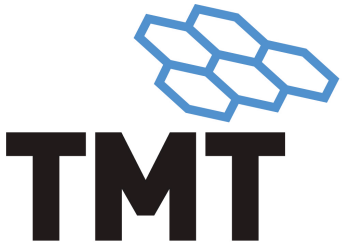

THIRTY METER TELESCOPE

REQUIREMENTS DOCUMENT

FOR

NFIRAOS RTC

TMT.AOS.DRD.08.001.REL05

November 7, 2011

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TABLE OF FIGURES

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1. INTRODUCTION

1.1 INTRODUCTION

This is the Thirty Meter Telescope (TMT) NFIRAOS Real Time Controller (RTC) Requirements Document. The requirements in this document flow down from the higher-level requirements defined in the NFIRAOS Design Requirements Document.

The NFIRAOS RTC Algorithm Description Document is a supporting document of the NFIRAOS RTC Requirement Document.

1.2 PURPOSE

The purpose of this document is to provide a comprehensive definition of the NFIRAOS RTC requirements.

The intended audience for this document is primarily the developers of the NFIRAOS RTC and also:

- The NFIRAOS team,
- The NFIRAOS instrument teams,
- And the reviewers of the NFIRAOS RTC.

1.3 SCOPE

The NFIRAOS RTC is a sub-system of NFIRAOS, which is the early light TMT AO facility. The RTC comprises the computer(s) and software responsible for wavefront correction. In particular, the RTC processes the outputs of a suite of WFS (located within NFIRAOS and within the NFIRAOS instruments) and computes the commands to the wavefront correctors.

The RTC does not control the NFIRAOS slow mechanisms such as the WFS acquisition mechanisms, the instrument selection mirror, etc., which are controlled by the NFIRAOS Component Controller.

The RTC does not include the readout and the processing of the Truth Wavefront Sensor (TWFS) located within NFIRAOS. The TWFS readout and TWFS processing is the responsibility of the TWFS Detector Controller sub-system.

Section 1 contains information about this document. Section 2 contains information about the NFIRAOS system and RTC sub-system, and Section 3 contains the requirements. Paragraphs in Section 3 marked as “Discussion” are for information only and are not requirements.

1.4 APPLICABLE DOCUMENTS

AD1 NFIRAOS Design Requirement Document (TMT.AOS.DRD.07.002)

AD2 Observatory Requirement Document (TMT.SEN.DRD.05.001)

AD3 Observatory Architecture Document (TMT.SEN.DRD.05.001)

AD4 Operations Concept Document (TMT.OPS.MGT.07.002)

1.5 REFERENCE DOCUMENTS

RD1 NFIRAOS RTC Algorithm Description Document (TMT.AOS.DRD.08.002)

RD2 NFIRAOS to NFIRAOS RTC ICD (TMT.AOS.ICD.08.001)

RD3 NFIRAOS RTC to NFIRAOS DME ICD (TMT.AOS.ICD.08.003)

RD4 NFIRAOS RTC to NFIRAOS TTS ICD (TMT.AOS.ICD.08.004)

RD5 NFIRAOS VCAM to NFIRAOS RTC ICD (TMT.AOS.ICD.08.002.DRF02)

RD6 NFIRAOS to IRIS ICD (TMT.SEN.ICD.07.035)

RD7 NFIRAOS to IRMS ICD (TMT.SEN.ICD.07.036)

RD8 TCS to NFIRAOS ICD (TMT.SEN.ICD.07.037)

RD9 NFIRAOS to LGSF ICD (TMT.SEN.ICD.07.027)

RD10 NFIRAOS to DMS ICD (TMT.SEN.ICD.11.003)

RD11 NFIRAOS to AOESW ICD (TMT.SEN.ICD.11.002)

RD12 TMT Software Vision Document (TMT.SFT.TEC.11.005)

1.6 CHANGE RECORD

Revision	Date	Section	Modifications
DRF01	January 18, 2008	All	C. Boyer - Initial draft
REL01	February 4, 2008		C. Boyer: - Modified: Table 1, Figure 3, Figure 4, Figure 5, Figure 6, REQ-3-NRTC-0035, REQ-3-NRTC-0070, REQ-3-NRTC-0075, REQ-3-NRTC-0085, Discussion of REQ-3-NRTC-0100, REQ-3-NRTC-0110, REQ-3-NRTC-0125, REQ-3-NRTC-0155, REQ-3-NRTC-0175, REQ-3-NRTC-0190, REQ-3-NRTC-0210, REQ-3-NRTC-0225, REQ-3-NRTC-0245, REQ-3-NRTC-0320, REQ-3-NRTC-0370, REQ-3-NRTC-0380, REQ-3-NRTC-0420, REQ-3-NRTC-0425, REQ-3-NRTC-0490, REQ-3-NRTC-0500, REQ-3-NRTC-0540, REQ-3-NRTC-0550, REQ-3-NRTC-0560, REQ-3-NRTC-0565, REQ-3-NRTC-0575, Table 8, REQ-3-NRTC-0640, Discussion of REQ-3-NRTC-0370, REQ-3-NRTC-0795 - Added: REQ-3-NRTC-0081, REQ-3-NRTC-0306, REQ-3-NRTC-0371, REQ-3-NRTC-0421, REQ-3-NRTC-0422, REQ-3-NRTC-0423, REQ-3-NRTC-0426, REQ-3-NRTC-0427, REQ-3-NRTC-0428, REQ-3-NRTC-0556, Discussions in $3.3.1, Discussion to REQ-3-NRTC-0720, REQ-3-NRTC-0796 - Deleted: REQ-3-NRTC-0330, REQ-3-NRTC-0335, REQ-3-NRTC-0360, REQ-3-NRTC-0365, REQ-3-NRTC-0450[1], section 3.5 and REQ-3-NRTC-0705, section 3.7 and REQ-3-NRTC-805
REL02	May 27, 2008		C. Boyer: - Replace TT(F) WFS with OIWFS - Modified: Figure 2, Figure 3, Figure 4, Figure 5, Figure 6, REQ-3-NRTC-0080, REQ-3-NRTC-0081, REQ-3-NRTC-0370, REQ-3-NRTC-375, REQ-3-NRTC-0670 - Added: REQ-3-NRTC-0076, REQ-3-NRTC-0077, REQ-3-NRTC-0082, REQ-3-NRTC-0083, REQ-3-NRTC-0491 - Deleted: REQ-3-NRTC-350, REQ-3-NRTC-515

[1] [REQ-3-NRTC-0450] corresponds to the invisible mode removal. This requirement has been deleted because the invisible mode removal is taken into account by the pseudo open loop control.

REL03	November 11, 2008		C. Boyer: - Modified: Figure 2, Table 1, Figure 3, 3.2.1 discussion, Figure 4, Figure 5, Figure 6, REQ-3-NRTC-0055, REQ-3-NRTC-0070 and discussion, REQ-3-NRTC-0081 and discussion, REQ-3-NRTC-0095 and discussion, REQ-3-NRTC-0110 and discussion, REQ-3-NRTC-0135, REQ-3-NRTC-0150 and discussion, REQ-3-NRTC-0165 and discussion, REQ-3-NRTC-0175 and discussion, REQ-3-NRTC-0195, REQ-3-NRTC-0205 and discussion, REQ-3-NRTC-0215 and discussion, REQ-3-NRTC-0220 and discussion, REQ-3-NRTC-0240, REQ-3-NRTC-0260 and discussion, REQ-3-NRTC-0300 and discussion, REQ-3-NRTC-0320 and discussion, table 5, REQ-3-NRTC-0420 and discussion, REQ-3-NRTC-0421 and discussion, REQ-3-NRTC-0422 and discussion, REQ-3-NRTC-0423 and discussion, table 8, table 9, REQ-3-NRTC-0735, REQ-3-NRTC-0750, REQ-3-NRTC-0760 Added: REQ-3-NRTC-0041, REQ-3-NRTC-0121, REQ-3-NRTC-0186, REQ-3-NRTC-0191, REQ-3-NRTC-0192 and discussion, REQ-3-NRTC-0211, REQ-3-NRTC-0212 and discussion, REQ-3-NRTC-0226 and discussion, REQ-3-NRTC-0251, REQ-3-NRTC-0291, REQ-3-NRTC-0330 and discussion, REQ-3-NRTC-0346, REQ-3-NRTC-0416, REQ-3-NRTC-0557, REQ-3-NRTC-0731, REQ-3-NRTC-0771 and discussion Deleted: REQ-3-NRTC-0200, REQ-3-NRTC-0225
REL04	December 18, 2008		C. Boyer Modified: REQ-3-NRTC-0251, REQ-3-NRTC-0291, REQ-3-NRTC-0380, REQ-3-NRTC-0590 Added: REQ-3-NRTC-0230 discussion, REQ-3-NRTC-0270 discussion, REQ-3-NRTC-0429

REL05	August 17, 2011	All	C. Boyer: Modified: REQ-3-NRTC-0010, REQ-3-NRTC-0015, REQ-3-NRTC-0020, REQ-3-NRTC-0040, REQ-3-NRTC-0060, REQ-3-NRTC-0076, REQ-3-NRTC-0077, REQ-3-NRTC-0082, REQ-3-NRTC-0150, REQ-3-NRTC-0175, REQ-3-NRTC-0325, REQ-3-NRTC-0380, REQ-3-NRTC-0405, REQ-3-NRTC-0415, REQ-3-NRTC-0421, REQ-3-NRTC-540, REQ-3-NRTC-730 Added: REQ-3-NRTC-0151, REQ-3-NRTC-0236, REQ-3-NRTC-0276, REQ-3-NRTC-0431, REQ-3-NRTC-0436, REQ-3-NRTC-0466 Deleted: REQ-3-NRTC-0083, REQ-3-NRTC-0100, REQ-3-NRTC-0115, REQ-3-NRTC-0180, REQ-3-NRTC-0429, REQ-3-NRTC-0445

1.7 ABBREVIATIONS

AO – Adaptive Optics

AOESW – Adaptive Optics Executive Software

AOSQ – Adaptive Optics Sequencer

BGS – Block Gauss Seidel

CBS – Cholesky Back Substitution

CG – Conjugate Gradient

DM – Deformable Mirror

DME – Deformable Mirror Electronics

DMS – Data Management System

FDPCG – Fourier Domain Preconditioned Conjugate Gradient

FSM – Fast Steering Mirror

GLAO – Ground Layer Adaptive Optics

IR – InfraRed

IRIS – InfraRed Imaging Spectrograph

IRMS – InfraRed Multi Object Spectrograph

LGS – Laser Guide Star

LGSF – Laser Guide Star Facility

LIS – Laser Interlock System

LUT – Look-Up-Table

MCAO – Multi Conjugate Adaptive Optics

MEMS – Micro-Electro-Mechanical Systems

MIRAO – Mid InfraRed Adaptive Optics

MOAO – Multi Object Adaptive Optics

NFIRAOS – Narrow Field Infrared Adaptive Optics System

NGS – Natural Guide Star

NIRES – Near InfraRed Echelle Spectrograph

OCS – Observatory Control System

OIWFS – On Instrument Wavefront Sensor

PCG –Preconditioned Conjugate Gradient

PSF – Point Spread Function

RPG – Reconstructor Parameter Generator

RTC – Real Time Controller

SH – Shack Hartmann

TCS – Telescope Control System

TTF – Tip Tilt Focus

TTS – Tip Tilt Stage

TWFS – Truth Wavefront Sensor

WFS – Wavefront Sensor

WIRC – Wide Field InfraRed Camera

2. OVERALL DESCRIPTION

2.1 PERSPECTIVE

The Thirty Meter Telescope (TMT) will implement a first light adaptive optics (AO) System called NFIRAOS, which will feed 3 science instruments on the telescope Nasmyth platform. This Narrow Field Infrared Adaptive Optics System is a Multi Conjugate AO (MCAO) system, which provides turbulence compensation over a moderately large field of view (1-2 arcmin) in order to sharpen the images of natural guide stars and improve the sky coverage. NFIRAOS includes:

- two Deformable Mirrors (DM) conjugated at 0km (DM0) and 11.2km (DM11.2),
- one Tip/Tilt Stage (TTS) serving as the mount for DM0,
- six Laser Guide Star (LGS) wavefront sensors observing the asterism illustrated in Figure 1,
- up to three low order Infrared natural guide star[2] wavefront sensors within each NFIRAOS instrument,
- one high order visible Natural Guide Star (NGS)[3] wavefront sensor, which is used for operation without LGS,
- one Truth Wavefront Sensor (TWFS), which is used to calibrate for slow-varying biases due to temporal variations in the sodium layer profile in LGS AO mode,
- and the RTC, which processes the inputs from the LGS or NGS and on instrument wavefront sensors to compute the commands of the deformable mirrors and tip/tilt stage.

