Vibration	TWFS, its mechanisms, and associated system must be consistent with observatory vibration standards. Additional standards for NGAO are TBD.

FR-215	3.2.3.5.4	Mechanism control software	The mechanism control software for the TWFS will be part of AO non real-time control system
FR-216	3.2.3.5.4	Real-time control	The detectors that are part of the TWFS will have a means to be externally controlled and send pixel data streams to the AO system RTC.
FR-217	3.2.3.5.4	Interface to AO acquisition system	The TWFS will interface to the AO acquisition system, the subsystem of the AO control software that is responsible for coordinating this task between AO subsystems and the telescopes
FR-218	3.2.3.5.4	Interface to AO non real-time control	The mechanism control and other status information (temperate, humidity, etc.) will be reported to the AO non real-time control system. The input optical pickoff will be controlled by the AO non real-time control system.
FR-219	3.2.3.5.4	Interface to AO real-time control system	The TWFS will be interfaced to the AO real-time control system. The AO RTC will be able to set the readout rate and other parameters of the detector focal plane. The pixel data from the focal plane will be interfaced to the RTC for the purpose of reconstruction of the wavefront

AO Optical-Mechanical, Wavefront Correctors

ID	WBS	NAME	DESCRIPTION
FR-483	3.2.3.6	Method of AO correction	AO correction for both tip tilt and higher order aberrations will be provided by a single optical surface.
FR-484	3.2.3.6	Actuators across telescope pupil	a) The first stage corrector will have 20 actuators across the relayed pupil of the Keck telescope for the corrections of higher order aberrations. b) The second stage of the cascaded relay (the high Strehl stage) correctors will have 64 actuators across the Keck telescope pupil. c) The LOWFS correctors will have 32 actuators across the Keck telescope pupil. d) The multi-object deployable near-IR IFU corrector will have 64 actuators across the Keck telescope pupil. For the purposes of this requirement, the pupil of the Keck telescope is 10.949 meters in diameter. This represents a circle that contains (circumscribes) all 36 hexagonal segments.
FR-501	3.2.3.6	Power supply	A power supply will be provided to drive all AO corrector actuators
FR-502	3.2.3.6	Input signal and # channel	These requirements are TBD
FR-503	3.2.3.6	Cut-off frequency	The cut-off frequency for driving all AO correctors is TBD
FR-504	3.2.3.6	Phase-shift	The phase shift for driving all AO correctors is TBD
FR-485	3.2.3.6	Pupil diameter	a) The pupil diameter for the first stage corrector in the cascaded relay will be consistent will a pupil diameter of 100 mm corresponding to 10.949 m at the telescope primary mirror. b) The pupil diameter for second stage correctors, the LOWFS correctors and the multi-object deployable near-IR IFU correctors will be 25.6 mm corresponding to 10.949 m at the telescope primary mirror.
FR-486	3.2.3.6	Optical quality	The optical quality for the AO correctors is TBD
FR-487	3.2.3.6	Stroke to flatten	The optical quality of the mirror should be high enough that only TBD % of the total mechanical motion of the mirror surface is needed to produce an optical surface that meets the optical quality specification above (see requirements in row 11)

FR-488 3.2.3.6	Correction residual during closed loop operation	The correction residual during closed loop operation will be TBD nm of optical aberration
FR-489 3.2.3.6	Surface roughness	The optical quality for the AO correctors is TBD.
FR-490 3.2.3.6	Reflectivity	The reflectivity of the AO correctors should be as high as possible for wavelength between 0.5-14 microns.
FR-491 3.2.3.6	Actuator Pitch	a) The actuator pitch for deformable mirrors in the two main relays will be commensurate with the required number of actuators across the pupil and the size of the pupil image determined from the design of the optical relay for the first and second stage correctors. These are currently 5 mm and 0.4 mm b) The actuator pitch for deformable mirrors in the LOWFS relay will be commensurate with the required number of actuators across the pupil and the size of the pupil image determined from the design of the first stage of the optical relay and the internal pupil relay of each LOWFS channel. These are currently set at 0.8 mm c) The actuator pitch for deformable mirrors in the multi-object deployable near-IR IFU relay will be commensurate with the required number of actuators across the pupil and the size of the pupil image determined from the design of the first stage of the optical relay and the internal pupil relay of each multi-object deployable near-IR IFU channel. These are currently set at 0.4 mm
FR-492 3.2.3.6	Actuator Geometry	The actuators will be arranged in a square geometry. A sufficient number of actuators will be provided such that at least one ring of “guard band” actuators will be outside the clear aperture of an effective 11m circular telescope pupil.
FR-493 3.2.3.6	Actuator Stroke	a) The actuator stroke for correction of aberrations excluding tilt should be 4 microns mechanical motion of the mirror surface corresponding to an optical correction of 8 microns in the reflected beam. b) The corrector stroke for tilt is TBD arc seconds (sky reference)
FR-494 3.2.3.6	Fitting Error	The fitting error for a tilt removed Kolmogorov wavefront characterized by a r0 of 18 cm will be: a) TBD nm for the first stage corrector b) TBD nm for the secondary stage corrector c) TBD nm for the LOWFS internal corrector and TBD nm for the multi-object deployable near-IR IFU internal correctors
FR-495 3.2.3.6	Inter actuator mechanical coupling	The inter-actuator coupling will be TBD %.
FR-496 3.2.3.6	Lowest mechanical frequency	Lowest mechanical frequency of the higher order corrector will be TBD Hz. The lowest mechanical frequency of the tip tilt stage will be TBD Hz.
FR-497 3.2.3.6	Phase lag	Requirement is TBD, this includes both the tip tilt correcting stage and the higher order deformable mirror actuators.
FR-498 3.2.3.6	Actuator hysteresis	Requirement is 21 nm rms wavefront error, this includes only the higher order deformable mirror actuators

FR-499 3.2.3.6 Operating environment

The correctors will be able to operate at standard temperature and humid environments as other instruments at Keck observatory. In order to meet its emissivity requirements the AO correctors must be able to meet spec at -20 C in a cooled AO enclosure.

Parameter	***Min.***	***Typ.***	***Max.***	***Units***	***Notes***
Altitude					
Keck I	0	-	4300	m	
Temperature					
Keck I	-10	0	20	¼C	
Rate of change	-0.8	-	0.8	¼C/h	
Humidity	0	-	90	%	
Gravity orientation	-	-1	-	g	
Vibration	-	-	$1x10^{-5}$	g^{2}/Hz	

FR-500 3.2.3.6 Vibrations

The tip tilt stages must not introduce extra vibration in the AO Bench and its optics, as well as other AO subsystems or instruments. Requirement value is TBD.

FR-505 3.2.3.6 Interface to the AO real-time control system

AO correctors must be interfaced to the real time control systems. the exact requirements are TBD

FR-506 3.2.3.6 Probability of actuator failure

The rate of actuator failure shall be low enough that one actuator would fail per 10 years of typical astronomical observations and daytime testing.

AO Optical-Mechanical, Acquisition Cameras

ID	WBS	NAME	DESCRIPTION
FR-1801	3.2.3.7	Acquisition capability	The AO acquisition system is responsible for the acquisition of natural stars for the low order natural guide star wavefront sensors (LOWFS), laser guide stars for the laser guide star wavefront sensor (LGS WFS), and the acquisition of the science target on the science instrument. These acquisition tasks shall occur in an automatic fashion with a minimum of telescope operator input. The field shall be accurately identified with a high probability of detecting natural guide stars and astronomical targets.
FR-1803	3.2.3.7	Interface to observer planning tools	Acquisition software will receive target information from the NGAO observer planning tools
FR-1802	3.2.3.7	Interface to AO non real-time control	Acquisition camera interface to AO non real-time control: AO non real time control is responsible for control of acquisition cameras, including selection of optics and setting the exposure time. AO control will determine when acquisition is successful in an automatic fashion with limited operator oversight
FR-1805	3.2.3.7.1	IR field Identification	The acquisition camera shall be capable of identify targets in the NIR wavelength bands between 1.0 and 2.5 microns. This may be accomplished by imaging sources in the near-IR (1.0-2.0 micron) or imaging sources in the visible (0.5-1.0 micron). In both cases use supplementary information about target locations from catalogs and surveys
FR-1806	3.2.3.7.1	Point source sensitivity	The acquisition cameras shall have a limiting magnitude of V=22 if uses visible detectors (CCDs). The acquisition camera shall have a limiting magnitude of J=19 if it uses NIR detectors. For the purpose of acquisition the limiting magnitude is defined as achieving a SNR of great or equal to 10 in an exposure time of less than or equal to 10 s
FR-1807	3.2.3.7.1	Position accuracy	The random errors from measurement noise when determining source positions in an acquisition camera image shall be 0.050 arc seconds rms or less. Measurement noise includes fundamental noise the detection process such as photon noise in the source and sky background, it also includes noise sources such as readout noise and detector dark current. Errors in registering the detector to a know coordinate system are part of the registration accuracy requirement
FR-1808	3.2.3.7.1	Minimal time overheads	The NGS acquisition shall take less than 90 seconds for NGS V ~ 18-20. Less than 50 seconds for NGS V < 17 with the goal of achieving less than 20 seconds for the brightest targets. This requirement includes time for telescope moves, camera exposure, and analysis.
FR-1809	3.2.3.7.1	Photometric imagery	Photometric error of 0.2 magnitudes under transparent conditions, in standard astronomical bands such as Johnson, UKIDDS, SDSS.

