7.4   Natural Guide Star Wavefront Sensor Subsystem Functional Requirements

The natural guide star wavefront sensor subsystem is composed of three distinct wavefront sensors that use natural guide stars in specific roles in the AO system. These three NGS wavefront sensors are the:

- NGS Wavefront Sensor (NGS WFS)
- The Low Order Wavefront Sensor (LOWFS)
- Truth Wavefront Sensor (TWFS)

The NGS wavefront sensor provides the capability to perform "classical" single natural guide star AO correction. In this mode, no LGS are used. The NGS capability is required for science on the very brightest of targets, for nights when weather conditions make it impractical to use LGS, and for diagnostic purposes.

The LOWFS is used in conjunction with the tomographic LGS mode of NGAO. The LOWFS use several natural stars to sense low order modes of the wavefront that are poorly sensed by the multiple LGS. These modes include tip, tilt, focus and astigmatism when the goal is optimizing on axis science performance. When the goal is optimizing science performance averaged over a larger field of view the LOWFS is used to estimate tip, tilt and tilt anisoplanatism modes. A more complete discussion of this issue is included in KAON 492. These sensors use natural guide stars and as a result they must be very photon efficient. They are also limited to sensing only the minimum of wavefront information necessary. The best measurements can be made with a multiplicity of natural stars just measuring tip tilt modes. Studies have determined that the minimum number of natural guide stars is three. The LOWFS will have three wavefront sensing channels that sense the tip tilt of a single natural star. To make use of fortuitously located brighter natural guide stars, at least one LOWFS channel will be configurable to also measure focus and astigmatism, as well as tip tilt. Such a sensor is often referred to as a tip tilt focus and astigmatism (TTFA) sensor. In order to have the highest sky coverage possible these stars are sensed in the near IR where they can be corrected by the higher order LGS AO system. IR stars are also favored because they are more numerous for a given flux level than in the visible bands. Although these stars will be partially corrected by the first stage of the Cascaded Relay deformable mirrors that are located inside each LOWFS channel will further sharpen them. The correction will be calculated by the RTC system and these mirrors will be driven in a go-to MOAO configuration.

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 are of a low spatial order. As such, a natural guide star WFS using long exposures and only measuring the lowest spatial wavefront error is sufficient. The issues have been partially studied by Richard Clare see KAON XX. The

wavefront sensors are distinct enough in function that each is treated separately in this section of the requirements.

As part of the NGAO system design process, a preliminary architecture selection was made during the months of July and August 2007. The result of this process was a two-staged AO system known as the "Cascaded Relay". A sketch of the optical relay is included in Figure 1. More details of the Cascaded Relay can be found in KAON 499. The exact location for the TWFS and NGS WFS were not selected in this KAON, the LOWFS was placed in front of the d-NIRI instrument.
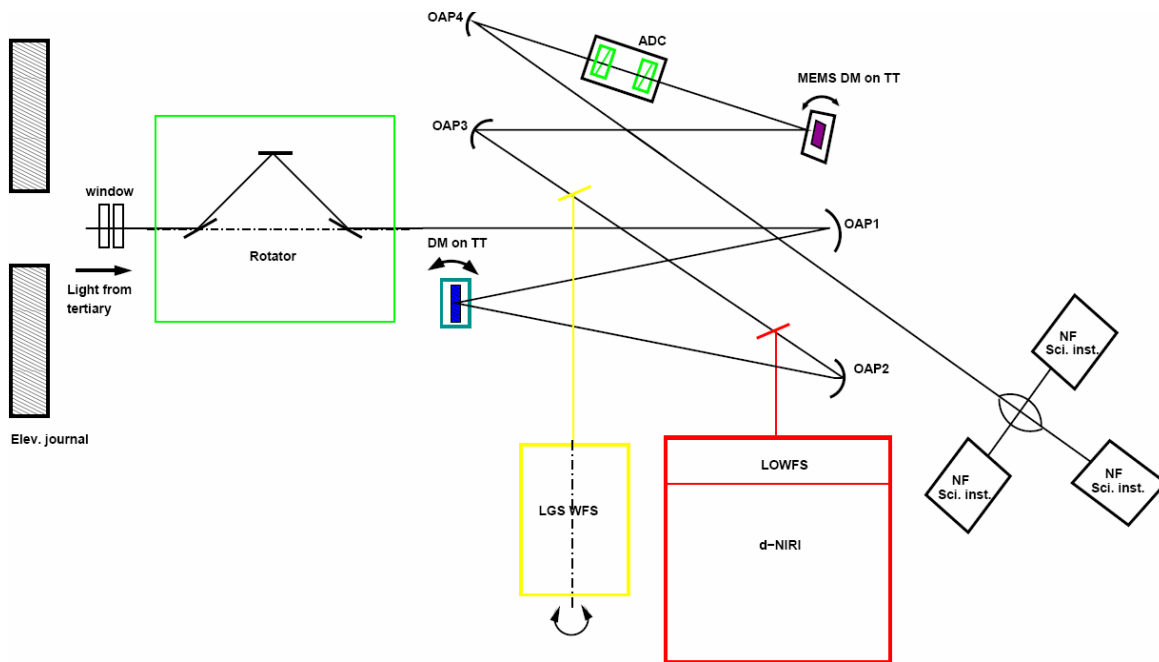