The RTC will interface with additional telescope and AO sub-systems, including the AO Sequencer, the NFIRAOS Component Controller, the Laser Guide Star Facility System, the NFIRAOS instruments, the NFIRAOS Truth Wavefront Sensor (TWFS) and the Data Management System (DMS).

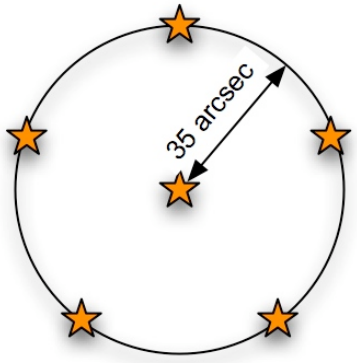

Figure 1: NFIRAOS asterism. NFIRAOS will utilize 6 laser guide stars, 5 equally spaced on a radius of 35 arcsec, and one additional on-axis guide star.

The following figure is a block diagram of the NFIRAOS facility.

[2] Referenced as OIWFS in the rest of the document.
[3] Referenced as NGS WFS in the rest of the document

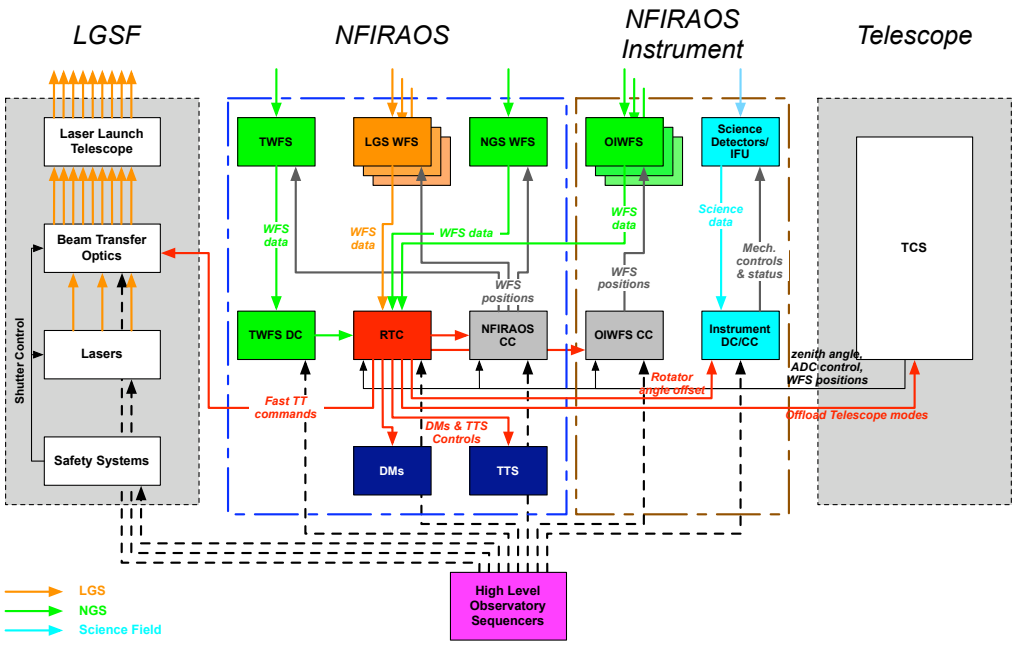

Figure 2: NFIRAOS AO LGS block diagram

2.2 SYSTEM FUNCTIONS

The RTC shall provide all control functions for the TMT NFIRAOS system that are required for calibration, test, and real-time atmospheric turbulence compensation. It shall operate under the control of the TMT Adaptive Optics Sequencer (AOSQ) to execute instructions provided either by users or the AOSQ itself. It shall accept and process input from a suite of wavefront sensors, including six LGS wavefront sensors, up to three low-order NGS wavefront sensors located within each NFIRAOS instrument, and a higher-order NGS wavefront sensor. It shall compute and apply commands to two deformable mirrors and one tip/tilt stage on the basis of these WFS measurements. It shall interface with additional telescope and AO subsystems as necessary for real-time atmospheric turbulence compensation. It shall update and optimize the control algorithms used for the above purposes in real time as observing parameters and atmospheric conditions change. It shall report status information in real time, and log inputs, intermediate quantities, and outputs for further data reduction and analysis. It shall provide built-in diagnostics and be fully operable and maintainable by observatory staff.

The RTC shall implement all the functions described above, but the responsibility to assemble these functions into overall calibration and observing sequences belongs to the AO Sequencer and the OCS.

2.3 USER AND OPERATOR CHARACTERISTICS

The RTC will be operated, during observations, via the AO Sequencer software. The users of this sub-system are:

- The telescope operator (during night time). The telescope operator shall be able to perform basic functions such as configuring the RTC and starting and stopping the loops. The telescope operator shall be able to assess the overall health and status of the RTC.

- The AO crew, who shall be able to run any function of the RTC during system integration, test, commissioning, and trouble-shooting.

2.4 EXTERNAL INTERFACES

The NFIRAOS RTC external interfaces are listed in Table 1.

External Interfaces	ICD	Description
Interface with NFIRAOS sub-systems.	Sections of the internal ICD: NFIRAOS to NFIRAOS RTC ICD [RD2]	- RTC mechanical and electrical interface (includes, but not limited to, weight, volume and power dissipation) - Interface between RTC and Component Controller: LGS trombone offset - Interface between RTC and TWFS Detector Controller: LGS/NGS reference vector and TWFS gradients in seeing limited mode - Interface between RTC and NGS Fast Steering Mirror drive electronics: NGS dither commands - Interface between NFIRAOS RTC and NFIRAOS Interlock System: RTC events
Interface with Deformable Mirror Electronics (DME)	Internal ICD: NFIRAOS RTC to NFIRAOS DME ICD [RD3]	- Commands of the DMs - Configuration is performed via AO Sequencer and DME Assembly software components
Interface with Tip Tilt Stage (TTS)	Internal ICD: NFIRAOS RTC to NFIRAOS TTS ICD [RD4]	- Commands of the TTS - Configuration is performed via AO Sequencer and TTS Hardware Control Daemon software components
Interface with LGS WFS	Internal ICD: NFIRAOS VCAM to NFIRAOS RTC ICD [RD5]	- Pixels - Configuration is performed via AO Sequencer and LGS WFS Assembly software components
Interface with NGS WFS	Internal ICD: NFIRAOS VCAM to NFIRAOS RTC ICD [RD5]	- Pixels - Configuration is performed via AO Sequencer and NGS WFS Assembly software components
Interface with IRIS	Sections of the level 2 ICD: NFIRAOS to IRIS ICD [RD6]	- Interface between NFIRAOS RTC and IRIS OIWFS DC: Pixels - Configuration is performed via AO Sequencer and IRIS OIWFS DC

		software components - Interface between NFIRAOS RTC and IRIS OIWFS Component Controller: rotator angle, OIWFS reference vectors, OIWFS ellipticities and rotator angle offset.
Interface with IRMS	Sections of the level 2 ICD: NFIRAOS to IRMS ICD [RD7]	- Interface between NFIRAOS RTC and IRMS OIWFS DC: Pixels. Configuration is performed via AO Sequencer and IRMS OIWFS DC software components - Interface between NFIRAOS RTC and IRMS OIWFS Component Controller: rotator angle, reference vector and OIWFS ellipticity
Interface with TCS	Section of the level 2 ICD: TCS to NFIRAOS ICD [RD8]	- From TCS: zenith angle - To TCS: Telescope modes including M1 scalloping
Interface with LGSF	Sections of the level 2 ICD: NFIRAOS to LGSF ICD [RD9]	- Interface between NFIRAOS RTC and LGSF BTO/LLT Component Controller: FSM commands and positions
Interface with DMS	Section of the level 2 ICD: NFIRAOS to DMS ICD [RD10]	- Engineering telemetry
Interface with AOESW	Sections of the level 2 ICD: NFIRAOS to AOESW ICD [RD11]	- Interface between NFIRAOS RTC and AO Sequencer: commands, telemetry data, events and status - Interface between NFIRAOS RTC and Reconstructor Parameter Generator (RPG): RTC reconstructors, tomography matrices and parameters, temporal filter optimization parameters, noise covariance matrices, turbulence parameters, LGS/NGS WFS unusable sub-apertures. - Interface between NFIRAOS RTC and the PSF post reconstruction module: PSF statistical data
Interface with time bus	TBD ICD	- Interface with time bus will be defined in TMT generic ICD.[4]
Interface with WIRC and NIRES	*Sections of the level 2 ICD*	- *Same as Interface with IRIS*

Table 1: NFIRAOS RTC External Interfaces

[4] Refer to the requirement [REQ-1-OAD-4855] of the Observatory Architecture Document [AD3]. A possible standard for the time bus is the IEEE-1588-2008 and Precision Time Protocol (PTP) V2.

The software and control interfaces are described in the following figure:

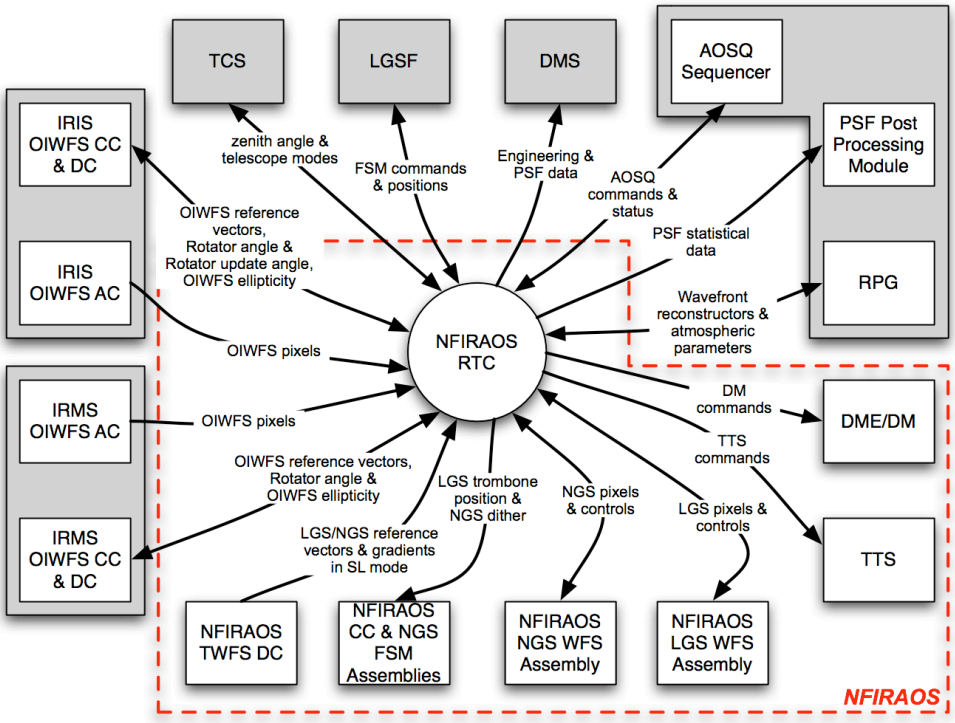

Figure 3: NFIRAOS RTC control context diagram

2.5 CONSTRAINTS

The RTC software shall be under the direct control of the Adaptive Optics Sequencer.

The RTC software shall comply with the TMT Observatory software standards and software development process specified in the OSW Vision Document.

The following areas may be updated in future releases:

- Computation of the LGS reference vector. In general, the architecture for the WFS reference vector computation may be reviewed (within TWFS, within RPG or other TBD component)
- Estimation of the residual uncorrected error
- Real time processing of any data required by PSF reconstruction
- DM and TTS control: treatment of clipping and including more sophisticated predictive algorithms for OIWFS modes
- OIWFS pixel processing: alternative algorithms to improve linear dynamic range
- OIWFS reconstruction: Non sideral objects tracking case should be considered. The current de-rotation architecture may need to be revisited
- Seeing limited mode processing
- NGS AO mode: new requirement for NGS WFS measurements offload to visible NGS path star selection mirror may be needed.

2.6 ASSUMPTIONS AND DEPENDENCIES

None

3. SPECIFIC REQUIREMENTS

3.1 ENVIRONMENTAL CONSTRAINTS

[REQ-3-NRTC-0005] The RTC design must be compatible with all operational, survival and transportation environmental conditions, stated in the ORD, [REQ-1-ORD-1050] through [REQ-1-ORD-1550], where applicable.

Discussion: the ORD refers to the Observatory Requirement Document [AD2].

3.2 FUNCTIONAL REQUIREMENTS

3.2.1 Main requirements

Discussion: NFIRAOS feeds up to three near IR instruments at once out of four possible options. IRIS and IRMS are the early light instruments.