FR-1813	3.2.3.7.1	Guiding mode	The NGS acquisition system shall offer the capability to be used as a guider for the Keck telescope.
FR-1814	3.2.3.7.1	Sky background limit	The acquisition system should be capable of working in conditions of high background such as at twilight and near a full moon. The background for these conditions are 16.88 magnitudes per square arc second in the V band (Johnson), 16.0 magnitudes per square arc second in the J band (Johnson) and 13.0 magnitudes per square arc second in the K band (Johnson). The acquisition camera can select appropriate filter to minimize background as need, but it must still meet the point source sensitivity requirement for V=22 magnitude M0 stars in the effective spectral of the sensor.
FR-1818	3.2.3.7.1	Telescope pointing	The telescope shall provide a pointing accuracy of 15 arc seconds rms and 30 arc seconds peak to valley after large telescope slews of 40 degrees in elevation and 5 hours in azimuth. The telescope shall be able to point with less than 0.5 arc second rms error (and 1 arc second peak to valley error) for any move of less than 30 arc seconds (which corresponds to the peak to valley value for telescope pointing after a large move).
FR-1804	3.2.3.7.1	Field of view	The NGS acquisition camera field of view shall be greater than or equal to 150 arc seconds
FR-1810	3.2.3.7.1	Registration accuracy	0.020 arc seconds rms, random error in determining positions of acquisition camera with respect to telescope optical axis The registration accuracy between the sensors and the NGS acquisition camera must be documented to less than 0.02 arc sec over the entire field-of-view.
FR-1817	3.2.3.7.1	LOWFS field of view	LOWFS pickoff mirror shall provide a field of view of 2 to 5 arc seconds in diameter.
FR-1811	3.2.3.7.1	Diagnostics, and troubleshooting tools	Report metrics for automatic acquisition and to aide observer decision making. Include manual override by astronomer or observing assistant
FR-1812	3.2.3.7.1	Data products	All acquisition images shall be stored on the NGAO data server. Images shall be in FITS file format and have standard FITS header information. The exact content of the header are TBD. The data product from the acquisition system and the information from available catalogs or literature shall be recorded in the same photometry system and with comparable spatial resolution.
FR-1819	3.2.3.7.1	Astronomical Catalogs	Keck observatory shall provide astronomical catalog to support NGAO. Exact catalogs are TBD but likely include 2-MASS, GSC-2, SDSS, and USNO 1.0B.
FR-1816	3.2.3.7.2	LGS source sensitivity	The LGS acquisition camera shall be able to detect LGS flux level as low as 80 photons/s/cm^2 which is comparable to a visual magnitude star. The SNR of the detection shall be 50 or greater, in a 1 second exposure. The Rayleigh sky background is assumed to be 13 magnitudes per arc square arc second.
FR-1815	3.2.3.7.2	Track LGS range	The LGS acquisition camera shall be able to track the range of the sodium layer as the telescope points away from zenith. The range of the sodium layer corresponding to zenith angles of 0 to 70 degrees is 80-270 kilometers. This range also accommodates variations in the mean zenith height of sodium layer 80-100 km

AO Optical-Mechanical, Atmospheric Dispersion Correctors

ID	WBS	NAME	DESCRIPTION
FR-73	3.2.3.8	Atmospheric dispersion compensation	Optical relay will include atmospheric dispersion compensation for the output of the 2nd optical relay. Atmospheric dispersion shall be controlled to 0.177 milli arc seconds across J band, 0.144 milli arc seconds across H band, and 0.077 milli arc seconds across K band (or specify particular bands in nm).

AO Optical-Mechanical, Alignment and Calibration

ID	WBS	NAME	DESCRIPTION
FR-1773	3.2.3.9	Flat field images	The instrument radiometric calibration source shall provide uniform illumination (flat fields) over the wavelength range from visible to near IR, covering at least the wavelength range 0.6-2.5 mm and over a field of view up to 150 arc seconds diameter. It is possible to have separate sources (lamps) covering the visible and near IR parts of the spectrum.
FR-1774	3.2.3.9	Spectral line sources	The instrument radiometric calibration spectral source lamps shall have enough strong emission lines so that at least 1 spectral line per 1 nm wavelength interval will reach an SNR of 100 in a 60 second exposure.
FR-1775	3.2.3.9	Uniformity	The radiometric calibration source shall be uniform to 0.2% over 40 arc seconds scales at the center of the AO field of view and uniform to 3% over a 180 arc second field of view, a random 10 arc second patch over this field shall be uniform to 0.5%.
FR-1776	3.2.3.9	Stable pupil shape	The pupil shape shall be constant to 1% over the course of a night of observing. This places limits on the mechanical stability of the radiometric calibration source and it sets limits on the repeatability of its insertion mechanism. The tolerance on the relative motion of optical components is to be determined (TBD)
FR-1777	3.2.3.9	Intensity	The radiometric calibration source shall have a signal to noise ratio of 1000 per pixel in a 60 second exposure with the proposed science instruments.
FR-1778	3.2.3.9	Time to deploy and remove	The radiometric calibration source shall be able to be inserted and removed from the AO beam in 60 seconds or less. The warm-up time for lamps to reach stable operational output shall be less than 30 seconds. This will likely require feedback control of the intensity from the source.

FR-1779	3.2.3.9	Control of lamps	Radiometric calibration lamps shall have an on and off intensity control as part of the AO non real-time software. It can also be control by the instrument control software either directly or through an interface to the AO software
FR-1780	3.2.3.9	Temporal stability	The intensity of the continuum sources shall be stable to 5% (with a goal of 1%) during any 12 hour period.
FR-1782	3.2.3.9	Astrometric calibration source	An astrometric calibration source will be provided for calibration of the various instruments in NGAO. Ideally, one source would be provided for calibration of all instruments, alternatively separate calibration sources could be installed in each instrument separately. The light output from these sources will be spatial uniform. Additionally, these sources will produce light consistent with the optical passband of the instruments they are intended to calibrate.
FR-1783	3.2.3.9	Astrometric grid spacing, size, and uniformity	The astrometric reference source shall have sources covering a 40 arc second field of view with a hole to hole spacing of about 0.5 arc seconds. The diameter of the holes shall correspond to 0.005 arc seconds with a tolerance of plus minus 700 nano arc seconds. The random error in the inter hole distance (center to center) shall vary by no more than plus minus TBD nano arc seconds. These tolerances are typical of the current NIRC2 astrometric grid [3] and are suitable for near IR instruments, tighter tolerance may be need for NGAO near-IR instruments and visible instruments.
FR-1784	3.2.3.9	Intensity	The light source used to illuminate the astrometric grid shall be intense enough to produce a signal to noise ratio of 100 per spot in a 20 second exposure.
FR-1786	3.2.3.9	Time to deploy and remove astrometric source	The astrometric grid shall be able to be inserted and removed from the AO beam in 60 seconds or less.
FR-1790	3.2.3.9	Number and location of LGS sources	The LGS sources shall be arrange in two asterisms of 5 stars in a regular pentagon. The pentagon diameter shall be equivalent to either 15 arc seconds or 100 arc seconds. A single LGS source shall be located at the center of the pentagons
FR-1791	3.2.3.9	Number and location of NGS sources	The number and location of the NGS sources is TBD
FR-1792	3.2.3.9	RMS wavefront error for NGS sources	The NGS sources that are sized at the diffraction shall produce “clean beams’ for wavefront calibration of the AO system and the instruments. The rms wavefront error of these sources shall be 1 nm rms or less or the wavefront error will be able to be calibrated to this level.
FR-1795	3.2.3.9	Seeing values and isoplanatic angle	The atmosphere shall be simulated by at least two phase screen that can be independently moved (rotated). The phase screen shall be matched to median (50%) seeing r0 and q0 of the Mauna Kea Ridge [11] model which are 16 cm and 2.7 arc seconds at a wavelength of 0.5 mm.
FR-1796	3.2.3.9	Greenwood frequency	The phase screen shall be movable with variable speeds and direction of rotation, such that they can simulate Greenwood frequencies between 60-10 Hz.
FR-1797	3.2.3.9	Transmission for NIR wavelengths	The phase screens shall have transmission of 80% or better for wavelengths of 0.5-2.5 mm.