Figure 1: A schematic representation of the NGAO Cascaded Relay

7.4.1 Natural Guide Star Wavefront Sensor

As mentioned above, the NGS wavefront sensor provides the capability to perform "classical" single natural guide star AO correction. In this mode, no laser guide stars are used. The higher order wavefront information will come solely from this sensor. The tip tilt information will come from this sensor or optionally as a combination of one or more channels of the NGS LOWFS. NGS will be a Shack-Hartman sensor with variable levels of pupil sampling. The NGS sensor will be able to be inserted and removed from the beam. The NGS WFS will be located after OAP 4 and before the instrument stack (see Figure 1). The NGS will have the capability to patrol the entire field of the second relay. The focal plane array of the sensor and its readout electronics are also considered part of the NGS WFS. The focal plane electronics will be interfaced to the AO real-time control

software, (see section 7.7). Other devices that are part of the NGS wavefront sensor, such as the mechanism for interchangeable optics, will be controlled by the AO non real-time software (see section 7.8).

7.4.1.1   NGS WFS Architectural Assumptions and Overall Requirements

Wavefront sensor performance:

The exact performance level of the NGS wavefront sensor system is TBD.

Location:

The NGS wavefront sensor will be located at the back of the high Strehl relay (OAP4), before the narrow field science instruments.

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.

The following is a list of architectural assumptions for the NGS WFS:

Type of sensor and geometry:

The NGS WFS will be of a Shack-Hartmann configuration, utilizing square lenslets in a rectangular array.

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.

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.

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.

Elevation distance:

The NGS WFS will meet its performance goals at 30 elevation. Requirement for atmospheric dispersion compensation (ADC) is TBD.

7.4.1.2   Optical Requirements

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).

Transmission:

The transmission will be TBD %.

Input focal ratio:

The optical input to the NGS will be from the second stage of the cascaded relay.

Static calibration errors:

The static wavefront calibration errors are TBD.

Pupil distortion:

The level of pupil distortion on the lenslet array is TBD.

WFS dynamic range:

The dynamic range of the wavefront sensor is TBD.

Athermalization:
The optical relay shall be able to satisfy its optical requirements at both cooled (-20 C) and ambient temperatures (0 C).

7.4.1.3 Mechanical Requirements

Packaging:
The optics, mechanisms, and electronics of the NGS WFS will be compatible with the AO enclosure and main optical relays (see section 7.2).

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.

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.

Vibration:
The NGS WFS, its mechanisms, and associated system must be consistent with observatory vibration standards. Additional standards for NGSO are TBD.

Motion control:
For devices that must track paralactic angle changes, the rate of compensation will be consistent with the zenith "dead zone" of Keck telescope's maximum azimuth tracking rate. Requirements on other 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.

Mechanism motions:
Number and type of mechanisms is TBD.
Speed of mechanism motions is TBD.
Accuracy of the mechanism motions is TBD.

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 from the second relay.

7.4.1.4 Electronic/Electrical Requirements

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. See interface requirements section7.4.1.7.

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.

CCD requirements:
The exact requirements on CCD pixel size, dark current, read noise, and quantum efficiency are TBD at this time.

7.4.1.5   Safety Requirements

These requirements are TBD.

7.4.1.6   Software Requirements

Mechanism control software:
The mechanism control software for the NGS WFS will be part of AO non real-time control system (see section 7.8).

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 system RTC.

7.4.1.7   Interface Requirements

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.

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.

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.

Thermal management:
The waste heat generated by the NGS WFS focal plane, electronics, and mechanism will be removed from the NGAO optical path.

7.4.1.8   Reliability Requirements

Downtime:
The NGS WFS shall be designed to minimize downtime.

Operational readiness:
The NGS WFS 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 is TBD.
      Nighttime setup time is TBD.
      Object setup time is TBD.

7.4.1.9   Spares Requirements

TBD pending results of a failure analysis of system.

7.4.1.10   Service and Maintenance Requirements

TBD pending results of a failure analysis of system.