IRIS will implement three identical OIWFS. Each OIWFS will be capable of sensing either tip/tilt/focus with a 2x2 Shack Hartmann lenslet array or only tip/tilt with a single lens. During AO operations, only one of these WFS will sense tip/tilt/focus (2x2 OIWFS), while the remainder will sense only tip/tilt. IRMS will only implement one 2x2 OIWFS.

IRMS will implement one 2x2 Shack Hartmann wavefront sensor capable of sensing tip/tilt/focus.

Two possible future instruments, WIRC and NIRES, will have the same configuration of three WFS as IRIS (IRMS would have to be replaced if both of these instruments are implemented). The RTC will interface to a maximum of 9 OIWFS.

[REQ-3-NRTC-0010] The RTC shall implement an LGS AO operation mode as illustrated in Figure 4.

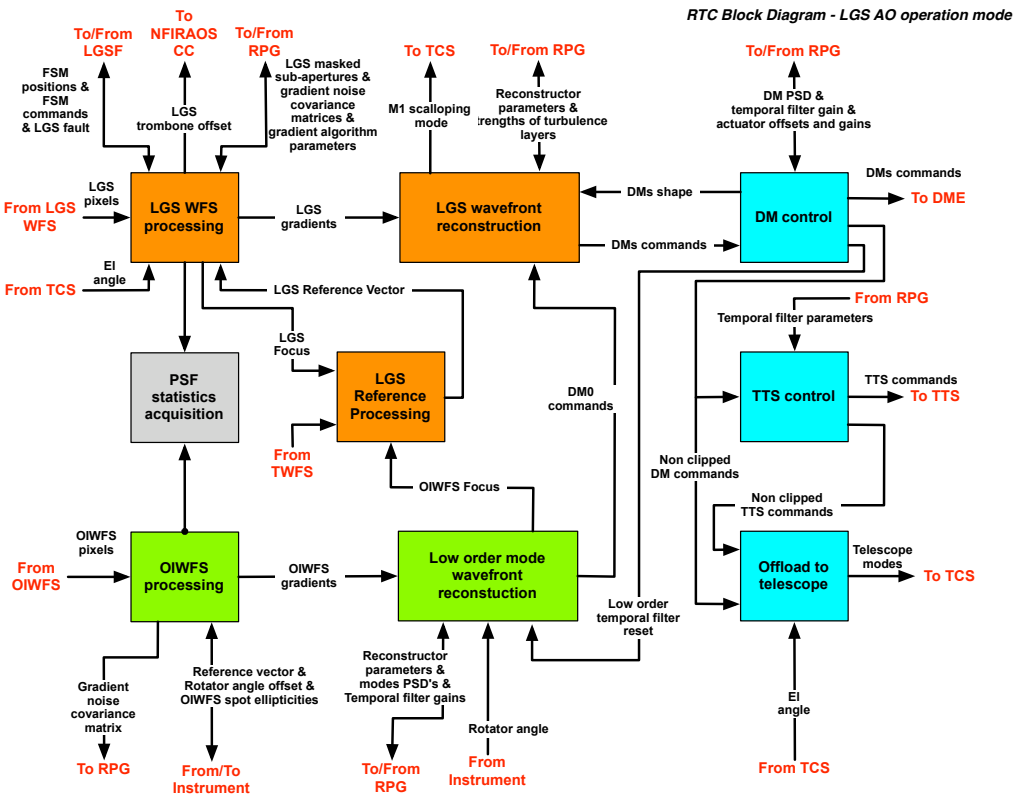

Figure 4: RTC block diagram for LGS AO operation mode

Discussion: In this mode, the RTC uses the six LGS WFS and up to three OIWFS to compute the commands of the two DMs and the TTS. The commands of the DMs and the TTS are offloaded to the telescope (active optics modes). A detailed version of the RTC block diagram for the LGS AO operation mode is given in the NFIRAOS RTC Algorithm Description document [RD1].

[REQ-3-NRTC-0015] The RTC shall implement an NGS AO operation mode as illustrated in Figure 5.

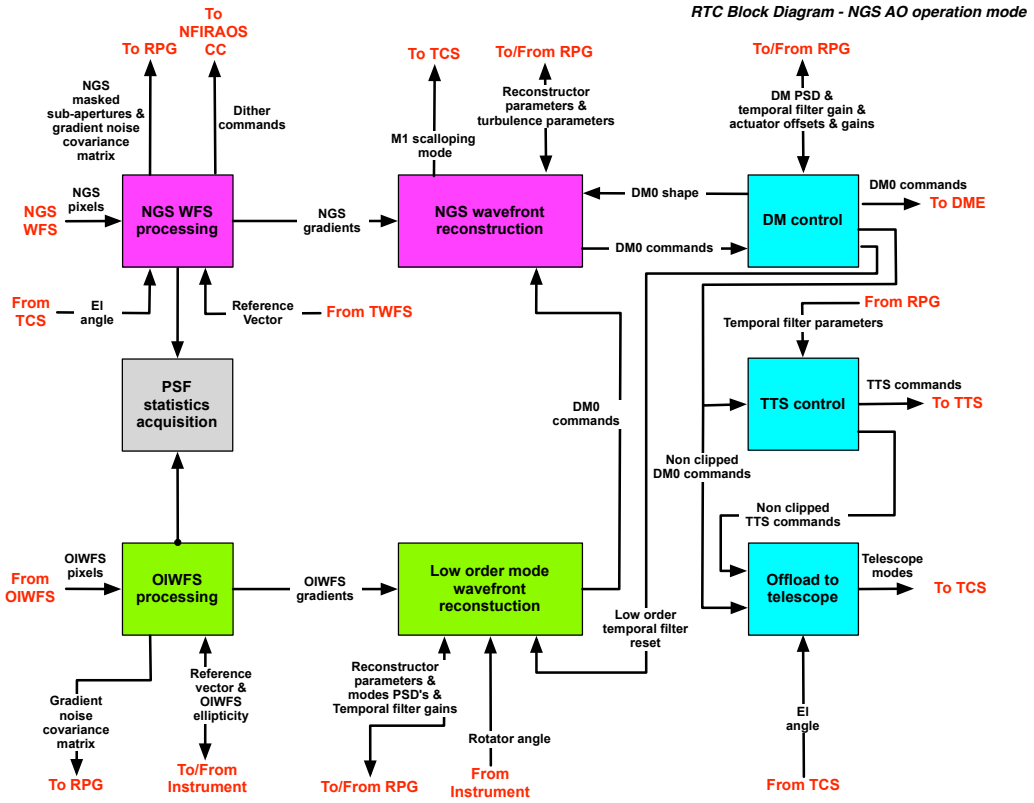

Figure 5: RTC block diagram for NGS AO operation mode

Discussion: In this mode, the RTC uses the high order NGS WFS and if possible the 2x2 OIWFS of the instrument to compute the commands of the DM0 and of the TTS (DM11.2 being flattened). The commands of the DM0 and the TTS are offloaded to the telescope (active optics modes). A detailed version of the block diagram for the NGS AO operation mode is given in the NFIRAOS RTC Algorithm Description document [RD1].

[REQ-3-NRTC-0020] The RTC shall implement a seeing limited operation mode as illustrated in Figure 6.

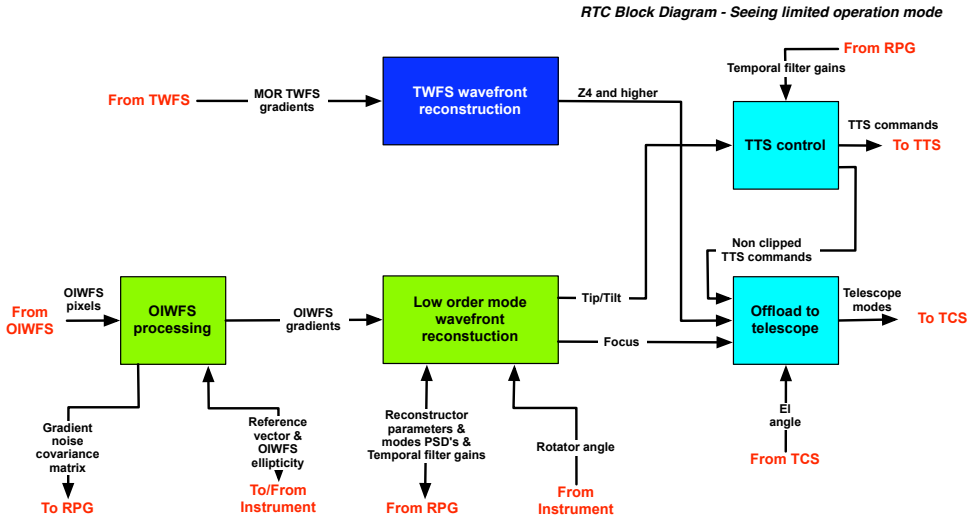

Figure 6: RTC block diagram for seeing limited operation mode

Discussion: In this mode, the RTC uses the TWFS and the 2x2 OIWFS to compute the TTS commands and the telescope modes (DM0 and DM11.2 being flattened). A detailed block diagram for the seeing limited operation mode is given in the NFIRAOS RTC Algorithm Description document [RD1].

[REQ-3-NRTC-0025] The RTC shall be configurable to select the AO operation mode, the client science instrument and which of the OIWFS within this instrument will be used.

3.2.2 LGS WFS Processing (LGS AO mode)

[REQ-3-NRTC-0030] The RTC shall be able to initialize the LGS WFS geometry to define which LGS WFS are active and which sub-apertures of each LGS WFS are illuminated. It is a requirement that the system will work with a reduced number of LGS WFS.

[REQ-3-NRTC-0035] The RTC shall input the LGS WFS pixel intensities from the six LGS WFS at the rates and in the formats specified in Table 2.

	1 LGS WFS	**6 LGS WFS**
Total number of illuminated sub-apertures per LGS WFS	2896	17376
Total number of pixels per frame	204792 pixels	~1.23 Mpixels
Total number of gradients per frame	5792	34752
Frame rate	800Hz	
Full frame readout time per LGS WFS	500μs	
Pixel format	2 bytes/pixel	
Pixel rate per LGS WFS	~410 Mpixel/s[5] per LGS WFS	

Table 2: LGS WFS parameters

Discussion: The LGS WFS CCD array is a "polar coordinate" CCD array designed specifically for use with elongated laser guide stars. The polar coordinates array is constituted of small rectangular islands of pixels oriented along lines radiating from the center of the array. The number of pixels per sub-aperture ranges from 6x6 to 6x15, and is

[5] With a 500μs readout time.

proportional to the amount of elongation. The interface between the LGS WFS and the RTC is described in the NFIRAOS VCAM to NFIRAOS RTC ICD [RD5].

[REQ-3-NRTC-0040] The RTC shall calibrate the LGS WFS pixel intensities, including flat fielding and dark subtraction (in particular Rayleigh background subtraction in case of CW lasers).

Discussion: The Rayleigh background calibration procedure is orchestrated by the AO Sequencer and involves the LGSF and the NFIRAOS RTC. It consists of the following steps:

- *LGSF: Shift the wavelength off the central frequency of the CW Lasers,*
- *RTC: Acquire a dark frame for the LGS WFS,*
- *LGSF: Shift back to the central frequency of the CW Lasers.*

[REQ-3-NRTC-0041] The RTC shall set to zero any LGS calibrated pixel intensities, which are negative.

[REQ-3-NRTC-0045] The RTC shall estimate the sub-aperture wavefront gradients from the LGS WFS pixel intensities using a constrained matched-filter processing algorithm.

Discussion: The wavefront gradients are computed as a weighted sum of the pixel intensities, with the matched filter weights computed as a background task. The algorithm is further described in the NFIRAOS RTC Algorithm Description document [RD1].

[REQ-3-NRTC-0050] The RTC shall null the gradients corresponding to sub-apertures, which are unusable due to the telescope structure obscuration.

Discussion: The lists of unusable sub-apertures due to telescope structure obscuration are pre-defined by the Reconstructor Parameter Generator (RPG) and stored into the RTC for all the zenith angles varying from 0 to 65 degrees with step of 0.1 degrees. The RTC gets the actual zenith angle from the TCS at a rate of 1Hz and retrieves the list of unusable sub-apertures corresponding to this angle. Note that the list is identical for all the LGS WFS. The interface between the Telescope Control System and NFIRAOS is described in the TCS to NFIRAOS ICD [RD8]. The interface between the NFIRAOS RTC and the RPG will be described in the NFIRAOS to AOESW ICD [RD11].

[REQ-3-NRTC-0055] While computing the gradients, the RTC shall estimate the intensity level for each sub-aperture and shall detect any additional sub-apertures, which are unexpectedly below the illumination threshold. The gradient measurements for such subapertures shall be set to zero.