FR-1798	3.2.3.9	Repeatable turbulence	The turbulent phase screens shall be repeatable in position, when static, such that the AO performance can be measured repeatability to an error of 10 nm rms or less.
FR-1785	3.2.3.9	Translation and rotation of source grid	It must be possible to rotate and translate these astrometric grid elements.
FR-1793	3.2.3.9	DM-to-lenslet misregistration	The source simulator must be consistent with the DM-to-Lenslet misregistration errors
FR-1772	3.2.3.9	Radiometric calibration source	A radiometric calibration source will be provided for calibration of the various instruments in NGAO. Ideally, one source would be provided for calibration of all instruments, alternatively separate calibration sources could be installed in each instrument separately. The light output from these sources will be spatial and temporally stable. Additionally, these sources will produce light consistent with the optical passband of the instruments they are intended to calibrate.
FR-1789	3.2.3.9	Source simulator	The AO system shall have white light (visible and NIR) artificial sources that simulate NGS sources for both seeing limited and diffraction limited observations. The AO system shall have narrow line (~580-600 nm) LGS sources that are approximately the same size and elongation as the expected LGS spot size on the sky.
FR-1794	3.2.3.9	Turbulence simulator	The system shall have a means of simulating dynamic atmospheric turbulence.
FR-1800	3.2.3.9	Image stability	The NGAO system will ensure the scientific image or spectrum is not degraded by mechanical drift or image rotator errors. This can be achieved by mechanical tolerances or an active alignment system, for example a laser metrology system.
FR-1781	3.2.3.9	Software control of radiometric source	Radiometric source interface to AO non real time control: The radiometric sources will be controlled by an interface to AO non real-time control software. The science instruments control software will also be able to control these sources whether directly or through an interface to the AO non real-time control software is TBD
FR-1787	3.2.3.9	Software control of astrometric source	The astrometric source will be controlled by an interface to AO non real-time control software. The science instruments control software will also be able to control these sources whether directly or through an interface to the AO non real-time control software is TBD
FR-1788	3.2.3.9	Measure science instrument wavefront error	The science instrument shall be able to measure the wavefront errors from the telescope Nasmyth focus to instrument focal plane to less than or equal to 22 nm rms.
FR-1799	3.2.3.9	Software control of turbulence simulator	Source simulator interface to AO non-real time control: The calibration sources and atmospheric simulator will be controlled by an interface to AO non real time control software.

AO Optical-Mechanical, Atmospheric Profiler

ID	WBS	NAME	DESCRIPTION
FR-1540	3.2.3.10	Data products	The atmospheric profiler will provide the following data products: 1) integrated seeing (units of arc seconds) 2) free atmospheric seeing (seeing above at 500 meters and above) (units of arc seconds) 3) isoplanatic angle (units of arc seconds) 4) Fried parameter (units of cm) 5) layer integrated turbulence profile (units of m^1/3)
FR-1541	3.2.3.10	Number of altitudes	The atmospheric profiler will provide turbulence profile Cn2(h) or the turbulence integrated (Cn2(h)xH) over altitude at 6 altitudes, from 500m up to 20 km.
FR-1542	3.2.3.10	Altitude resolution	The profiler shall provide a turbulence profile with a spatial resolution of at least altitude/2.
FR-1543	3.2.3.10	Accuracy	The errors in the reported profile and integrated parameters will be as given in the following table: relative errors absolute errors seeing 0.02 0.02 arc seconds free-atm seeing 0.05 0.05 arc seconds individual layer <0.1 <0.01 arc seconds isoplanatic angle <0.01 <0.2 arc seconds
FR-1544	3.2.3.10	Duty cycle	The turbulence profiler will update at 90 second intervals during normal operations
FR-1546	3.2.3.10	Location	The atmospheric profiler will be located as close as possible to the Keck telescopes. Tomography may be less dependent on accuracy of ground layer turbulence allowing a relaxation of this requirement.
FR-1549	3.2.3.10	Elevation	The elevation of the atmospheric profiler will be as close as possible to the elevation of the Keck telescope primary mirror that hosts NGAO with a goal of 10 meters or less
FR-1556	3.2.3.10	Time Stamp data	All data products will be time stamped to a precision better than 1 second. Time stamping should include the start and end of data collection for each sample.
FR-1560	3.2.3.10	Operation when telescopes operate	Operate autonomously on Mauna Kea on nights when optical/IR telescopes are observing. Typically this means
FR-1561	3.2.3.10	Sensitivity	The turbulence profiler will be able to operate when the atmospheric transparence is 0.90 magnitude/air mass or less
FR-1562	3.2.3.10	Greenwood frequency	As a goal provide an estimate of the optical turbulence layer velocities and the Greenwood frequency

FR-1536	3.2.3.10	Atmospheric profiler	A monitor for atmospheric turbulence will be part of the NGAO system. The atmospheric profile will use optical measurements of natural stars to infer the turbulence distribution with height over the telescope.
FR-1550	3.2.3.10	Protected against inclement weather	The turbulence profiler will be able to survive exposure to the exterior environment of the Mauna Kea summit or be enclosed in a dome or other structure that can open to provide access to the sky. If enclosed in a building it must contribute minimal "local seeing" to the measurements reported by the atmospheric profiler.
FR-1557	3.2.3.10	Archive calibration and processed data	Archive calibration and processed data in a central archive, transfer data to NGAO data server.
FR-1558	3.2.3.10	Continuous sky coverage	The instrument will provide continuous sky coverage so that an estimate of r0 and atmospheric profile is possible whenever it is operating. Observations will be limited to zenith angles < 60 degrees.
FR-1545	3.2.3.10	Use Mauna Kea facility seeing monitor	If it meets all final requirements the facility Mauna Kea atmospheric profiler will be used for NGAO
FR-1539	3.2.3.10	Standard wavelength and zenith distance for reported data	All atmospheric data will be reported at a wavelength of 0.5 microns and corrected for elevation effects to observation made at the zenith
FR-1555	3.2.3.10	Integrated into WM Keck summit facility	If possible the atmospheric profiler should be contained inside the footprint of the current W.M. Keck observatory facility
FR-1551	3.2.3.10	Operate at Mauna Kea summit	The instrument must be able to operate in environmental conditions that exist at the Mauna Kea summit
FR-1547	3.2.3.10	Size	The atmospheric profile will occupy a space not greater than 3m by 3m by 3m in volume
FR-1548	3.2.3.10	Weight	The weight of the atmospheric profiler will less than TBD kg
FR-1552	3.2.3.10	automatic operation	The profiler will include the capability for automatic operation. This should include automatic startup and verification of status at start of a night. At the end of the night the profiler will perform an orderly shutdown. The profiler will determine if humid or clouds are present, and then enter a sleep mode of TBD minutes, after which time it will check to see if conditions have improved to allow operations. The profiler will provide diagnostics for data verification during operations. The profiler will warn the NGAO non real-time control of bad data.
FR-1537	3.2.3.10	Network interface	The atmospheric profiler will provide a network interface to the Keck observatory local network

FR-1538	3.2.3.10	Interface to non real-time software	The AO non real-time software will be able to report the pointing of the telescope to the profiler and request that it use the most appropriate (nearby) star. The AO control software will relay the profile data to the AO real-time control system (RTC) to assist in tomographic estimation. The AO software will also relay the profile information to the observatory data archive for use in AO PSF estimation.
FR-1553	3.2.3.10	Uptime	The mean time between failure of the profiler will be such that if doesn't effect NGAO operations. Required mean time between failure is TBD
FR-1559	3.2.3.10	Startup shutdown time	Startup operations will take less than 5 minutes. Shutdown operations will take less than 5 minutes. The system can change to a weather-safe mode in less than 1 minute
FR-1554	3.2.3.10	Maintenance	The atmospheric profiler should be design to minimize maintenance

AO Optical-Mechanical, PSF Monitor Camera

ID	WBS	NAME	DESCRIPTION
FR-325	3.2.3.12	PSF monitoring camera	The main NGAO optical relay will include an interface to a camera for recording images of natural sources that have been corrected by the AO system. This camera will provide point spread function for calibration of scientific data for systematic errors in the NGAO performance, Strehl variations, and angular anisoplanatism, etc.
FR-326	3.2.3.12	PSF monitoring camera interface to observatory data archive	The PSF camera will be controlled by the AO non real-time control software. PSF images will be relayed to the observatory data archive for use in AO PSF estimation and calibration of scientific data

4.1. AO Non-Real-Time Control

ID	WBS	NAME	DESCRIPTION
FR-456	3.2.4	Definition	The AO non real-time control system is defined as the AO control functions that are not directly concerned with the high speed measurement and correction of atmospherically distorted wavefronts.
FR-457	3.2.4	Roles for the AO non real-time control	1. A coordination role during setup, calibration, and observations. 2. Interface role between the AO system, the laser facility, the instruments, the data server, and the telescope. 3. User interfaces including graphical, command line, and scripts. 4. Monitoring completion of commands inside the AO system. 5. Monitoring the health of the AO sub-systems and relaying the information to the observer or telescope operator. 6. Logging data about the AO system into the data server for NGAO. 7. Control of AO enclosure and subsystem mechanisms.
FR-458	3.2.4.1	User interfaces	The AO non real-time control will have graphical, command line, and script based user interfaces.
FR-459	3.2.4.1	Monitoring	AO control will monitor health of the AO system including the AO RTC.
FR-460	3.2.4.1	Mechanism Control	AO control system will provide control of all AO mechanisms. This will include the following functions: 1. Initialize all device mechanisms. 2. Control all devices that track the telescope position such as: the rotators for LGS subsystem, K-mirror, and atmospheric dispersion correctors (ADC). 3. Control calibration devices (integrating spheres, point source simulators, etc). 4. Provide tracking control to the LGS WFS pickoff/selection mechanism. 5. Provide tracking control to the LGS focus and aberration correction mechanisms. 6. Provide tracking control to the LOWFS pickoffs. 7. Provide tracking control to the multi-object dIFS pickoffs.
FR-461	3.2.4.1	Truth Wavefront Sensor	AO non real-time control is responsible for control of the TWFS and interfacing the information to the AO RTC.