7.4.1.11   Documentation

Standard documentation provided including:
Mechanical drawings
Electrical schematics
Optical design prescription
Optical alignment plan

7.4.2   Low Order Wavefront Sensor

The LOWFS is used in conjunction with the tomographic LGS mode of NGAO. In addition, it may be used in NGS mode to supplement the tracking information from the higher order NGS WFS (see section 7.4.1). The LOWFS use three natural stars to sense low order modes of the wavefront that are poorly sensed by the multiple LGS. These sensors use natural guide stars. As a result, they must be very photon efficient and be limited to sensing only the minimum of wavefront information necessary. The LOWFS will have three wavefront sensing channels that sense the tip tilt of a single natural star. To make use of fortuitously located brighter natural guide star, at least one LOWFS channel will be configurable to also measure focus and astigmatism as well as tip tilt, such a sensor is often refer to as a tip tilt focus and astigmatism (TTFA) sensor. In order to have the highest sky coverage possible, these stars are sensed in the near IR where the

stars can be corrected by the higher order LGS AO system. The LOWFS natural guide stars will be sharpened by MOAO deformable mirrors that are located inside each LOWFS channel. The correction will be calculated by the RTC system and these mirrors will be driven in a go-to MOAO configuration.

7.4.2.1   LOWFS Architectural Assumptions and Overall Requirements

Tracking and wavefront sensor performance:

The exact performance level of the LOWFS system is TBD.

Location:

The LOWFS will be located with the d-NIRI instrument and share the same pickoff mechanism location.

Cooling:

The optical components of the LOWFS are located inside the AO enclosure, which will be cooled to -20 C (see KAON 501). If needed, parts of the LOWFS, 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.

Cooling of LOWFS detectors:

In order to sense wavefronts in the near infrared (1.0-2.5 microns) parts of the LOWFS detector and associated optics may need to be cooled to temperatures lower than the rest of the NGAO AO enclosure (-20C). The exact specification is TBD pending selection of the LOWFS detector.

MOAO correction:

Each LOWFS will have its own deformable mirror. The shape to place on this deformable mirror will be calculated by the AO RTC system. The AO non real-time control system will receive the position of the LOWFS stars so that the correct wavefront can be calculated from the AO RTC tomographic estimate.

The following is a list of architectural assumptions for the LOWFS:

Type of sensor and geometry:

The 2 LOWFS channels are tip tilt only and the third channel can be configured to measure tip tilt focus and astigmatism. The third channel is referred to as a tip tilt focus

astigmatism sensor (TTFA). The TTFA channels of the LOWFS WFS will be of a Shack-Hartmann configuration, utilizing square lenslets in a rectangular array.

Pupil sampling:

LOWFS tracking channels will have one subaperture. The TTFA sensor will have 2 x 2 subapertures in a rectangular array.

Deployable about the field of view:

The LOWWFS will be able to make measurements on any star that is in the field of view passed by the first stage of the Cascaded Relay. The LOWFS design should endeavor to keep the smallest required minimum distance between the three pickoffs for the tracking heads.

Tracking on extended objects:

The LOWFS wavefront sensor shall be capable of tracking on partial resolved objects with reduced performance. Examples include large asteroids, active galactic nuclei and other objects with "point like" structures correction on these large objects is at a TBD level.

Elevation distance:

The LOWFS will meet its performance goals at an elevation of 30 degrees. Requirement for atmospheric dispersion compensation (ADC) is TBD.

7.4.2.2   Optical Requirements

Wavelength of operation:

The exact wavelength range of operation is TBD. At present, the architecture assumes that it is in 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.

Transmission:

The transmission will be TBD %.

Input focal ratio:

The optical input to the LOWFS will be from the first stage of the cascaded relay.

Static calibration errors:

The static wavefront calibration errors are TBD.

Pupil distortion:

The level of pupil distortion on the lenslet array is TBD.

WFS dynamic range:

The dynamic range of the wavefront sensor is TBD.

Athermalization:
The optical relay shall be able to satisfy its optical requirements at both cooled (-20 C) and ambient temperatures (0 C).

7.4.2.3   Mechanical Requirements

Packaging:
The optics, mechanisms, and electronics of the LOWFS will be compatible with the AO enclosure and main optical relays (see section 7.2).

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.

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.

Vibration:
LOWFS, its mechanisms, and associated system must be consistent with observatory vibration standards. Additional standards for NGAO are TBD.

Motion control:
For devices that must track paralactic angle changes, the rate of compensation will be consistent with the zenith "dead zone" of Keck telescope's maximum azimuth tracking rate. Requirements on other motion control aspects of the NGS WFS are dependent on the detailed optical design of the wavefront sensor which is not completed at this time.