[REQ-3-NRTC-0060] The RTC shall generate an internal interlock signal to the NFIRAOS Interlock System, if the number of non-illuminated subapertures for an individual LGS WFS exceeds a pre-defined threshold. In this case, the RTC shall automatically stop all the loops and processes associated with the LGS AO mode.

Discussion: This interface is described in details in the NFIRAOS to NFIRAOS RTC ICD [RD2].

[REQ-3-NRTC-0065] The RTC shall detect sub-apertures with a consistently low or highly variable intensity level, and output the list of these sub-apertures to the Reconstructor Parameter Generator (RPG) at a rate of 1 Hz.

Discussion: This process will enable the detection of additional unusable sub-apertures due to M3 alignment problems or Rayleigh backscatter variability. The algorithm to detect these unusable sub-apertures is described in NFIRAOS RTC Algorithm Description document [RD1]. The RPG will update the LGS wavefront reconstructor based on this list. The interface between the NFIRAOS RTC and the RPG will be described in the NFIRAOS to AOESW ICD [RD11].

[REQ-3-NRTC-0070] The RTC shall update the constrained matched filter coefficients for estimating the sub-aperture wavefront gradients in real time at a rate of 1 Hz, with a **goal** of 10 Hz, to adapt to variations in the seeing and the sodium layer profile. The LGS pointing mirrors shall be dithered for this purpose. The update of the LGS constrained matched filter coefficients shall not disturb the computation of the LGS WFS gradients (e.g., by increasing latency or skipping a frame).

Discussion: The LGS constrained matched filter coefficients are updated all at once without disturbing the gradient computation process (for example use of double buffering mechanisms, etc…). Line-of-sight dithering is used to measure the derivatives of the LGS WFS pixel intensities with respect to sub-aperture x- and y-tilt. These derivatives are one of the quantities used to compute the matched filter algorithm. The algorithm used to optimize the LGS gradient estimation algorithm coefficients is described in the NFIRAOS RTC Algorithm Description document [RD1].

[REQ-3-NRTC-0075] The RTC shall compute the LGS WFS gradient noise (and associated inverse) matrices and output them to the RPG, in real time at a rate of 1 Hz, with a **goal** of 10 Hz, concurrently with the optimization of the coefficients of the constrained matched filter.

Discussion: The algorithm used to compute the LGS WFS noise covariance matrices is described in the NFIRAOS RTC Algorithm Description document [RD1]. The interface between the NFIRAOS RTC and the RPG will be described in the NFIRAOS to AOESW ICD [RD11].

[REQ-3-NRTC-0076] For each LGS WFS, the RTC shall reconstruct the tip/tilt and focus drift terms from the corresponding reference pixel intensity vector of the LGS constrained matched filter using a standard center of gravity algorithm and a simple matrix multiplication at a rate of 3.33Hz.

Discussion: The computation of the LGS drift modes consists of 3 steps: (i) the computation of the centroids using a standard center of gravity algorithm with the reference pixel intensity vectors as inputs, (ii) the nulling of the unusable sub-apertures as defined in [REQ-3-NRTC-0050] and (iii) the computation of the drift modes themselves using a simple matrix multiplication per LGS. The LGS gradient-to-TTF control matrices are also used to compute the LGS tip/tilt/focus modes in [REQ-3-NRTC-0080] and updated at a rate of 1Hz synchronously with the computation of the LGS WFS gradient noise covariance matrix [REQ-3-NRTC-0081]. The algorithm used to compute the tip/tilt and focus drift terms is described in the NFIRAOS RTC Algorithm Description document [RD1].

[REQ-3-NRTC-0077] The RTC shall output the focus drift term (averaged from the LGS drift focus modes) to adjust the position of the LGS trombone mechanism in order to track the variations in the range of the sodium layer.

Discussion: The RTC is not responsible for controlling the LGS trombone mechanism. The RTC is responsible for computing the focus drift terms from the LGS reference pixel intensity vectors and transferring the averaged value to the NFIRAOS Component Controller. The NFIRAOS Component Controller uses this term to adjust the position of the

LGS trombone corrector mechanism. The interface between the RTC and the NFIRAOS Component Controller is described in the NFIRAOS to NFIRAOS RTC ICD [RD2].

[REQ-3-NRTC-0080] The RTC shall compute the full aperture tip/tilt/focus modes for each LGS WFS at a 800Hz rate.

Discussion: The LGS tip/tilt modes are used to compute the commands of the LGSF fast tip/tilt mirrors, which in turn are used to stabilize the LGS pointing on the sky. The LGS focus term is used to compute the LGS WFS reference vector.

[REQ-3-NRTC-0081] The RTC shall update the matrices used in the computation of the full aperture LGS tip/tilt/focus modes at a rate of 1 Hz, synchronously with the computation of the LGS WFS gradient noise covariance matrices without disturbing the computation of the full aperture LGS tip/tilt/focus modes.

Discussion: The full aperture LGS tip/tilt/focus mode computation parameters are updated all at once without disturbing the LGS tip/tilt/focus mode computation process (for example, by implementation of double buffering mechanisms, etc…). The algorithm used to compute the LGS gradient-to-TTF control matrices is described in the NFIRAOS RTC Algorithm Description document [RD1].

REQ-3-NRTC-0082] The RTC shall combine the LGS tip/tilt drift terms with the LGS tip/tilt modes at a 800Hz rate.

[REQ-3-NRTC-0085] The LGS pointing commands shall be temporally filtered and modulated by a dither component, to optimize the matched filter coefficients used to estimate the LGS gradients as described in the requirement [REQ-3-NRTC-0070] stated above.

Discussion: The LGSF implements one high-bandwidth tip/tilt Fast Steering Mirror (FSM) per laser beam. These mirrors are dedicated to compensate for jitter in the position of the LGS on the sky as measured by the associated LGS WFS. The algorithm to compute the LGS pointing commands is described in the NFIRAOS RTC Algorithm Description document [RD1]. The interface between the LGSF and the RTC is described in the NFIRAOS to LGSF ICD [RD9].

[REQ-3-NRTC-0090] The RTC shall subtract the LGS WFS reference measurements from the LGS gradient measurements.

[REQ-3-NRTC-0095] The RTC shall input updates of the LGS WFS reference measurements at a rate of 800Hz without disturbing the LGS process.

Discussion: The LGS WFS reference measurements are updated all at once without disturbing the LGS WFS reference measurements subtraction process (for example, by use of double buffering mechanisms, etc…). The algorithm used to compute the LGS WFS reference measurements from the TWFS inputs and the focus measurements from both the LGS WFS and OIWFS is described in the NFIRAOS RTC Algorithm Description document [RD1].

Discussion: The start of the exposure and the readout time for the LGS WFS CCD arrays are synchronized with the laser pulse in the event that a pulsed laser is utilized, with a timing error no greater than 1 μsec. The LGS WFS timing signals are generated by the NFIRAOS Time Generator, which is synchronized to the AO master clock and controlled by the AO Sequencer. The LGS WFS timing signals are generated based on the laser pulse start and length and the range to the sodium layer.

3.2.3 NGS WFS Processing (NGS AO mode)

[REQ-3-NRTC-0105] The RTC shall initialize the geometry of the NGS WFS (list of illuminated sub-apertures).

[REQ-3-NRTC-0110] For NGS AO observations, the RTC shall input the pixel intensities from the high-order NGS WFS at the rates and in the formats specified in Table 3.

	NGS WFS
Number of pixels per sub-aperture	4x4 or 2x2
Total number of illuminated sub-apertures	2896
Total number of pixels per frame	Up to 46336 pixels
Total number of gradients per frame	5792
Frame rate	10Hz to 800Hz as required by the NGS signal level[6].
Full frame readout time	Minimum of 500μs
Pixel format	2 bytes/pixel
Pixel rate	Up to 93 Mpixel/s[7]

Table 3: NGS WFS parameters

Discussion: The NGS WFS will use a sub-electron read noise 256x256 CCD: the MIT/LL AODP CCID74. Two readout modes will be implemented: full frame readout with 4x4 pixels per sub-aperture and closed loop readout mode with 2x2 pixels per sub-aperture. The interface between the NGS WFS and the RTC is described in the NFIRAOS VCAM to NFIRAOS RTC ICD [RD5].

Discussion: The exposure of the NGS WFS is synchronized with the 2x2 OIWFS in the event that 2x2 OIWFS is utilized in addition to the NGS WFS, with a timing error no greater than 1 μs. The synchronization is performed by the NFIRAOS Time Generator, which is synchronized to the AO master clock and controlled by the AO Sequencer.

[REQ-3-NRTC-0120] The RTC shall calibrate the NGS WFS pixel intensities, including flat fielding and sky background subtraction.

[REQ-3-NRTC-0121] The RTC shall set to zero any NGS calibrated pixel intensities which are negative.

[REQ-3-NRTC-0125] The RTC shall estimate the sub-aperture wavefront gradients from the above pixel intensities using a standard quadrant detector algorithm.

Discussion: The NGS WFS quadrant detector algorithm is described in the NFIRAOS RTC Algorithm Description document [RD1].

[REQ-3-NRTC-0130] The RTC shall null the gradients corresponding to the sub apertures which are unusable due to the telescope structure obscuration.

Discussion: The lists of unusable sub-apertures due to telescope structure obscuration are pre-defined by the RPG and stored into the RTC for all the zenith angles varying from 0 to 65 degrees with step of 0.1 degrees. The RTC gets the actual zenith angle from the TCS at a rate of 1Hz and retrieves the list of unusable sub-apertures corresponding to this angle. The interface between the Telescope Control System and NFIRAOS is described in

[6] There is no requirement to adjust the frame rate in real time.
[7] With a 500μs readout time.

the TCS to NFIRAOS ICD [RD8]. The interface between the NFIRAOS RTC and the RPG will be described in the NFIRAOS to AOESW ICD [RD11].

[REQ-3-NRTC-0135] While computing the gradients, the RTC shall also estimate the intensity level for each sub-aperture, and shall detect at each frame any additional sub-apertures, which are unexpectedly below the illumination threshold. The gradient measurements for such sub-apertures shall be set to zero.

[REQ-3-NRTC-0140] The RTC shall automatically stop all the loops and processes associated with the NGS AO mode if more than a pre-defined number of the NGS sub-apertures falls below the illumination threshold.

[REQ-3-NRTC-0145] The RTC shall detect sub-apertures with a consistently low intensity level, and output the list of these sub-apertures to the RPG at a rate of 1Hz.

Discussion: This process will allow the detection of additional unusable sub-apertures due to an M3 alignment problem. The algorithm to detect these unusable sub-apertures is described in NFIRAOS RTC Algorithm Description document [RD1]. The RPG will update the NGS wavefront reconstructor based on this list. The interface between the NFIRAOS RTC and the RPG will be described in the NFIRAOS to AOESW ICD [RD11].

[REQ-3-NRTC-0150] The RTC shall update the NGS WFS gradient estimation algorithm in real-time based upon variations in seeing and AO system performance at a rate of at least 0.1 Hz. The update of the NGS WFS gradient estimation algorithm parameters shall be done without disturbing the NGS WFS gradients estimation process. A dedicated fast steering mirror located in the NGS path shall be dithered for this purpose.

[REQ-3-NRTC-0151] The RTC shall output the commands of the NGS fast steering mirror to the NGS fast steering mirror drive electronics at a rate of NGS WFS sampling rate.

Discussion: The NGS WFS gradient estimation algorithm parameters are updated all at once without disturbing the NGS WFS gradient estimation process (for example, by use of double buffering mechanisms, etc…). The algorithm to optimize the NGS gradient estimation algorithm coefficients is described in the NFIRAOS RTC Algorithm Description document [RD1]. The interface between the RTC and NFIRAOS to control the NGS fast steering mirror is described in the NFIRAOS to NFIRAOS RTC ICD [RD2].

[REQ-3-NRTC-0155] The RTC shall compute the NGS WFS gradient noise covariance matrix in real time at a rate of at least 0.1 Hz and output it to the RPG, concurrently with the optimization of the NGS WFS gradient algorithm parameters.

Discussion: The algorithm used to compute the NGS WFS noise covariance matrix is described in the NFIRAOS RTC Algorithm Description document [RD1]. The interface between the NFIRAOS RTC and the RPG will be described in the NFIRAOS to AOESW ICD [RD11].

[REQ-3-NRTC-0160] The RTC shall subtract the NGS WFS reference measurements from the NGS gradient measurements at the NGS frame rate.

[REQ-3-NRTC-0165] The RTC shall input updates of the NGS WFS reference measurements from the TWFS at rate of up to 0.1 Hz without disturbing the NGS process.