FR-462 3.2.4.1	Acquisition Camera	AO control is responsible for control of the acquisition camera, including selection of optics and setting the exposure time. AO control will determine when acquisition is successful in an automatic fashion with limited operator oversight.
FR-463 3.2.4.1	Configuration	AO control system will be able to configure (setup) the AO system for observation. This will include selecting the AO mode, the configuration and location of LGS wavefront sensors, as well as the configuration of the NGS LOWFS and location of the LOWFS pickoffs.
FR-464 3.2.4.1	Interface to laser control system	AO control will also request from the laser facility the correct LGS locations and orientation of the LGS constellation. AO control will request startup of LGS rotation mechanism.
FR-465 3.2.4.1	Acquisition mode setup	AO control will setup the acquisition mode for science targets and LOWFS natural guider stars.
FR-466 3.2.4.1	RTC setup	AO control will setup the RTC by either loading pre-computed reconstruction matrices or initializing an iterative algorithm.
FR-467 3.2.4.1	Altitude tracking	AO control will start/stop the altitude tracking mechanism in LGS WFS (in LGS mode)
FR-468 3.2.4.1	dIFS configuration	If the instrument is the multi-object deployable IFS, the AO control system will configure the pick off and MOAO system in each multi-object deployable IFS input beam train.
FR-469 3.2.4.1	Coordination of calibration tasks	AO control will coordinate periodic calibration tasks for the AO facility including: calibrating the deformable mirror actuator gains, calibrating the WFS non-linearity, measuring the deformable mirror to wavefront sensor registration.
FR-470 3.2.4.1	Coordination of background measurements	AO control will coordinate the background calibration (sky and dark frames) for LGS wavefront sensors, NGS wavefront sensors, the LOWFS, truth wavefront sensors, and acquisitions sensors.
FR-471 3.2.4.1	Motion control	AO control will coordinate the motion control and other tasks need to perform dithering and chopping for science observation.
FR-472 3.2.4.1	Interface to LTCS	AO control will respond appropriately to protect the AO system and recover gracefully from a laser traffic control event.
FR-473 3.2.4.1	Self monitoring	AO control will coordinate the archiving of AO data for science data calibration (i.e. PSF estimation, determine quality of AO correction).
FR-474 3.2.4.1	Interface to telescope	The AO control will compute the appropriate tip-tilt, focus, and coma offloads to be sent periodically to the telescope drive control system (DCS).
FR-475 3.2.4.1	Interface to data archive	AO control system will record configuration and status information about the AO system in the NGAO data server. An architectural assumption is that NGAO instrument data, AO RTC engineering data and AO RTC data for calibrating scientific data (i.e. PSF estimation) will be archived in this data server as

		well.
FR-476 3.2.4.1	Interface to the multi-object deployable near-IR IFU	The AO control system will receive information about the multi-object deployable IFS targets and configure the MOAO channels. The AO control system will control the IFS pickoff and other non real-time mechanisms of the MOAO input to each IFS channel.
FR-477 3.2.4.1	Interface to AO RTC	The AO control system will interface with the AO RTC system. The AO control system will be able to make the following requests: 1. Configure RTC mode to LGS or NGS mode. 2. Configure the RTC reconstruction as required: this could include providing the RTR with previously computed reconstruction matrices or initialization of an iterative RTR algorithm. 3. In LGS/NGS mode, set the frame rates for the sensors directly interfaced to the RTC (LGS, NGS, and LOWFS). 4. In LGS and NGS mode, request dark and background frames be recorded for any of the sensors directly interfaced to the RTC sensor (LGS, NGS, and LOWFS). 5. In LGS mode, open and close the LOWFS tip tilt control loop on any of the three NGS LOWFS channels. 6. In LGS mode, open and close the first stage higher order AO atmospheric compensation loop. 7. In LGS mode, open and close the second stage higher order AO atmospheric compensation control loop. 8. In LGS mode, open and close the MOAO atmospheric correction in any of the LOWFS channels. 9. In LGS mode, open and close the MOAO atmospheric correction in any of the dIFS instrument channels. 10. In LGS and NGS associate a time stamp on the AO RTC engineering data with the start of science instrument exposure. 11. In NGS mode open and close the AO loops. 12. Check the health and status of the AO RTC system.
FR-478 3.2.4.1	Interface to the LGS facility	1. AO control system will initiate configuration of the LGS constellation. AO control will initiate rotation compensation for the LGS constellation. AO control will be able to open and close the up link tip tilt compensation loop. 2. AO control facility will receive status and diagnostics (i.e. laser power, polarization etc) from the laser facility control system.
FR-479 3.2.4.1	interface to the turbulence Profiler	AO non real-time control system will get atmospheric turbulence profile (Cn2) information from an onsite monitor. The information will be transferred to the AO RTC for its tomography algorithm. The data will also be transferred to the observatory data archive for calibration of science and AO engineering data.

AO Real-Time Control

ID	WBS	NAME	DESCRIPTION
FR-1406	3.2.5	Bandwidth	RTC latency and AO system bandwidth: The AO system 0 db closed-loop error cutoff frequency in LGS mode will be 54.3 Hz.
FR-1407	3.2.5	Latency	The RTR end to end processing latency is TBD
FR-1408	3.2.5	Numeric Precision	Numerical Precision: The RTC numerical precision including digitization of the drive signals sent to the deformable mirrors must be consistent with a final wavefront error of 1 nm rms.
FR-1426	3.2.5	Control Parameter Information	The RTC will take in the following information for control purposes as necessary. The time to update information should be less than 1 sec: 1) Layer information (Height and Cn2) 2) Gain(s) for reconstruction an other system functions 3) Pre conditioning (and other) matrices 4) Kolmogorov profile 5) Guide star cone effect scaling factors 7) Tomography, centroid, and any other algorithm selection 8) All look up tables and matrixes for DM or Centroid processing
FR-1428	3.2.5	Number of laser guide stars in LGS mode	The RTC will accept wave front information from anywhere between 5 and 9 laser guide star wavefront sensors
FR-1429	3.2.5	Natural guide star (Tip/Tilt/Focus/Astigmatism) processing in LGS mode	The RTC will take input from 3 NGS sensors. Two of the sensors are imagers from which tip/tilt information is extracted. One of the sensors is a low-order wavefront sensor from which tip/tilt/focus/astigmatism information will be extracted. The RTC must take the raw pixel data from these sensors and product the appropriate tip/tilt/focus/astigmatism measurements. The RTC must take the tip/tilt/focus/astigmatism measurements and process them into the overall tomography calculations
FR-1430	3.2.5	Number of DM's - narrow field mode	The RTC will provide control information to 2 DMs, the first is a woofer with _____(TBD) degrees of freedom, the second is a tweeter DM with 64x64 degrees of freedom
FR-1431	3.2.5	Number of DM's - wide field mode	The RTC will provide control information to 6 DMs: 1 woofer and 5 MOAO tweeter DMs.
FR-1432	3.2.5	Number of atmospheric tip/tilt stages - narrow field mode	The RTC will provide control information to 1 tip/tilt mirror
FR-1433	3.2.5	Number of atmospheric tip/tilt stages - wide field mode	The RTC will provide control information to 6 tip/tilt controls 1 woofer and 5 MOAO tweeter tip/tilt controllers

FR-1434	3.2.5	Accuracy of wavefront reconstruction	The accuracy of the wavefront information to be applied to the deformable mirrors shall be 5 nm rms
FR-1435	3.2.5	Accuracy of tip/tilt reconstruction	The accuracy of the tip/tilt information to be applied to the tip/tilt mirrors shall be 1 millarcsecond (as referenced to on-sky)
FR-1436	3.2.5	Update rate	The atmospheric estimate will be updated at a minimum of 500 mSec intervals during normal operations. It must be possible to vary the rate to accommodate the effect of future additions of wind prediction, etc.
FR-1438	3.2.5	atmospheric information update rate	The RTC must be able to accept updates to CN2, layer height, layer wind velocity at a minimum rate of TBD
FR-1439	3.2.5	Location	At 15,000 altitude.
FR-1452	3.2.5	Time Stamp data	All data products will be time stamped to a precision better than 1 second. Time stamping should include the start and end of data collection for each sample.
FR-1455	3.2.5	Operation when telescopes operate	The RTC must operate autonomously on Mauna Kea on nights when optical/IR telescopes are observing.
FR-1456	3.2.5	DM data rate	The RTC must be able to pass information to each of the 5 DM's (64x64) at a minimum rate of 165MB/Sec
FR-1457	3.2.5	Layer and wind	The RTC must include a means of supplying layer information for wind analysis and accepting layer wind information should be provide, with a minimum update rate of TBD
FR-1401	3.2.5	Real Time Computer	The AO real time control (RTC) system provides the main system for correction of atmospherically distorted wavefronts. In its primary mode, when used with laser guider stars, the RTC analyzes the LGS wavefront from 9 laser beacons. In addition, inputs from three NGS wavefront sensors will be used to estimate tilt and other low order aberrations such as focus and astigmatism. The totality of these wavefront sensor inputs is used to estimate the three dimensional volume of atmospheric turbulence over the telescope. This estimation step is commonly called tomography. The RTC is responsible for using the tomographic solution to determine the shape applied to the various deformable mirrors in the AO system. The RTC also receives input on the difference between LGS and NGS measurement of atmospheric turbulence from a NGS truth wavefront sensor (TWFS). Additionally, the RTC will support a NGS mode (no LGS) where natural guider stars will provide all the wavefront information.
FR-1402	3.2.5	Other duties	The AO real-time control is also responsible for the calibration and test of the AO system in coordination with higher level control functions.
FR-1403	3.2.5	Source of Control	The AO non real-time control system provides the high level supervisory control of the RTC.