Mechanism motions:
Speed of mechanism motions is TBD.
Accuracy of the mechanism motions is TBD.

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.

7.4.2.4   Electronic/Electrical Requirements

Focal plane array control:
The basic readout functions of the LO WFS detectors will be controlled by a set of dedicated electronics. These electronics will interface to the AO RTC system (see interface requirements section 7.4.2.7).

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.

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.

7.4.2.5   Safety Requirements

These requirements are TBD.

7.4.2.6   Software Requirements

Mechanism control software:
The mechanism control software for the LOWFS will be part of AO non real-time control system (see section 7.8).

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.

7.4.2.7   Interface Requirements

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.

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.

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.

Thermal management:
The waste heat generated by the NGS WFS focal plane, electronics, and mechanism will be removed from the NGAO optical path.

7.4.2.8   Reliability Requirements

Downtime:
The LOWFS shall be designed to minimize downtime.

Operational readiness:
The LOWFS shall be designed for operation on a TBD basis.

The LOWFS 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 is TBD.*
> *Nighttime setup time is TBD.*
> *Object setup time is TBD.*

7.4.2.9   Spares Requirements

TBD pending results of a failure analysis of system.

7.4.2.10　Service and Maintenance Requirement

TBD pending results of a failure analysis of system.

7.4.2.11　Documentation

Standard documentation provided including:
Mechanical drawings
Electrical schematics
Optical design prescription
Optical alignment plan

7.4.3　Truth wavefront sensor

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.

7.4.3.1　Architectural Assumptions and Overall Requirements

Wavefront sensor performance:

The exact performance level of the NGS wavefront sensor system is TBD.

Location:

The TNGS wavefront sensor will be located after the first stage optical relay. The exact pickoff mechanism is TBD.

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.

The following is a list of architectural assumptions for the NGS WFS:

Type of sensor and geometry:

The TWFS will be of a Shack-Hartmann configuration, utilizing square lenslets in a rectangular array.

Pupil sampling:

The pupil sampling for the TNGS wavefront will have one mode that has five subapertures across the Keck (10.949 m) pupil. Options for other pupil sampling values is a goal. Exact values are TBD, but might include 10 and 20 subapertures across the Keck telescope pupil.

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.

7.4.3.2   Optical Requirements

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).

Transmission:

The transmission will be TBD %.

Input focal ratio:

The optical input to the NGS will be from the first stage of the cascaded relay.

Static calibration errors:

The static wavefront calibration errors are TBD.

Pupil distortion:

The level of pupil distortion on the lenslet array is TBD.

WFS dynamic range:

The dynamic range of the wavefront sensor is TBD.

Athermalization:
The optical relay shall be able to satisfy its optical requirements at both cooled (-20 C) and ambient temperatures (0 C).

7.4.3.3　Mechanical Requirements

Packaging:
The optics, mechanisms, and electronics of the TWFS will be compatible with the AO enclosure and main optical relays (see section 7.2).

Mechanisms:
As needed the TWFS 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 direct these mechanisms.

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.

Vibration:
TWFS, its mechanisms, and associated system must be consistent with observatory vibration standards. Additional standards for NGAO are TBD.

Motion control:
For devices that must track paralactic angle changes, the rate of compensation will be consistent with the zenith "dead zone" of Keck telescope's maximum tracking rate in azimuth. 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.

Mechanism motions:
Number and type of mechanisms are TBD.
Speed of mechanism motions is TBD.
Accuracy of the mechanism motions is TBD.

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.

7.4.3.4   Electronic/Electrical Requirements

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 (see interface requirements section 7.4.2.7).

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.

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.

7.4.3.5   Safety Requirements

These requirements are TBD.

7.4.3.6   Software Requirements

Mechanism control software:
The mechanism control software for the TWFS will be part of AO non real-time control system (see section 7.8).

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.

7.4.3.7   Interface Requirements

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.

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.

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

Thermal management:
The waste heat generated by the TWFS focal plane, electronics, and mechanism will be removed from the NGAO optical path.

7.4.3.8   Reliability Requirements

Downtime:
The enclosure and optical relay shall be designed to minimize downtime.

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 is TBD.
Nighttime setup time is TBD.
Object setup is TBD.

7.4.3.9   Spares Requirements

TBD pending results of a failure analysis of system.

7.4.3.10   Service and Maintenance Requirement

TBD pending results of a failure analysis of system.

7.4.3.11   Documentation

Standard documentation provided including:
Mechanical drawings
Electrical schematics
Optical design prescription
Optical alignment plan