Discussion: The NGS WFS reference measurements are updated all at once without disturbing the NGS WFS reference measurements subtraction process (for example, by use of double buffering mechanisms, etc…) from the TWFS. Mainly the NGS WFS

reference measurements are computed based on the science non-common path aberration vector de-rotated in real time to account for the instrumentation rotation and the NGS path non-common path aberration vector. The interface between the NFIRAOS RTC and the TWFS is described in the NFIRAOS to NFIRAOS RTC ICD [RD2].

[REQ-3-NRTC-0170] During an NGS AO acquisition sequence, the RTC shall check whether the NGS falls within the FOV of the NGS WFS and, if it is the case, shall define the appropriate NGS WFS integration time.

Discussion: The algorithm used to check the presence of NGS WFS spots and to define the NGS WFS integration time during an NGS AO acquisition sequence is described in the NFIRAOS RTC Algorithm Description document [RD1]. The interface between the RTC and the AO Sequencer will be described in the NFIRAOS to AOESW ICD [RD11].

3.2.4 OIWFS Processing

[REQ-3-NRTC-0175] The RTC shall input the pixel intensities from up to 3 OIWFS located in the NFIRAOS instrument at the rates and in the formats specified in Table 4.

	OIWFS
Number of OIWFS per instrument	2 1x1 SH 1 2x2 SH
Number of pixels per OIWFS	1024x1024 (full frame) Windowing down to 4x4 with a 14x14 (TBC) re-capture window during closed loop operations
Frame rate	10Hz to 800Hz as required by the OIWFS signal level[8].
Full frame readout time	Minimum of 500μs
Pixel format	2 bytes/pixel
Pixel rate per OIWFS	TBD

Table 4: OIWFS Parameters

Discussion: The current baseline for the IRIS OIWFS implements one quadrant of an Hawaii2RG 2048x2048 HgCdTe detector. The interface between the OIWFS and the RTC is described in the NFIRAOS to IRIS ICD [RD6] and in the NFIRAOS to IRMS ICD [RD7].

Discussion: The exposures of the OIWFS are synchronized with the LGS WFS, with a timing error no greater than 1 μs. The synchronization is performed by the NFIRAOS Time Generator, which is synchronized to the AO master clock and controlled by the AO Sequencer.

[REQ-3-NRTC-0185] The RTC shall calibrate the OIWFS pixel intensities, including flat fielding and background subtraction.

[REQ-3-NRTC-0186] The RTC shall set to zero any OIWFS calibrated pixel intensities, which are negative.

[REQ-3-NRTC-0190] The RTC shall estimate sub-aperture wavefront gradients, or the full aperture wavefront tilt in the case of a tip/tilt sensor, using a constrained matched filter algorithm.

[8] There is no requirement to adjust the frame rate in real time.

[REQ-3-NRTC-0191] The RTC shall determine the peak pixel intensity of each OIWFS sub-apertures and apply the constrained matched filter to a subset of pixels centered around the sub-aperture peak pixel.

[REQ-3-NRTC-0192] During a small telescope move, the RTC shall be able to switch the OIWFS gradient estimation algorithm to a standard thresholded centroid algorithm in no more than one OIWFS frame, and compute centroids only for the 2x2 subaperture OIWFS.

Discussion: The constrained matched filter algorithm is described in the NFIRAOS RTC Algorithm Description document [RD1]. During a small telescope move performed during a line-of-sight telescope dither, the NFIRAOS RTC will keep the tip/tilt loop closed with the brightest guide star (via an update of the modal reconstructor) and will switch the gradient estimation algorithm to a standard centroid algorithm.

[REQ-3-NRTC-0195] While computing the gradients, the RTC shall also estimate the intensity level for each sub-aperture, and shall detect any sub-apertures where the illumination falls below a specified threshold. The gradient measurements for such sub-apertures shall be set to zero.

[REQ-3-NRTC-0205] The RTC shall update the OIWFS gradient estimation algorithm in real-time based upon variations in seeing and AO system performance at a rate of at least 0.1 Hz and without disturbing the OIWFS gradient estimation algorithm.

Discussion: The OIWFS gradient estimation algorithm parameters are updated all at once without disturbing the OIWFS gradient estimation process (for example, by use of double buffering mechanisms, etc…). The algorithm to optimize the OIWFS gradient estimation algorithm coefficients is described in the NFIRAOS RTC Algorithm Description document [RD1].

[REQ-3-NRTC-0210] The RTC shall compute the OIWFS gradient noise covariance matrices in real time at a rate of at least 0.1 Hz and output them to the RPG, concurrently with the optimization of the NGS WFS gradient algorithm parameters.

Discussion: The algorithm used to compute the OIWFS gradient noise covariance matrix is described in the NFIRAOS RTC Algorithm Description document [RD1]. The interface between the NFIRAOS RTC and the RPG will be described in the NFIRAOS to AOESW ICD [RD11].

[REQ-3-NRTC-0211] The RTC shall subtract the OIWFS reference vectors from the OIWFS gradient measurements at the OIWFS frame rate.

[REQ-3-NRTC-0212] The RTC shall initialize the OIWFS reference vectors before each science observation.

Discussion: The OIFWS reference vectors are initialized by the OIWFS Component Controller. By default the OIWFS reference vectors are set to zero. Updating the OIWFS reference vectors in real time to compensate for positioning errors of the OIWFS mechanisms is TBD at the moment. The interface between the RTC and the OIWFS Component Controller is described in the NFIRAOS to IRIS ICD [RD6] and in the NFIRAOS to IRMS ICD [RD7].

[REQ-3-NRTC-0215] During an acquisition sequence (Either LGS AO mode, NGS AO mode, or seeing limited mode), the RTC shall verify that a low order NGS guide star falls within the FOV of the corresponding OIWFS, compute the spot position errors and focus

error in the case of the 2x2 OIWFS, adjust the position of the tip/tilt stage if required, and report missing spots and spot brightness to the AO Sequencer.

Discussion: The acquisition sequences are not completely defined at the moment but it is expected that the RTC, OIWFS Component Controller, and OIWFS Detector Controller will work in concert to adjust the position of the spots on the detector while reducing the window size. The focus mode will be sent to the LGS reference vector computation process as during closed loop operation. The tip/tilt modes will be sent directly to the TTS using a simple integrator instead of the type II control algorithm. The algorithm used to check OIWFS spots during an acquisition sequence is described in the NFIRAOS RTC Algorithm Description document [RD1]. The interface between the RTC and the AO Sequencer will be described in the NFIRAOS to AOESW ICD [RD11].

[REQ-3-NRTC-0220] When 3 OIWFS are used in the LGS AO mode, the RTC shall compute the residual field rotation based on the OIWFS measurements at a rate of 20Hz and output it to the NFIRAOS instrument.

Discussion: The algorithm to compute the residual field rotation is described in the NFIRAOS RTC Algorithm Description document [RD1]. The interface between the RTC and the OIWFS Component Controller is described in the NFIRAOS to IRIS ICD [RD6].

[REQ-3-NRTC-0226] The RTC shall compute the average ellipticity (orientation and magnification) of each OIWFS spot at a rate of 20Hz and output the OIWFS ellipticities to the OIWFS Component Controller.

Discussion: The algorithm to compute the OIWFS ellipticities is TBD at the moment and will be included in the NFIRAOS RTC Algorithm Description document [RD1]. The interface between the NFIRAOS RTC and the OIWFS Component Controller is described in the NFIRAOS to IRIS ICD [RD6] and in the NFIRAOS to IRMS ICD [RD7].

3.2.5 LGS wavefront reconstruction

[REQ-3-NRTC-0230] In LGS AO mode, the RTC shall reconstruct each frame of the LGS WFS measurements into DMs commands at the rate of 800Hz using a computationally efficient implementation of a minimum variance wavefront reconstructor.

Discussion: Unless specified otherwise, the DM commands in this section are defined as an offset to the DM flat command needed to correct for the DM figure errors and non common path aberrations.

[REQ-3-NRTC-0235] First, the RTC shall compute the LGS pseudo open loop gradients based upon the DM commands and the LGS WFS gradient measurements.

[REQ-3-NRTC-0236] The RTC shall compute at a 0.2Hz rate the M1 scalloping mode from the LGS open loop gradients and output the M1 scalloping mode to the Telescope Control System.

Discussion: *The algorithm to compute the M1 scalloping mode is described in the NFIRAOS RTC Algorithm Description document [RD1]. The interface to transfer the telescope modes is described in the TCS to NFIRAOS ICD [RD8].*

[REQ-3-NRTC-0240] Then, the tip/tilt and differential focus modes shall be removed from the LGS pseudo open loop gradients.

[REQ-3-NRTC-0245] Next, the RTC shall use one of the following algorithms for the tomography step:

- Fourier Domain Pre-Conditioned Conjugate Gradient (FDPCG),
- Conjugate Gradient (CG),
- Un-symmetric Block Gauss-Seidel (BGS) with Cholesky Back Substitution (CBS) solution of the diagonal blocks,
- Un-symmetric BGS with CG solution of the diagonal blocks,

Discussion: The algorithms used for the LGS tomography step are described in the NFIRAOS RTC Algorithm Description document [RD1].

[REQ-3-NRTC-0250] Finally, the RTC shall use a combination of sparse matrix vector multiplications and the CG algorithm for the DM fitting step.

Discussion: The algorithms used for the DM fitting step are described in the NFIRAOS RTC Algorithm Description document [RD1].

[REQ-3-NRTC-0251] The RTC shall subtract the DM commands from the output of the fitting step.

[REQ-3-NRTC-0255] The RTC shall initialize the LGS wavefront reconstruction parameters before each science observation.

Discussion: The LGS wavefront reconstruction parameters are initialized by the RPG based upon the low order NGS WFS asterism geometry, the LGS signal levels, the pupil orientation upon the deformable mirrors and the WFS lenslet arrays (which determines which sub-apertures are obscured by the secondary mirror and the tripod legs), the estimated range to the sodium layer and the estimated atmospheric turbulence profile. The interface between the RPG and the RTC will be described in the NFIRAOS to AOESW ICD [RD11].

[REQ-3-NRTC-0260] The RTC shall input updates of the LGS wavefront reconstruction parameters from the RPG at a rate of 0.1 Hz without disturbing the LGS wavefront reconstruction process.

Discussion: The LGS wavefront reconstruction parameters are computed and updated in real time by the RPG based upon variations in the estimated range to the sodium layer, pupil orientation upon the wavefront correctors and the WFS lenslet arrays and the estimated atmospheric turbulence parameters. This includes not only the parameters of the tomography step, but also the parameters of the fitting step and of the tip/tilt and tip/tilt anisoplanatism mode removal. The wavefront reconstruction parameters are updated at once without disturbing the wavefront reconstruction process (for example, by using double buffering mechanisms, etc…). The interface between the RPG and the RTC will be described in the NFIRAOS to AOESW ICD [RD11].

[REQ-3-NRTC-0265] The tip/tilt and tip/tilt anisoplanatism modes shall be removed from the DM actuator commands following the LGS fitting step.

Discussion: The tip/tilt and tip/tilt anisoplanatism modes of the overall wavefront reconstruction are computed separately from the higher order LGS modes determined by the LGS AO wavefront reconstruction process (split tomography). The algorithm used to remove the tip/tilt and tip/tilt anisoplanatism modes from the output of the fitting step is described in the NFIRAOS RTC Algorithm Description document [RD1].

3.2.6 NGS wavefront reconstruction

[REQ-3-NRTC-0270] In NGS AO mode, the RTC shall reconstruct each frame of the NGS WFS measurements into DM0 commands at the NGS WFS frame rate using a computationally efficient implementation of a minimum variance wavefront reconstructor.

Discussion: Unless specified otherwise, the DM commands in this section are defined as an offset to the DM flat command needed to correct for the DM figure errors and non common path aberrations.

[REQ-3-NRTC-0275] First, the RTC shall reconstruct the NGS pseudo open loop gradients based upon the DM commands and the measured NGS WFS gradients.

[REQ-3-NRTC-0276] The RTC shall compute at a 0.2Hz rate the M1 scalloping mode from the NGS open loop gradients and output the M1 scalloping mode to the Telescope Control System.

Discussion: *The algorithm to compute the M1 scalloping mode is described in the NFIRAOS RTC Algorithm Description document [RD1]. The interface to transfer the telescope modes is described in the TCS to NFIRAOS ICD [RD8].*

[REQ-3-NRTC-0280] Then, the tip/tilt modes shall be removed from the NGS pseudo open loop gradients if the client instrument 2x2 OIWFS is used in addition to the NGS WFS

[REQ-3-NRTC-0285] Next, the RTC shall use one of the proposed LGS tomography algorithms for the NGS tomography step, simplified to the case of a single WFS and atmospheric layer.

Discussion: The algorithms used for the NGS tomography step are described in the NFIRAOS RTC Algorithm Description document [RD1].

[REQ-3-NRTC-0290] Finally, the RTC shall use a combination of sparse matrix vector multiplication and Conjugate Gradient algorithms for the DM fitting step.