FR-1404	3.2.5	Main Tasks	The AO real-time control is responsible for estimation of the wavefront correction to be applied to the correction elements (deformable and tip tilt stages) in the: • Main AO relay • High Strehl AO relay (2nd stage of the cascade) • The LOWFS to sharpen The RTC will provide the following data products per frame: 1) Tomographic information per layer (Fourier) 2) DM commands per DM 3) RMS error per guide star (spatial or Fourier) 4) WFS input per fWFS 5) Camera output per Camera
FR-1405	3.2.5	RTC Control functions	RTC control functions: a) The RTC will offload focus from the AO system to the telescope secondary. b) The RTC will offload tip tilt errors to telescope elevation and azimuth drive control system c) The RTC will filter the build up of un-sensed modes, such as piston and global waffle. d) The RTC will compute commands for deformable mirror actuators that fall outside the illuminated foot print of the deformable mirror, i.e. slaved actuator commands. e) If needed the RTC will provide functionality for determining the shape of the common deformable mirror in the first stage of the cascaded relay. Alternatively some means of monitoring the shape of the first stage deformable mirror directly will be provided (for instance a high speed interferometer).
FR-1409	3.2.5	LGS WFS Processing	LGS WFS processing: a) The RTC will input WFS pixels from multiple LGS sensors and calibrate them for sensor and sky backgrounds. Includes provisions for subtraction of Rayleigh background if CW sodium lasers are used. b) The RTR will estimate wavefront slopes from WFS pixel intensities using TBD algorithm or algorithms. c) The RTR will update its estimate algorithm of the wavefront slopes as atmospheric and sodium layer conditions change. d) The RTC will estimate the full aperture tip tilt from each LGS wavefront and export this information to the appropriate subsystem for LGS tip tilt control, also know as uplink tip tilt. (This subsystem could be located at either LGS launch telescope or input to each LGS WFS channel, this is TDB). Specific rate is TBD. e) If the selected laser is pulsed, to reduce background form Rayleigh scattering, the LGS WFS CCD should be synchronized with laser pulse rate. The timing error and clock source are TBD at this time. f) The RTC shall allow adjustable frame rates for LGS observations.
FR-1410	3.2.5	LOWFS processing	Low-order wave front sensor (LOWFS) high-bandwidth NGS processing (LGS AO mode): a) The RTC will input WFS pixels from multiple low order NGS and calibrate them for sensor and sky backgrounds. b) The RTR will estimate wavefront slopes from pixel intensities using TBD algorithm or algorithms. c) The RTR will update its estimate of the wavefront slopes as atmospheric conditions and AO performance change. RTR will optimize the setting of the NGS WFS based on NGS star brightness, atmospheric conditions, and AO performance. d) RTC will adjust frame rates of the tip tilt sensors between 10-TDB Hz as the brightness of the NGS changes, under control of the AO non RTC. The rate of each LOWFS sensor will be independently selectable.
FR-1411	3.2.5	Truth WFS processing	Truth WFS Processing (TWFS) LGS AO mode: a) Calibrate slow variations and biases in AO control from changes in sodium layer profile, flexures, and drifts. At this time, the expected update rate of the Truth wavefront sensor maybe slow enough that the information could be processed by either an RTC subsystem or a dedicated TWFS software that would perform wavefront reconstruction on the TWFS input and not the RTR. For the purposes of this document, we assume that the TWFS software performs the reconstruction. Details for the TWFS software are included in section 7.8 non real time control. b) The TWSF software will provide low order NGS wavefront information c) The focus information from the TWFS will be used to change the focus of the LGS wavefront sensors.

FR-1413	3.2.5	High-order WFS Processing	High-order NGS WFS Processing NGS (NGS AO): a) The RTC will input WFS pixels from single NGS and calibrate them for sensor and sky backgrounds. b) The RTR will estimate wavefront slopes from CCD pixel intensities using TBD algorithm or algorithms. c) Update slope estimation algorithm for seeing and AO performance at a TBD rate. d) Adjust frame rate of wavefront sensor between 1-2000 Hz as NGS guide star brightness varies.
FR-1414	3.2.5	Wavefront reconstruction	Wavefront Reconstruction: a) In LGS mode the RTC will take wavefront gradient information from LGS WFS, the LOWFS to make a tomographic estimate of the atmospheric turbulence above the telescope using a TBD algorithm. b) In LGS mode, the RTC will estimate the proper correction to apply to the various correcting elements in the system (see Table 1) based on the tomographic solution in the step a) above. c) The RTC will be able to initialize the wavefront reconstruction algorithm using information about the LGS constellation, the NGS constellation for the LOWFS, the science mode and instrument, the atmospheric turbulence profile, wavefront sensor signal levels, the orientation of the telescope pupil, the orientation between wavefront sensor measurements, and AO deformable mirror actuators. d) In NGS mode, the RTC will estimate the wavefront from a bright NGS guide star and optionally use wavefront information from other NGS in the field that are measured by the LOWFS.
FR-1415	3.2.5	Temporal Filtering	Temporal Filtering: a) The RTC will temporally filter the wavefront estimate from the LGS WFS, LOWFS, and the TWFS to achieve stability and optimal correction of the wavefront. The RTC will perform analogous function for NGS mode observations. b) The RTC will temporally filter the correction between first stage and second stage mirrors in the main cascade relay for optimal performance. c) The RTC will temporally filter the correction between the main deformable and the deformable mirrors inside the LOWFS channels and the multi-object deployable near-IR IFU science channels.
FR-1416	3.2.5	Data acquisition	Data Acquisition: a) The RTC will provide high speed data to support AO engineering tasks (this is sometimes referred to as telemetry data). b) The RTC will provide high speed data to support PSF reconstruction.
FR-1417	3.2.5	WFS calibration	Wavefront corrector and WFS calibration: The RTC will be capable of supporting the calibration of the deformable mirror act gains. The RTC will be capable of calibrating the WFS linearity. The RTC will also be capable of measuring the deformable mirror to wavefront sensor registration. Additionally, the RTC will be capable of supporting the determination the pupil orientation and illumination of various correctors and wavefront sensors in the NGAO system.
FR-1425	3.2.5	Real Time Computer	A Real Time Computer (RTC) to compensate for atmospheric turbulence and common path effects will be part of the NGAO system. The RTC will use measurements of natural and laser guide stars to calculate the turbulence distribution with height and azimuth angle over the telescope. It will use this reconstruction to optimally control deformable and tip/tilt mirrors (DM's and TT) to compensate for optical aberrations.
FR-1453	3.2.5	Archive calibration and processed data	The RTC through control by the non RTC must be capable of archiving calibration and processed data in a central archive, transfer data to NGAO data server.
FR-1458	3.2.5	Data format	Any data that may be loaded into the RTC by the non RTC must be directly readable by non RTC, i.e., lookup tables, system matrixes, Cn2 profiles...