Discussion: The algorithm used for the NGS fitting step is described in details in the NFIRAOS RTC Algorithm Description document [RD1].

[REQ-3-NRTC-0291] The RTC shall subtract the DM0 commands from the output of the fitting step.

[REQ-3-NRTC-0295] The RTC shall initialize the NGS wavefront reconstruction parameters before each science observation.

Discussion: The NGS wavefront reconstruction parameters are initialized by the RPG based upon the guide star separation (TBC), the NGS signal/noise level, the pupil orientation upon the deformable mirrors and the WFS lenslet arrays (which determines which sub-apertures are obscured by the secondary mirror and the tripod legs), and the estimated atmospheric turbulence profile. The interface between the RPG and the RTC will be described in the NFIRAOS to AOESW ICD [RD11].

[REQ-3-NRTC-0300] The RTC shall input updates of the NGS wavefront reconstruction parameters from the RPG at a rate of 0.1 Hz without disturbing the NGS wavefront reconstruction process.

Discussion: The NGS wavefront reconstruction parameters are computed and updated in real time by the RPG based upon variations in the estimated NGS signal/noise level, pupil orientation upon the wavefront correctors and the WFS lenslet arrays and the estimated

atmospheric turbulence parameters. . This includes not only the parameters of the NGS phase estimation step, but also the parameters of the fitting step. The wavefront reconstruction parameters are updated at once without disturbing the wavefront reconstruction process (for example, by using double buffering mechanisms, etc…). The interface between the RPG and the RTC will be described in the NFIRAOS to AOESW ICD [RD11].

[REQ-3-NRTC-0305] The tip/tilt/focus modes shall be removed from the DM0 actuator commands after the NGS fitting step if the client instrument 2x2 OIWFS is used in addition to the NGS WFS.

Discussion: The low rank modes of the overall wavefront reconstruction are computed separately from the higher order NGS modes in the NGS AO tomographic reconstruction (split tomography) if the client instrument 2x2 OIWFS is used in addition to the NGS WFS. The algorithm used to remove the tip/tilt/focus modes from the output of the fitting step is described in the NFIRAOS RTC Algorithm Description document [RD1].

[REQ-3-NRTC-0306] The DM0 actuator commands shall be scaled by a gain coefficient and resampled to the 2x2 OIWFS frame rate if the client instrument 2x2 OIWFS is used in addition to the NGS WFS.

3.2.7 On-instrument wavefront reconstruction

[REQ-3-NRTC-0310] The RTC shall estimate the following low-rank wavefront modes from the OIWFS gradient measurements:

- tip/tilt/focus and tip/tilt anisoplanatism in LGS AO mode
- tip/tilt/focus in NGS AO mode and seeing limited mode

Discussion: The algorithm to compute these low-rank modes is described in the NFIRAOS RTC Algorithm Description document [RD1]. The low rank modes of the overall wavefront reconstruction are computed via a direct matrix vector multiply, separately from the higher order modes, in either LGS AO or NGS AO wavefront reconstruction (Split tomography).

[REQ-3-NRTC-0315] The RTC shall initialize the OIWFS reconstructor before each science observation.

[REQ-3-NRTC-0320] The RTC shall input updates of the OIWFS reconstructor from the RPG at a rate of 0.1Hz without disturbing the OIWFS wavefront reconstruction process.

Discussion: The OIWFS reconstructor is computed, initialized and (in the case of observations utilizing multiple OIWFS) updated in real time by the RPG based on the OIWFS asterism, the OIWFS probe arm mechanism angle, the OIWFS measurement noise, and the telescope line-of-sight dither. For example, during a telescope dither move, the tip/tilt loop is kept closed based only on the inputs from the 2x2 OIWFS (a new OIWFS reconstructor is updated for that purpose). The tipt/tilt anisoplanatism and focus feed to the LGS reference vector computation process are stopped. The OIWFS reconstructor is updated at once without disturbing the wavefront reconstruction process (for example, by using double buffering mechanisms, etc…). The interface between the RPG and the NFIRAOS RTC will be described in the NFIRAOS to AOESW ICD [RD11].

[REQ-3-NRTC-0325] The RTC shall apply a lead controller followed by an integrator with gain to the OIWFS modes (i) at the LGS WFS frame rate in LGS AO mode, (ii) at the 2x2 OIWFS frame rate in NGS AO mode with additional 2x2 OIWFS and (iii) at the 2x2 OIWFS frame rate in seeing limited operation mode, to enhance control loop stability.

Discussion: The lead filter parameters and integrator gain are updated from the RPG synchronously with the DM and TTS temporal filter parameters (see [REQ-3-NRTC-420] and [REQ-3-NRTC-422]).

[REQ-3-NRTC-0330] The RTC shall de-rotate the OIWFS modes into the NFIRAOS coordinate system based on the instrument rotator angle. The RTC shall input updates of this angle at a rate of 20Hz.

Discussion: The OIWFS rotator angle is transferred to the RTC by the OIWFS Component Controller. The interface between the RTC and the OIWFS Component Controller is described in the NFIRAOS to IRIS ICD [RD6] and in the NFIRAOS to IRMS ICD [RD7]. Note that the OIWFS probe arm angles are fixed and are included in the computation of the modal reconstructor by the RPG.

[REQ-3-NRTC-0340] In NGS AO mode, the RTC shall transform the filtered tip/tilt/focus modes into DM0 actuator commands and add them to the outputs of the NGS wavefront reconstruction process.

[REQ-3-NRTC-0345] In LGS AO mode, the RTC shall transform the filtered tip/tilt and tip/tilt anisoplanatism modes into the DMs actuator commands, and add them to the output of the LGS wavefront reconstruction process.

Discussion: In LGS AO mode, only tip/tilt and tilt anisoplanatism modes are projected to the DMs. The focus mode is used to compute the LGS WFS reference vector. In NGS AO mode, the tip/tilt/focus modes are projected to the DM0. In seeing limited operation mode, the tip/tilt modes [REQ-3-NRTC-0325] are directly used to control the TTS and the focus mode [REQ-3-NRTC-0325] is directly offloaded to the telescope.

[REQ-3-NRTC-0346] During an acquisition process, the RTC shall be able to transform the tip/tilt modes computed from the 2x2 OIWFS into TTS error signals and send the TTS error signals to the TTS.

3.2.8 Active Optics mode computation in the seeing limited operation mode

[REQ-3-NRTC-0355] In the seeing limited mode, the RTC shall use the TWFS gradients to compute the high order telescope active optics modes. The RTC shall obtain the high order telescope active optics modes via a simple vector matrix multiply.

Discussion: This includes zernike modes up to the 5^{th} radial order and excludes the tip/tilt/focus modes which are computed from the 2x2 OIWFS measurements. In seeing limited mode, tip/tilt modes computed from the 2x2 OIWFS measurements are used to drive the TTS. Focus computed from the 2x2 OIWFS measurements is directly offloaded to the telescope with the higher order modes computed from the TWFS measurements. The TTS commands are then offloaded to the telescope. The interface between the TWFS and the RTC is described in the NFIRAOS to NFIRAOS RTC ICD [RD2].

3.2.9 Turbulence profile estimation

[REQ-3-NRTC-0370] In LGS AO mode, the RTC shall estimate the following atmospheric and AO performance parameters at a rate of at least 0.1 Hz:

- The strengths of the turbulence layers,
- The Fried parameter r_0 and the seeing,
- The atmospheric time constant τ_0,
- The isoplanatic angle θ_0,
- The outer scale L_0,

- The generalized isoplanatic angle θ_M for two fixed DMs (θ_2),
- An estimate of the residual uncorrected error.

[REQ-3-NRTC-0371] In LGS AO mode, the RTC shall output the strengths of the turbulence layers to the RPG.

Discussion: The algorithms used to estimate the atmospheric parameters are described in the NFIRAOS RTC Algorithm Description document [RD1]. The strengths of the turbulence layers are used as input to the RPG to define the wavefront reconstruction parameters in the case of the BGS-CBS and FDPCG tomography algorithms. The interface between the RPG and the NFIRAOS RTC will be described in the NFIRAOS to AOESW ICD [RD11].

[REQ-3-NRTC-0375] In NGS AO mode, the RTC shall estimate the following atmospheric and AO performance parameters at a rate of at least 0.1 Hz:

- The Fried parameter r_0 and the seeing,
- The atmospheric time constant τ_0,
- The outer scale L_0,
- An estimate of the residual uncorrected error.

Discussion: The algorithms used to estimate the atmospheric parameters are described in the NFIRAOS RTC Algorithm Description document [RD1].

3.2.10 Wavefront corrector control

[REQ-3-NRTC-0380] The RTC shall initialize the geometry of the DMs (which DM, and which active and slaved actuator locations per DM). It is a requirement that the system will work with DM0 only and/or with a number of reduced actuators (in the case of dead or detached actuators). The number of DM actuators is given in the Table 5.

	Active actuators	**Edge actuators**	**Total actuators/DM**
DM0	2821	304	3125
DM11.2	4160	388	4548
Total	6981	692	7673

Table 5: DM0 and DM11.2 number of actuators

Discussion: The interface between the RTC and the DM's electronics is described in the NFIRAOS RTC to NFIRAOS DME ICD [RD3].

[REQ-3-NRTC-0385] During calibration sequences, the RTC shall move individual actuators or specified pattern of actuators of one or both of the DM's.

[REQ-3-NRTC-0390] The RTC shall flatten DM11.2 during NGS AO operation and both DM0 and DM11.2 during seeing limited operation. The flat vector shall be updated in real time from the RPG at a rate of up to 20Hz to account for the instrumentation rotation.

Discussion: "Flattening" actually applies a static command vector to the DM actuators to correct the fixed wavefront aberrations in NFIRAOS and its client instrument.

[REQ-3-NRTC-0395] During calibration sequences, the RTC shall command the individual modes of the TTS.

Discussion: The interface between the RTC and the TTS electronics is described in the NFIRAOS RTC to NFIRAOS TTS ICD [RD4].

[REQ-3-NRTC-0400] In LGS and NGS AO mode, the RTC shall apply a simple integrator with adjustable gain to the DM commands computed by the wavefront reconstruction process, to enhance loop stability and balance the residual wavefront errors due to WFS measurement noise and time delay.

[REQ-3-NRTC-0405] In LGS and NGS AO mode, the RTC shall implement a type II control algorithm for tip/tilt and tip/tilt anisoplanatism correction.

Discussion: Note that the TTS is used as the woofer (low-bandwidth-high-stroke device) and the DM0 is used as the tweeter (high-bandwidth-low-stroke device).

[REQ-3-NRTC-0410] In LGS and NGS AO mode, the RTC shall project the DM actuator commands into TTS commands.

[REQ-3-NRTC-0415] In LGS and NGS AO mode, the RTC shall apply a low pass filter to the TTS commands.

[REQ-3-NRTC-0416] During acquisition sequences, the RTC shall apply a simple integrator with adjustable gain to the tip/tilt modes computed by the OIWFS wavefront reconstruction process.

[REQ-3-NRTC-0420] In LGS AO mode, the RTC shall input from the RPG at a rate of 0.1Hz, the DM, OIWFS and TTS temporal filter parameters and update them synchronously without disturbing the LGS closed loop processes.

Discussion: The temporal filter parameters are updated at once without disturbing the OIWFS wavefront reconstruction and the wavefront corrector control processes (for example, by using double buffering mechanisms, etc…).

[REQ-3-NRTC-0421] In NGS AO mode with an additional 2x2 OIWFS, the RTC shall input from the RPG at a rate of 0.1Hz, the DM, OIWFS and TTS temporal filter parameters, and update them synchronously without disturbing the NGS closed loop processes.

Discussion: The temporal filter parameters are updated at once without disturbing the wavefront corrector control and the OIWFS wavefront reconstruction processes (for example, by using double buffering mechanisms, etc…).

[REQ-3-NRTC-0422] In NGS AO mode without additional OIWFS, the RTC shall input from the RPG at a rate of 0.1Hz, the DM and TTS temporal filter parameters and update them synchronously without disturbing the NGS closed loop processes.

Discussion: The temporal filter parameters are updated at once without disturbing the wavefront corrector control process (for example, by using double buffering mechanisms, etc…).

[REQ-3-NRTC-0423] In seeing limited mode, the RTC shall input from the RPG at a rate of 0.1Hz the TTS temporal filter gain without disturbing the seeing limited closed loop processes.

Discussion: The temporal filter parameters are updated at once without disturbing the wavefront corrector control process (for example, by using double buffering mechanisms, etc…). The interface between the RPG and the NFIRAOS RTC will be described in the NFIRAOS to AOESW ICD [RD11].