FR-1444	3.2.5	WFS style	The wavefront sensors are Hartmann sensors and will include compensation for non linearity
FR-1445	3.2.5	WFS sub aperture size in pixels	TBD
FR-1446	3.2.5	DM influence function and non linearity compensation	Required for MOAO open loop
FR-1447	3.2.5	Tomography	Fourier domain algorithm will be used for tomography
FR-1437	3.2.5	wavefront sensor input data rate	The RTC must be able to accept wave front camera data at a minimum rate of 2,000 frames per second of 32000 pixels/frame
FR-1427	3.2.5	Standard units for reported data	All atmospheric data will be reported in nanometers The RTC will provide tomography over altitude at 7 altitudes, from ground up to 20 km. The RTC shall provide a turbulence estimate with a height resolution of at least 8-bits
FR-1451	3.2.5	Integrated into WM Keck summit facility	If possible the RTC be contained inside the footprint of the Nasmyth platform at the current W.M. Keck observatory facility. However, location within the computer room is acceptable if cabling between the RTC and the WFS cameras and DMs does not exceed 250 feet.
FR-1440	3.2.5	Size	The RTC will occupy a space not greater than 8 cubic meters volume
FR-1441	3.2.5	Weight	The weight of the RTC will less than TBD kg
FR-1442	3.2.5	Power Dissipation	The power dissipation of the RTC will less than 20 kW
FR-1443	3.2.5	Single Event Upset (SEU) rate	The RTC must be able to detect and automatically recover from cosmic or gamma ray events. Event rate that causes a change in the state of the control system should be less than TBD per hour. Time to detect and event should be less than 1 min. Recovery time should be less than TBD seconds
FR-1448	3.2.5	automatic operation	The RTC will include the capability for automatic operation. This should include automatic startup and verification of status at the start of a start of a night. At the end of the night the RTC will perform an orderly shutdown. The RTC will provide diagnostics for data verification during operations. The RTC will warn the NGAO non real-time control of bad data.
FR-1412	3.2.5	TWFS interface	The RTC will interface with the truth wavefront sensor (TWFS) software. The RTC will receive information about the NGS wavefront in order to correct for structure in the sodium layer and elongation of the LGS.

FR-1418	3.2.5	Non RT controller interface	The RTC will interface with the Adaptive Optics non real-time control system as a means of high level control and coordination functions for the NGAO system through as network interface.
FR-1419	3.2.5	Observatory interface	The RTC will interface with an observatory data system for storage of AO telemetry data for AO engineering and science data analysis (i.e. PSF estimation, data quality assessment, and other TBD tasks). This will be through a local network interface
FR-1420	3.2.5	Telescope control interface	The RTC will interface with the telescope control system. The RTC will offload focus to the telescope secondary. The RTC will offload tip and tilt errors back to the telescope azimuth and elevation drives. The RTC will get information on the telescope pointing and pupil rotation to assist in wavefront reconstruction tasks.
FR-1421	3.2.5	LGS interface	The RTC will interface with the laser guider star facility in order to support the acquisition of each LGS on its intended wavefront sensor. In addition the RTC will send the average full aperture tip and tilt of each LGS to the Laser control software for stabilization of the LGS on the sodium layer.
FR-1422	3.2.5	DM interface	RTC will have an electrical interface with the AO deformable mirror and tip tilt correctors listed in table 1 (see comments)
FR-1423	3.2.5	WFS detector and camera interface	The RTC will interface with the detectors used in the LGS WFS, the LOWFS, and the NGS wavefront sensor. The RTC will read pixel intensities from these devices. The RTC will be able to control the readouts rates and other TBD characteristics of these devices, under control of the non RTC.
FR-1424	3.2.5	Non RT controller interface	RTC will interface with the AO non real-time control system in order to control the focus of the LGS wavefront sensors, aberration correction optics in the LGS wavefront sensor, the pickoffs for the various wavefront sensors in the NGAO system these include the LGS, NGS, and LOWFS. The AO RTC software will be able to report the ______________. The RTC will accept new CN2 profile data from the AO non real-time control system to assist in tomographic estimation. The RTC software will also relay __________ for use in AO PSF estimation.
FR-1449	3.2.5	Uptime	The mean time between failure of the RTC will be such that if doesn't effect NGAO operations. Required mean time between failure is TBD
FR-1454	3.2.5	Startup shutdown time	Startup operations will take less than 20 minutes. Shutdown operations will take less than 5 minutes.
FR-1450	3.2.5	Maintenance	The RTC should be design to minimize maintenance

Laser Facility

ID	WBS	NAME	DESCRIPTION
FR-1267	3.3	Number of laser guider stars	The design shall have 9 LGS beacons
FR-1268	3.3	LGS asterism size and shape	There is a central beacon with 5 beacons arranged on equidistant from each other on a circle of radius varying from 11”-101”.
FR-1269	3.3	Roving laser guider stars	There are 3 roving beacons to perform MOAO on tip-tilt stars that can be independently pointed anywhere in the 202” FoV.
FR-1270	3.3	LGS asterism motion	The asterism shall be fixed with respect to the sky.
FR-1271	3.3	altitude of operation	The laser facility shall be operational at 4300 m
FR-1272	3.3	temperature of operation	The laser facility shall work between -10 to 20 degrees
FR-1273	3.3	temperature rate of change	The laser facility shall work with a 0.8 degree C/h temperature change.
FR-1274	3.3	humidity of operation	The laser facility shall be operational between 0 and 90% humidity.
FR-1275	3.3	gravity vector	The following parts (list to be enclosed; architecture dependent) of the laser facility shall work over all gravitational orientations
FR-1276	3.3	Altitude change for shipment	The laser facility components shall survive an altitude of 4572 m during shipping
FR-1277	3.3	Temperature change for shipment	The laser facility components shall survive temperature ranges between -33 to 71 deg. C

FR-1278	3.3	Temperature shock in shipment	The laser shall be able to withstand temperature shocks of -54 to 72 deg. C
FR-1279	3.3	acceleration during shipment	The laser facility components shall survive 4g acceleration during transportation.
FR-1280	3.3	Power dissipation	The laser system must dissipate less than xx Watts into the ambient air. Rest of the heat will be dissipated via. Glycol cooling lines provided.
FR-1281	3.3	Cooling with facility glycol	Cooling requirements: The laser module shall dissipate less than xxx KW of total heat into the facility glycol.
FR-1282	3.3	Monitor cooling system	Cooling system monitoring requirements
FR-1284	3.3	Motion Control	Servo control requirements (still to be added)
FR-1285	3.3	Clean room	Clean room requirement: The clean room shall conform to class100 with appropriate filters installed.
FR-1286	3.3	Downtime	Downtime: NGAO shall be designed to minimize downtime.
FR-1289	3.3	Power dissipation	LSE: Heat dissipation into glycol (TBD KW)
FR-1313	3.3	Wiring standards	Electrical Standards: All wiring within the LSE shall conform to the latest revision of the NEC and NFPA 79 standards.
FR-1319	3.3	Laser Safety	Class IV laser: The LSE shall conform to ANSI standard Z136.1-2000 “American National Standard for the Safe Use of Lasers”.
FR-1335	3.3	replacement oxygen sensor	Service and maintenance requirements: 2. Oxygen Sensor Replacement (Annually: 1 Hr)
FR-1336	3.3	prefilter replacement	Service and maintenance requirements: 3. LSE Room Prefilter replacement (Quarterly: 1 Hr)
FR-1337	3.3	HEPA filter replacement	Service and maintenance requirements: 4. HEPA Filter replacement (Annually: 2 Hr)

FR-1338	3.3	Replaceable cleanliness supplies	Service and maintenance requirements: 5. LSE cleanliness and replacement of consumables such as sticky mats (Monthly: 1 Hr)
FR-1340	3.3	Spares list	Spares: A recommended spares list including costing for each component will be provided
FR-1341	3.3	Manuals from 3rd party suppliers	Documentation: Manuals shall be provided for all 3rd party equipment.
FR-1342	3.3	Drawings	Documentation: All drawings designate and formats shall conform to NGAO TBD Drawing Standards.
FR-1343	3.3	Laser control software	Software requirements: Laser software system consists of vendor supplied laser control system software that has been tested.
FR-1344	3.3	Laser user interface	The laser control GUI shall display: lasers power(s), spectral profile, absolute wavelength, polarization, sodium cell absorption, M^2 measurements, near and far field spot patterns, laser control/ dither lock performance at xx Hz.
FR-1345	3.3	Laser telemetry and diagnostics	laser diagnostics and telemetry requirements: laser power(s), spectral profile, absolute wavelength, polarization, sodium cell absorption, M^2 measurements, near and far field spot patterns, control/ dither loop performance
FR-1346	3.3	LGS asterism (1)	Asterism requirement: There shall be nine LGS’s
FR-1347	3.3	LGS asterism (2)	Asterism requirement: All observing scenarios shall have a central LGS
FR-1348	3.3	LGS asterism (3)	Asterism requirement: Around the central LGS there shall be five LGS's that are on a circle
FR-1349	3.3	LGS asterism (4)	Asterism requirement: The five LGS’s shall be arranged on the circle such that they are 72 degrees apart.
FR-1350	3.3	LGS asterism diameter	Asterism requirement: diameter of 5 LGSs shall be between 20" - 202".
FR-1351	3.3	Roving laser guider stars	There shall be 3 LGS beacons that can point anywhere in the 202” to sharpen TT stars.
FR-1352	3.3	Uplink tip tilt corrector	Each LGS beacon shall have a separate uplink tip-tilt correction.