REQ-3-NRTC-0425] In LGS AO mode, the RTC shall compute at a rate of 0.1Hz the Power Spectra Densities (PSD) of (i) the error signals to a subset of the DM actuators and (ii) the OIWFS modes. The RTC shall pass the computed PSD's to the RPG for use in the optimization of the temporal filters.

REQ-3-NRTC-0426] In NGS AO mode with an additional 2x2 OIWFS, the RTC shall compute at a rate of 0.1Hz the Power Spectra Densities (PSD) of (i) the error signals to a subset of the DM actuators and (ii) the OIWFS modes. The RTC shall pass the computed PSD's to the RPG for use in the optimization of the temporal filters.

[REQ-3-NRTC-0427] In NGS AO mode without additional OIWFS, the RTC shall compute the Power Spectra Densities (PSD) of the error signals to a subset of the DM actuators at a rate of 0.1Hz and pass them to the RPG for use in the optimization of the temporal filters.

[REQ-3-NRTC-0428] In seeing limited mode, the RTC shall compute the Power Spectra Densities (PSD) of the OIWFS modes at a rate of 0.1Hz and pass them to the RPG for use in the optimization of the temporal filters.

Discussion: The algorithm used to compute the PSD's is described in NFIRAOS RTC Algorithm Description document [RD1]. The interface between the RPG and the NFIRAOS RTC will be described in the NFIRAOS to AOESW ICD [RD11].

[REQ-3-NRTC-0430] In LGS and NGS AO mode, the RTC shall clip the DM actuator commands to avoid saturation based upon the dynamic range and slew rate limits of the DMs.

[REQ-3-NRTC-0431] In LGS and NGS AO mode, the RTC shall input the DM actuator thresholds used in the DM clipping process from the RPG at a rate of 1Hz without disturbing the LGS or NGS closed loop processes.

Discussion: The DM actuator thresholds are updated without disturbing the wavefront corrector control process (for example, by using double buffering mechanisms, etc…). The DM actuator thresholds are computed by the RPG based on the DM physical actuator limits and the system non-common path aberration flat vector for a given observation. The interface between the NFIRAOS RTC and the RPG is described in the NFIRAOS to AOESW ICD [RD11].

[REQ-3-NRTC-0435] In LGS and NGS AO mode, the RTC shall subtract the difference between the DM commands before and after clipping from the inputs to the integrator in order to prevent DM integrator windup.

[REQ-3-NRTC-0436] In LGS and NGS AO mode with an additional 2x2 OIWFS, the RTC shall project back to the NGS modes the difference between the DM commands before and after clipping to prevent OIWFS integrator windup.

[REQ-3-NRTC-0440] In LGS and NGS AO mode, the RTC shall clip the TTS actuator commands to avoid saturation based upon the dynamic range and slew rate limits of the TTS.

[REQ-3-NRTC-0455] In LGS and NGS AO mode, the RTC shall feedback the final DM actuator commands to the LGS and NGS wavefront reconstruction process for use in computing the pseudo-open loop WFS measurements.

[REQ-3-NRTC-0460] In LGS and NGS AO mode, the RTC shall compute "slaving" commands for the DM edge actuators in order to maintain a continuous mirror figure at the boundary.

[REQ-3-NRTC-0465] In LGS and NGS AO mode, the RTC shall calibrate DM actuator commands to account for any variations in the actuator gains and offsets due to temperature, via a lookup table.

[REQ-3-NRTC-0466] In LGS and NGS AO mode, the RTC shall input the DM actuator gains and offsets from the RPG at a rate of 0.1Hz and update them synchronously without disturbing the LGS or NGS closed loop processes.

Discussion: The DM actuator gains and offsets are updated at once without disturbing the wavefront corrector control process (for example, by using double buffering mechanisms, etc…). The DM actuator gains and offsets are computed by the RPG based on the temperature and the DM flat commands needed to correct to the DM figure errors and non common path aberrations for a dedicated observation. The interface between the NFIRAOS RTC and the RPG is described in the NFIRAOS to AOESW ICD [RD11].

[REQ-3-NRTC-0470] In the seeing limited case, the RTC shall apply a simple integrator with adjustable gain to the tip/tilt commands computed by the low order wavefront reconstruction process.

[REQ-3-NRTC-0475] In the seeing limited case, the RTC shall clip the TTS actuator commands to avoid saturation based upon the dynamic range and slew rate limits of the TTS.

[REQ-3-NRTC-0480] In the seeing limited case, the RTC shall subtract the difference between the TTS commands before and after clipping from the inputs to the integrator in order to prevent TTS integrator windup.

[REQ-3-NRTC-0485] In LGS and NGS AO mode, the RTC shall offload the persistent, low-spatial frequency components of the DM actuator commands and the TTS commands to the telescope.

[REQ-3-NRTC-0490] In LGS and NGS AO mode, the following low spatial frequency modes shall be transferred to the telescope:

- tip/tilt modes in arcsec on the sky, at a rate of 5Hz with a maximum latency of 2ms
- focus mode in RMS μm on the sky, at a rate of 1Hz with a maximum latency of 10ms
- coma modes in RMS μm on the sky, at a rate of 1Hz with a maximum latency of 10ms
- up to 100 M1 modes in the Noll Zernikes basis (TBC), excluding piston, tip/tilt, focus and coma, in RMS nanometer of wavefront, at a rate of 1Hz with a maximum latency of 10ms

[REQ-3-NRTC-0491] For LGS AO mode observations in which all 3 OIWFS are used, the following additional low spatial frequency modes shall be transferred to the telescope as part of the offload process:

- The curvature plate scale mode, in RMS nanometer of wavefront, at a rate of 1Hz with a maximum latency of 10ms. This mode is a combination of telescope primary mirror curvature and telescope secondary mirror focus.

[REQ-3-NRTC-0495] In the seeing limited case, the RTC shall offload the reconstructed higher-order wavefront errors and the persistent components of the TTS tip/tilt commands to the telescope.

[REQ-3-NRTC-0500] In the seeing limited case, the following telescope modes shall be transferred to the telescope:

- tip/tilt modes in arcsec on the sky, at a rate of 5Hz with a maximum latency of 2ms
- focus mode in RMS μm on the sky, at a rate of 1Hz with a maximum latency of 10ms
- coma modes in RMS μm on the sky, at a rate of 1Hz with a maximum latency of 10ms
- up to 5th order radial M1 modes in the Noll Zernikes basis (TBC), excluding piston, tip/tilt, focus and coma, in RMS nanometer of wavefront at a rate of 1Hz with a maximum latency of 10ms

[REQ-3-NRTC-0505] The RTC shall update the pupil rotation parameters of the offload process based upon the zenith angle of the telescope at a rate of 20 Hz.

Discussion: The process of offloading the wavefront corrector modes to the telescope is split into 3 steps: (i) low pass filter (ii) projection/scaling to the low-order wavefront mode and (iii) rotation into telescope pupil coordinates. It is still TBD whether the third step will be implemented within the RTC. The offload algorithm is described for all the cases in the NFIRAOS RTC Algorithm Description document [RD1]. The interface to transfer the telescope modes will be described in the TCS to NFIRAOS ICD [RD8]. The interface between the Telescope Control System and the RTC to receive the telescope zenith angle is described in the TCS to NFIRAOS ICD [RD8].

[REQ-3-NRTC-0510] In LGS and NGS AO mode, the AO loops shall remain closed unless a certain number of DM actuators reach their amplitude limits. Above this value, the AO loops shall be automatically stopped.

3.2.11 LGS reference processing

[REQ-3-NRTC-0520] In LGS mode only, the RTC shall estimate the NGS-to-LGS focus differences based upon the estimated 3D turbulence profile at a rate of 800Hz, and compute the average difference between the LGS WFS focus terms computed in [REQ-3-NRTC-0080] and the NGS-to-LGS focus differences.

[REQ-3-NRTC-0525] In LGS mode only, the RTC shall sum the defocus term computed from the OIWFS measurements with the difference computed in [REQ-3-NRTC-0520] at a rate of 800Hz.

[REQ-3-NRTC-0530] In LGS mode only, the RTC shall apply a low pass filter to the obtained “defocus” term at a rate of 800Hz.

[REQ-3-NRTC-0535] In LGS mode only, the RTC shall convert the output of the filtered defocus term into LGS gradients at a rate of 800Hz.

[REQ-3-NRTC-0540] In LGS mode only, the RTC shall receive LGS reference vector updates from the TWFS at a rate of 0.333Hz, without disturbing the LGS process.

[REQ-3-NRTC-0545] In LGS AO mode only, the RTC shall compute the LGS WFS reference vector by subtracting the LGS gradients obtained in [REQ-3-NRTC-0535] from

the LGS reference vector computed by the TWFS in [REQ-3-NRTC-0540] at a rate of 800Hz.

Discussion: The algorithm used to compute the LGS WFS reference vector is described in the NFIRAOS RTC Algorithm Description document [RD1]. The vector is computed based upon the defocus term estimated from the low order NGS measurements, the NGS-to-LGS delta focus derived from the 3D turbulence estimate, the defocus term estimated from the LGS measurements and the TWFS inputs (which are computed from the TWFS measurements, the science non-common path aberration vector de-rotated in real time to account for the instrument rotation and the LGS path non-common path aberration vector). The interface between the TWFS and the RTC is described in the NFIRAOS to NFIRAOS RTC ICD [RD2].

3.2.12 Telemetry

[REQ-3-NRTC-0550] The RTC shall implement a storage system to acquire and store up to one night of any combination of AO telemetry data as specified in Table 6:

RTC telemetry required storage	90TB (140TB as a goal)
RTC telemetry required data rate	3.5GB/s (5GB/s as a goal)

Table 6: RTC Telemetry Storage Requirements

Discussion: The AO telemetry data that can be selected include but are not limited to the WFS raw pixel values, the WFS gradients, the WFS sub-aperture intensities, all wavefront corrector commands, the servo loop parameters and all intermediate quantities computed by the wavefront reconstruction process.

[REQ-3-NRTC-0555] The AO telemetry data shall be accessible for diagnostic purposes, and for real time displays from the RTC or directly from MATLAB.

[REQ-3-NRTC-0556] The RTC telemetry storage shall be located in the TMT Observatory Computer Room with the following requirements as specified in Table 7:

RTC telemetry storage maximum volume	60U
RTC telemetry storage maximum power dissipation	6000Watts
RTC to RTC telemetry storage	Fibre channel

Table 7: RTC Telemetry Storage Interface Requirements

Discussion: Eventually, this requirement will be moved in the TMT Computer Room Requirement Document.

[REQ-3-NRTC-0557] The RTC telemetry storage shall be readable and writable simultaneously.

[REQ-3-NRTC-0560] The RTC shall interface with the engineering database of the Data Management System to archive all internal and relevant RTC time-stamped engineering variables (RTC health, RTC loop status, etc.) at selected rates of up to 20 Hz, as well as all commands received and responses sent.

3.2.13 PSF computation

[REQ-3-NRTC-0565] In LGS AO mode, the RTC shall acquire and output the following AO PSF statistical data to the RTC telemetry storage system at the indicated rate and in the specified format.

	Format	Rate
LGS WFS gradients	2 bytes/gradient	800Hz
LGS WFS noise gradient covariance matrices	4 bytes/element	1 Hz
OIWFS gradients	2 bytes/gradient	Between 10Hz and 800Hz
OIWFS noise gradient covariance matrices	4 bytes/element	0.1 Hz
Strengths of the turbulence layers	4 bytes/layer	0.1Hz
$r_{0,l}$(Fried parameter for layer *l*)	4 bytes/layer	0.1Hz
Maximum total rate		~60MB/s

Table 8: PSF statistical data for the LGS AO mode

Discussion: The PSF statistical data are used to post process the AO PSF for the corresponding observation.

[REQ-3-NRTC-0570] As a **goal**, the RTC shall compute the following quantities in real time while in LGS AO mode: (i) the LGS WFS structure functions from the LGS WFS measurements, and (ii) the gradient covariance matrix from the OIWFS measurements. The RTC shall output the LGS WFS structure functions and the OIWFS gradient covariance matrix to the Data Management System, along with the science observation data. As a **goal**, the size of each LGS WFS structure function shall be 128x128.

Discussion: The LGS structure functions and the gradient covariance matrix will be used to post-process the LGS AO PSF. The LGS WFS structure functions are computed based upon the LGS gradient covariance matrix computed during the science observation and the statistics of the LGS intensities per sub-aperture during the science observation. The algorithm used to compute the LGS structure functions and the gradient covariance matrix is described in the NFIRAOS RTC Algorithm Description document [RD1]. The LGS WFS structure functions are stored within the Data Management System along with the science data. The interface between the RTC and the Data Management System will be described in the NFIRAOS to DMS ICD [RD10].