FR-1353	3.3	Upgradeable for Uplink AO correction	Each LGS beacon shall have separate uplink high order correction option built into the design, though not implemented as part of current design
FR-1354	3.3	Single launch telescope	A single Laser Launch Telescope shall be used to propagate all nine laser beams.
FR-1355	3.3	size constraint	The LLT and any other beam splitting mechanism must fit within the volume suggested by xxx document
FR-1356	3.3	Transmission	The loss from laser output to the exit of the LTA shall be less than 30%.
FR-1357	3.3	Launch telescope location	The LLT shall be mounted behind the secondary and the LGS's launched from the optical axis.
FR-1358	3.3	LGS geometry	The LGSs shall conform to geometry (and tolerances) specified in xxx document.
FR-1359	3.3	Interface to Keck telescope	The LTA must interface to the K1 telescope as described in document KAON xx and CARA drawing # xx.
FR-1373	3.3	Number of laser guider stars	The design shall have 9 LGS beacons
FR-1374	3.3	LGS asterism size and shape	There is a central beacon with 5 beacons arranged on equidistant from each other on a circle of radius varying from 11”-101”.
FR-1390	3.3	documented assemble	The mechanical assembly shall be documented
FR-1391	3.3	alignment procedure	The alignment procedure of the LTA shall be documented
FR-1392	3.3	overall LGS facility documentation	A system level document describing the LGS facility and sub-systems shall be prepared.
FR-1393	3.3	software documentation	A software document shall be written describing the software architecture and implementation.
FR-1394	3.3	user manual	A laser user manual shall be written

FR-1395	3.3	BTO and LTA user manual	A BTO and LTA user manual shall be written
FR-1256	3.3	polarization state	The laser beam leaving the LTA must be right (or left circular) polarization.
FR-1257	3.3	polarization contrast	The ratio polarization contrast should be better than 100:1
FR-1258	3.3	polarization control	The BTO should have the ability to arbitrarily control the polarization of each laser beam propagated out of the LTA
FR-1259	3.3	Laser guide star size at sodium layer	LGS spot shall be 1.13 " at median conditions avg. over all subapertures at the WFS
FR-1371	3.3	photon return	The laser shall produce photon return > 0.12 photons/cm^2/ms/W at the telescope entrance from exciting the Mesospheric sodium layer.

Laser Facility, Laser Enclosure

ID	WBS	NAME	DESCRIPTION
FR-1283	3.3.2	Enclosure temperature	Enclosure temperature (A/C requirement)
FR-1287	3.3.2	Mass constraint	LSE : Mass constraint ()
FR-1288	3.3.2	size constraint	LSE size constraint (a,b,c mm)
FR-1290	3.3.2	Ventilation	LSE: Ventilation air (xxx cuft/min)
FR-1291	3.3.2	Heat dissipation	LSE: Heat dissipation into environment (W)
FR-1292	3.3.2	Doors	LSE: Doors, Access and covers (will add specifics based on laser)
FR-1293	3.3.2	Glycol cooling	LSE shall use facility glycol-water mix. The glycol pressure is 45-100 psi at -5 to 5 degrees. @ xx l/min flow rate
FR-1294	3.3.2	weight load on floor	LSE shall be able to support 40 lbs/in^2 floor load
FR-1295	3.3.2	point load	LSE shall be able to support xxx lbs/in^2 point load.
FR-1296	3.3.2	AC Power format	LSE shall have sufficient power for the laser, laser electronics, diagnostics, lights, internal HVAC equipment to maintain routine operation. The power shall be 3 ph. 208 VAC.
FR-1297	3.3.2	AC Power	LSE shall provide xx KW.
FR-1298	3.3.2	Access	The LSE shall provide sufficient space for maintenance of the laser. Such space shall also include area for auxiliary equipment such as computer monitors and keyboards. This will depend on the maintenance requirements of the laser.

FR-1299	3.3.2	Auxiliary equipment	The LSE shall provide auxiliary equipment such as dry nitrogen for cleaning of optical components or vacuum equipment rated with the proper filters.
FR-1300	3.3.2	Environmental Controls	The LSE shall have the following control points: Laser bench area temperature and laser bench area relative humidity
FR-1301	3.3.2	Environmental monitoring	The LSE shall have the following monitor points: Laser room particulates, bench area temperature, bench area RH, gowning area temperature, Gowning area RH
FR-1302	3.3.2	Exterior laser status lights	The LSE shall provide status indicators on the outside of the enclosure. These indicators are for personnel to determine the laser status prior to entry. The indicators shall be momentary if any light source is used to not contaminate the environment.
FR-1303	3.3.2	Access for laser installation into enclosure	The LSE shall provide the proper environment allowing the installation of the laser. This will dependent on the laser. The environment may include removable ceilings, floor contact points or supports as required by the laser manufacturer.
FR-1304	3.3.2	Output for laser beam	The LSE shall provide a proper output for the laser beam as required by the laser manufacturer.
FR-1305	3.3.2	Auxiliary equipment	The LSE shall provide any additional auxiliary equipment such as pneumatics or dry nitrogen as required by the laser.
FR-1306	3.3.2	Vibration transmitted to observatory	The design of the LSE shall use best engineering practices in order to minimize vibrations that may be transmitted to the telescope. In particular, the design of the LSE shall vibration isolate any active components such as fans, pumps, and motors.
FR-1307	3.3.2	Fit and finish	The LSE shall be fabricated to remove all sharp edges. The fit and finish shall comply with TBD standards.
FR-1308	3.3.2	Network communication	Network communications: The LSE shall provide a minimum of TBD network ports for operation of the laser and auxiliary equipment.
FR-1309	3.3.2	telephone	Phone communications: The LSE shall provide a telephone line for operation of the laser
FR-1310	3.3.2	lighting	Lighting: The LSE shall provide lighting at a minimum of 2 watts / sq ft.
FR-1311	3.3.2	Exterior laser status lights	Hardware Status: The LSE shall provide status on doors, access ports, emergency stops in a suitable format to the laser safety system for interlocking the laser beam.
FR-1312	3.3.2	Electrical outlets	Electrical Outlets: The LSE shall provide TBD outlets for the laser and auxiliary equipment.

FR-1314	3.3.2	Cable routing	Cable routing: The LSE may provide cable chases to support cable and wire routing.
FR-1315	3.3.2	Fall restraints	Mechanical: The LSE shall provide restraint railings to meet OSHA requirements.
FR-1316	3.3.2	Yield strength	Mechanical: The LSE shall be designed and constructed to a minimum safety factor of 4 on yield strength for all structural elements.
FR-1317	3.3.2	Ladder	Mechanical: The LSE shall provide a ladder to the roof if access to the roof of the LSE is necessary. The ladder may require additional caging to protect personnel during ascent and descent if deemed necessary by the Safety Officer.
FR-1318	3.3.2	Weight load on roof	Mechanical: The roof of the LSE shall be able to support 2 personnel and its environmental controller such as HVAC as necessary.
FR-1320	3.3.2	Light tight	Class IV laser: The LSE shall be light tight to contain a class IV laser environment.
FR-1321	3.3.2	Interior finish	Class IV laser: The inside of the LSE shall be a surface to suitable for a Class IV Laser.
FR-1322	3.3.2	Emergency lighting	Electrical: The LSE shall have emergency lighting for egress in case of power failure.
FR-1323	3.3.2	Emergency laser stop	Electrical: The LSE shall provide emergency stop buttons to terminate laser light.
FR-1324	3.3.2	Smoke detectors	Environmental: The LSE shall provide smoke detectors with an audible alert located on the exterior of the LSE. The smoke detectors shall be tied to safety system to terminate the laser.
FR-1325	3.3.2	Fire extinguishers	Environmental: The LSE shall provide appropriate fire extinguishers inside and outside of the laser room.
FR-1326	3.3.2	Oxygen deficiency alarms	Environmental: The LSE may have a standalone oxygen monitor unit to alert personnel of a low oxygen environment. The notifier shall be on both the inside and outside of the LSE when the oxygen level is lower than 19.5%. The determination will be made by the Safety Officer based on confined space criteria.
FR-1327	3.3.2	Video Camera	Environmental: The LSE may provide a camera inside the LSE to be viewed remotely if deemed necessary by the Safety Officer.
FR-1328	3.3.2	Glycol fittings	Mechanical: The LSE shall use Parker Hannifin series FS quick disconnects for glycol fitting.

FR-1329	3.3.2	pneumatic fittings	Mechanical: The LSE pneumatic connections shall be TBD.
FR-1330	3.3.2	Electrical panel	Electrical: The LSE shall have a single electrical panel on the outside of the LSE for all power entering the LSE. This panel shall provide the properly sized breakers for individual connections within the LSE.
FR-1331	3.3.2	Network cables	Electrical: The LSE shall have a CAT5 cable with RG45 connections for network access.
FR-1332	3.3.2	Phone connection	Electrical: The LSE shall have a TBD phone connection that is standardize with the observatory environment.
FR-1333	3.3.2	Maintenance	Service and maintenance requirements: The LSE shall be designed to minimize the effort required to maintain the LSE. An acceptable level of effort is defined as not to exceed 4 hours of maintenance / month by 2 personnel.
FR-1334	3.3.2	calibration oxygen sensor	Service and maintenance requirements: 1. Calibration service of the Oxygen Sensor (Quarterly: 1 Hr)
FR-1339	3.3.2	Operational lifetime	Reliability: All components of the LSE shall have a lifetime of 10 years except for consumables. The list of consumables and their individual lifetime must be provided as part of documentation.
FR-1223	3.3.2	laser enclosure size	The size of the laser electronics enclosure shall be axbxc mm

Laser Facility, Lasers

ID	WBS	NAME	DESCRIPTION
FR-1197	3.3.3	Laser power	Total laser power out of the NGAO laser module shall be xx W
FR-1201	3.3.3	beam quality factor	The NGAO laser must have an M^2<1.2 at the exit of the laser.
FR-1202	3.3.3	beam size	Beam diameter of the laser beam at the output shall be xx mm.
FR-1203	3.3.3	beam profile	Beam profile - X and Y FWHM measurements
FR-1204	3.3.3	Diagnostics	Laser system must provide quasi-real-time diagnostic of power, beam position, spectral measurement and M^2.
FR-1205	3.3.3	low power operation	The laser module shall operate in "low power" mode for alignment and testing without any change in characteristics other than power.
FR-1206	3.3.3	spectral format	Spectral requirements
FR-1207	3.3.3	Wavelength	Nominal wavelength shall be 589.xxxx nm
FR-1208	3.3.3	spectral bandwidth	Spectral BW shall be X.X +/- 0.0X GHz
FR-1209	3.3.3	frequency stability	The frequency stability about the central wavelength shall be 50 MHz
FR-1210	3.3.3	optical power out of band	Out of band power shall be less than X%
FR-1211	3.3.3	Tunable	Tunability Requirements

FR-1212	3.3.3	tunable laser: step size	Central frequency change step size shall be 1/20th of the spectral BW.
FR-1213	3.3.3	tunable laser: step range	Central frequency step range shall be 500 MHz.
FR-1214	3.3.3	tunable laser: settling time	Time for frequency shifts shall be xx sec.
FR-1215	3.3.3	pointing stability	Pointing stability of the laser beam at output
FR-1216	3.3.3	transverse pointing stability	Transverse stability: Positional stability Long term +/- 0.x mm/hr. over a 12 hr. period [TBD] Short term +/- x um/min [TBD]
FR-1217	3.3.3	Angular pointing stability	Angular stability: Long term +/- x mrad/hr. over a 12 hr. period [TBD] Short term +/- x urad/min [TBD]
FR-1218	3.3.3	Pulse format and modelocking	Pulse format and Mode locking requirements [TBD, depends on the laser]
FR-1219	3.3.3	optical pumping	The laser(s) should have the ability to optically pump the sodium layer.
FR-1222	3.3.3	laser electronics mass	The mass of the electronics rack for the laser power supply and controls shall be xxx kgs
FR-1220	3.3.3	laser bench mass	The mass of the laser bench shall be xxx kgs
FR-1221	3.3.3	laser bench size	The size of the laser bench shall be axbxc mm
FR-1224	3.3.3	Control laser wavelength	AO interface to LF: Shall be able to get tune/detune commands from the AO system.
FR-1225	3.3.3	Software shutter control	AO interface to LF: Shall be able to shutter and propagate the laser beam(s).
FR-1226	3.3.3	control laser guide star focus	AO interface to LF: Shall have the ability to focus the laser spot.

FR-1227	3.3.3	Laser telemetry and diagnostics	AO interface to LF: Shall have the ability to query and display parameters that are recorded as part of telemetry
FR-1228	3.3.3	remote power up/down	AO interface to LF: Shall be able to remotely power up and power down the lasers
FR-1229	3.3.3	control laser wavelength	AO interface to LF: The software shall facility shall be able to tune/detune of the sodium D2 line remotely.
FR-1230	3.3.3	laser remotely adjustable	AO interface to LF: Shall be able to perform basic tweaking up of laser performance [TBD]
FR-1231	3.3.3	Power up to operational time	Reliability: Time for full operational condition from start up in xx min.
FR-1198	3.3.3	long term power fluctuation	The fluctuation in power over 12 hrs of operation shall be less than 10% [TBWO] at the output
FR-1199	3.3.3	long term power fluctuation	The "long term" (12 hr. time period) shall be < 10%
FR-1200	3.3.3	long term power fluctuation	The power fluctuation in "short term" shall be < 5%[
FR-1232	3.3.3	Period of continuous operation	Reliability: The laser system shall operate for a period of 12 hrs./ day continuously as part of routine operation

Laser Facility, Laser Launch Facility

ID	WBS	NAME	DESCRIPTION
FR-1233	3.3.4	Operational lifetime	Lifetime of the LGS facility sub-system and its components is a nominal 10 year operation including handling, maintenance and repair unless otherwise stated with a specific MTBF.
FR-1234	3.3.4	minimum elevation	The LGS asterism shall point up till 60 degrees off zenith
FR-1236	3.3.4	Launch telescope alignment to Keck telescope	LTA: Alignment accuracy/tolerance (internal and to the optical axis of the K1 telescope) shall be TBD
FR-1235	3.3.4	Transmission	The throughput of the BTO shall be >75%
FR-1237	3.3.4	Coating damage threshold	LTA: The optical coatings used in the LTA optics shall withstand xx J of power in xx mSec.
FR-1238	3.3.4	Input beam format	LTA: The input beam shall be (beam format)
FR-1239	3.3.4	Output beam format	LTA: the output beam shall be xx mm dia.
FR-1240	3.3.4	Depth of focus at sodium layer	. And shall focus anywhere between 90 Km -180k
FR-1241	3.3.4	Testable without 589 nm light	LTA: The LTA shall be testable without the use of a 589 nm laser
FR-1242	3.3.4	Wavefront error	LTA: The total RMS error of the LTA shall be xx nm
FR-1243	3.3.4	Elevation range	LTA: The LTA shall work between -5° to 90.5°.
FR-1244	3.3.4	transmission	LTA: The LTA throughput shall be > 95%.

FR-1245	3.3.4	Optical bandwidth	LTA: The LLT shall work over 400-700 nm so that star-light can be used to align it properly (should we specify some chromatic spec. here?)
FR-1246	3.3.4	Star viewing mode	LTA: Shall work both in laser projecting mode and star viewing mode
FR-1247	3.3.4	Focus mechanism	LTA: Shall have a active focus mechanism
FR-1248	3.3.4	Focus resolution	LTA: The focus resolution shall be TBD
FR-1249	3.3.4	Focus range	LTA: The active focus range shall be TBD
FR-1250	3.3.4	Field of view	LTA: The LTA shall have a unvignetted FoV of 202" with an RMS error over this field as specified in
FR-1251	3.3.4	LGS positioning accuracy	LTA: Each LGS beacon shall have a pointing accuracy of 0.x arc sec.
FR-1252	3.3.4	Uplink tip tilt bandwidth	LTA/ BTO: The uplink TT shall have a closed loop BW of xx Hz.
FR-1253	3.3.4	High power operation	The LTA shall be able to withstand xx Watts of 589 nm laser power with spectral and temporal format specified by
FR-1254	3.3.4	Obscuration in beam	LTA: The secondary structure and spiders shall have an area of 1/100th or lesser as compared to the laser beam.
FR-1255	3.3.4	In-situ testing	LTA: The optical quality of the LTA shall be testable in-situ.

Laser Facility, Laser Launch Facility, Laser Launch Telescope

ID	WBS	NAME	DESCRIPTION
FR-1261	3.3.4.3	Launch telescope volume	The LTA must fit within a volume of 610x680x635 mm
FR-1364	3.3.4.3	Laser Launch Telescope location	The LLT shall be mounted behind the secondary, on-axis w.r.t. the Keck telescope optics axis.
FR-1372	3.3.4.3	Motion control	LTA: Motion control lines (TBD)
FR-1375	3.3.4.3	Cooling	LTA: Cooling - The LTA electronics shall be cooled using facility glycol lines
FR-1376	3.3.4.3	Storage and shipment	LTA: Storage and shipping requirements - need to cross reference a table or write out as individual requirements
FR-1377	3.3.4.3	Power usage	LTA: The LTA and associated electronics shall consume less than xx KW of electrical power
FR-1378	3.3.4.3	Glycol cooling	LTA: LTA electronics shall use facility glycol to vent heat.
FR-1379	3.3.4.3	Heat dissipation	LTA: The LTA shall not dissipate more than xx W of heat to the ambient air
FR-1260	3.3.4.3	Launch telescope flexure	Flexure/ FEA: The LTA flexure and strain characteristics shall conform to those prescribed by xxx document.
FR-1262	3.3.4.3	Center of gravity	LTA: Center of Gravity (TBD)
FR-1263	3.3.4.3	Mechanical eigen modes	LTA: Eigen modes (TBD)
FR-1264	3.3.4.3	Hermetically sealed	LTA: The LTA shall be hermetically sealed with dry N2.

FR-1265	3.3.4.3	Nitrogen filled	The LTA unit shall be kept in a controlled atmosphere filled with dry N2. The LTA shall be air-tight from the entrance window to the exit window between xx-yy PSI pressure prevailing inside the assembly.

Laser Facility, Laser Safety Systems

ID	WBS	NAME	DESCRIPTION
FR-1396	3.3.5	Laser Air Traffic Safety System	Laser Air Traffic Safety System