[REQ-3-NRTC-0575] In NGS AO mode, the RTC shall acquire and output the following AO PSF statistical data to the RTC telemetry storage system at the indicated rate and in the specified format:

	Format	Rate
NGS WFS gradients	2 bytes/gradient	Between 10Hz and 800Hz
NGS WFS noise gradient covariance matrix	4 bytes/element	0.1 Hz
OIWFS gradients	2 bytes/gradient	Between 10Hz and 800Hz
OIWFS noise gradient covariance matrices	4 bytes/element	0.1 Hz
r0 Fried parameter	4 bytes	0.1Hz
Maximum total rate		~10MB/s

Table 9: PSF statistical data for the NGS AO mode

Discussion: The AO PSF statistical data are used to post process the AO PSF for the corresponding observation.

[REQ-3-NRTC-0580] As a **goal**, the RTC shall compute the following quantities in real time while in NGS AO mode: (i) the NGS WFS structure function from the NGS WFS measurements and (ii) the gradient covariance matrix from the OIWFS measurements in the case that the 2x2 OIWFS is utilized. The RTC shall output the NGS WFS structure functions and the gradient covariance matrix to the Data Management System along with the science data. As a **goal**, the size of the NGS WFS structure function shall be 128x128.

Discussion: The NGS structure function and the gradient covariance matrix will be used to post-process the NGS AO PSF. The NGS WFS structure function is computed based upon the NGS averaged slope covariance matrix computed during the science observation and the statistics of the NGS intensity per sub-aperture during the science observation. The algorithm used to compute the NGS structure function and the gradient covariance matrix is described in the NFIRAOS RTC Algorithm Description document [RD1]. The NGS WFS structure function and the tip/tilt covariance matrix are stored within the Data Management System along with the science data. The interface between the RTC and the Data Management System will be described in the NFIRAOS to DMS ICD [RD10].

3.2.14 Calibration mode

[REQ-3-NRTC-0585] The RTC shall operate in a calibration mode to apply wavefront corrector actuator commands on individual actuator or patterns, and input and process WFS pixels (LGS WFS, NGS WFS, OIWFS) as necessary to compute and store: WFS pixel gains and biases, WFS gradients and gradient algorithm parameters, DM-to-WFS influence matrices, and pupil alignment measurements on each WFS.

Discussion: It is currently planned that the WFS pixel gains, DM-to-WFS influence matrices, and pupil alignment estimates will be computed by the RPG. For these computations, the RTC will implement commands to: take WFS images, compute gradients, average these images and gradients, and pass the average values to the RPG. The control of the internal light sources used during the calibration process is the responsibility of the AO Sequencer and the NFIRAOS Component Controller.

3.3 PERFORMANCE REQUIREMENTS

3.3.1 End to End latency

[REQ-3-NRTC-0590] During LGS AO operation, the LGS WFS processing shall be performed synchronously with the digitization of the LGS WFS pixel intensities, with the final sub-aperture gradient computed within 10μsec after the final pixel has been received.

[REQ-3-NRTC-0595] During LGS AO operation, all the DM commands shall be computed within 1000 μsec after the final LGS WFS gradient has been computed, with a strong goal of 400 μsec.

[REQ-3-NRTC-0600] During LGS AO operation, the allowable latency to compute the LGS pointing commands shall be 50 μsec after the final LGS WFS pixel has been digitized.

Discussion: The total end-to-end latency for the LGS AO case is 1510 μsec with a goal of 910μsec. It includes the LGS WFS gradient computation, the wavefront reconstruction and the DM commands computation. It does not include the time to transfer the DM commands to the DME.

[REQ-3-NRTC-0605] During NGS AO operation, the NGS WFS processing shall be performed synchronously with the digitization of the NGS WFS pixel intensities, with the final sub-aperture gradient computed within 10μsec after the final pixel has been digitized.

[REQ-3-NRTC-0610] During NGS AO operation, DM0 commands shall be computed within 1000 μsec after the final NGS WFS gradient has been computed, with a strong goal of 400 μsec.

Discussion: The total end-to-end latency for the NGS AO case is 1510 μsec with a goal of 910μsec. It includes the NGS WFS gradient computation, the wavefront reconstruction and the DM commands computation. It does not include the time to transfer the DM commands to the DME.

[REQ-3-NRTC-0615] The real time updates of the algorithms used in WFS processing and wavefront reconstruction shall be implemented without skipping control loop cycles or opening control loops.

3.3.2 Initialization

[REQ-3-NRTC-0620] The time required to initialize and configure the RTC before each science observation shall be less than 10 sec.

Discussion: This includes but is not limited to the initialization of wavefront reconstruction parameter as described in the requirements [REQ-3-NRTC-0625], [REQ-3-NRTC-0630] and [REQ-3-NRTC-0635].

[REQ-3-NRTC-0625] The time to initialize the LGS tomographic reconstruction parameters shall be less than 1 s.

[REQ-3-NRTC-0630] The time to initialize the NGS tomographic reconstruction parameters shall be less than 1 s.

[REQ-3-NRTC-0635] The time to initialize the OIWFS reconstructor shall be less than 1 s.

3.3.3 Numerical precision

[REQ-3-NRTC-0640] The computations shall be done with a numerical precision of two bytes fixed point arithmetic except for the following cases, where four bytes floating point arithmetic is recommended (TBC):

- WFS gradient computation optimization (LGS WFS, NGS WFS and OIWFS)
- FSM command computation
- Wavefront reconstruction in particular the tomography and fitting tasks (includes also all real time and background tasks for all the wavefront reconstruction)
- Offload to telescope
- LGS reference processing

3.3.4 Stabilization

[REQ-3-NRTC-0645] For the first observation of a new science field in either LGS or NGS AO, the RTC loops shall stabilize in less than 20 sec, including all the optimization and background loops.

[REQ-3-NRTC-0650] During a dither in either LGS or NGS AO mode, the RTC loops shall stabilize in less than 5 sec.

Discussion: This is limited to the stabilization of the offloading loop with the telescope

[REQ-3-NRTC-0655] During a nod in LGS AO mode, the RTC loops shall be closed and stabilized in less than TBD sec.

Discussion: This includes the acquisition of new IR low order NGS guide star(s), closing the low order loops and stabilization of all the optimization and background loops

3.3.5 Acquisition

[REQ-3-NRTC-0660] During NGS AO acquisition, the process of NGS spot detection shall take less than 1 sec. The result shall be reported to the AO Sequencer.

Discussion: The interface between the RTC and the AO Sequencer will be described in the NFIRAOS to AOESW ICD [RD11].

[REQ-3-NRTC-0665] During NGS AO, LGS AO or seeing limited acquisition sequences, the process of OIWFS spot detection shall take less than 1 sec. The result shall be reported to the AO Sequencer.

Discussion: The interface between the RTC and the AO Sequencer will be described in the NFIRAOS to AOESW ICD [RD11].

3.4 SYSTEM ATTRIBUTES

3.4.1 Reliability & Availability

[REQ-3-NRTC-0670] The downtime budget of the RTC shall not exceed 0.1% of the overall science time budget.

Discussion: This corresponds to 3 hours of the 3000 hours of scheduled science observations per year. The NFIRAOS downtime budget is stated in the OAD, [REQ-1-OAD-0348]. It is defined as 0.4% of the overall science time budget.

[REQ-3-NRTC-0675] The RTC shall be designed for a lifetime of 10 years, with a maximum of 3200 hours/year of usage.

[REQ-3-NRTC-0680] The RTC mean time between failures shall be at least TBD hours with a goal of TBD hours.

3.4.2 Safety and Security

[REQ-3-NRTC-0685] The RTC design shall comply with the Environmental, Health, Safety and Security Requirements described in the ORD, [REQ-1-ORD-7000] through [REQ-1-ORD-7610].

3.4.3 Maintainability

[REQ-3-NRTC-0690] The RTC shall comply with the requirements defined in the ORD regarding preventive maintenance [REQ-1-ORD-1000] and maintainability [REQ-1-ORD-6105 and REQ-1-ORD-6110].

[REQ-3-NRTC-0695] The RTC shall be designed to be consistent with the servicing and replacement intervals and scenarios presented in the OAD [REQ-1-OAD-2845].

[REQ-3-NRTC-0700] All operation and routine maintenance of the RTC shall be performed by TMT AO staff.

3.5 SOFTWARE REQUIREMENTS

[REQ-3-NRTC-0710] The RTC shall include an engineering user interface. The engineering user interface shall (i) allow the control of all the individual functions implemented in the RTC and (ii) give access to all the parameters and data used by these functions for monitoring or editing.

[REQ-3-NRTC-0715] The RTC shall include very high bandwidth, flexible real time display tools.

[REQ-3-NRTC-0720] The following real time data shall be displayed, as raw data and/or temporal averages, RMS variability, and PSD's, at a rate of 20Hz and in the appropriate formats (3D, 2D, scope-type plots and images):

- LGS WFS images (pixels)
- LGS WFS gradients measurements and sub-aperture intensities
- LGS WFS trombone offset (including all intermediate quantities)
- LGS WFS reference vector
- LGSF FSM commands
- OIWFS images (pixels)
- OIWFS gradients and sub-apertures intensities
- The DMs and TTS actuator commands (including all intermediate vectors)
- Telescope offload modes
- NGS WFS images (pixels)
- NGS WFS gradients and sub-apertures intensities

Discussion: It is recommended that the display tool utilize standard windowing techniques to allow flexible selection, sizing, and positioning of the individual displays.

[REQ-3-NRTC-0725] The RTC shall support remote user interfaces and remote real time displays.

[REQ-3-NRTC-0730] The RTC shall interface with the AO Sequencer to receive commands and parameter messages and to send back response, status or event messages using the command service and event service of the TMT Common Software.

Discussion: The interface between the NFIRAOS RTC and the AO Sequencer will be described in the NFIRAOS to AOESW ICD [RD11]. This interface will be implemented via the TMT Observatory Common Software. Additional requirements may be defined to include compulsory commands and/or status required by the TMT Common Software (TBC).

[REQ-3-NRTC-0731] The RTC parameters used during WFS processing, WFS reconstruction or wavefront corrector control shall be initialized as specified by the AO Sequencer, via the AO Sequencer itself, via the RPG, via predefined configuration files, or LUT, or simply by using the previous values of these parameters.

[REQ-3-NRTC-0735] The RTC shall implement the following steps of the LGS acquisition sequence as individual commands:

- Init the RTC, which includes configuring the RTC for LGS operations, defining which instrument is used, which OIWFS are used and setting the WFS parameters
- Check the LGS WFS flux and report for error.
- Calibrate the LGS WFS (This is the LGS WFS dark measurement).
- Start LGS WFS processing. This includes the LGS WFS gradient computation, LGS WFS sub-aperture masking and reference vector subtraction, real-time parameter optimization for the LGS WFS gradient algorithm, drift modes computation, LGS zoom

offset computation, Tip/Tilt/Focus mode computation and LGSF FSM command computation.
- Close the high order loop. This includes the LGS wavefront reconstruction, the real time update of the wavefront reconstruction parameters, the DM/TTS control, the atmospheric parameters computation and offload to the telescope except for the focus mode.
- The following step will be executed in a loop controlled by the AO Sequencer:
    - Check for images on the 2x2 OIWFS, compute the centroids by using a thresholded standard centroid algorithm, compute the tip/tilt/focus modes, feed the focus mode to the LGS WFS reference vector computation process and control the TTS directly via a simple integrator filter. Report missing spots and spot brightness to the AO Sequencer.
- Close the tip/tilt loop with the 2xw2 OIWFS. This includes, switching the OIWFS standard centroid algorithm to the OIWFS constrained matched filter algorithm, optimizing the matched filter parameters in real time, computing the tip/tilt/focus modes, applying the low pass filter to the tip/tilt modes, and rotating/projecting the tip/tilt modes to the DM commands.
- Start the LGS WFS reference vector update process.
- Check if the other 2 OIWFS are illuminated (if multiple OIWFS are used):
    - Report for missing spots and spot brightness to the AO Sequencer
    - Compute centroids and report centroid offsets to the AO Sequencer
- Close the tip/tilt loop with all the OIWFS and close the tip/tilt anisoplanatism loop if 3 OIWFS are used. This includes an update of the OIWFS reconstructor.
- Start the OIWFS ellipticity computation and the instrument rotator angle offset computation if 3 OIWFS are used
- Start the temporal filter update .

Discussion: The LGS AO mode acquisition sequence is orchestrated by the Observatory Control System, the AO Sequencer, the TCS and the Instrument Sequencer. It includes additional steps, which are not described in the list given above.

[REQ-3-NRTC-0740] The RTC shall be able to stop all loops, background tasks, and optimization processes of the LGS AO operation mode at once.

[REQ-3-NRTC-0745] The RTC shall implement the following steps of the LGS AO stopping sequence as individual commands:

- Stop all loops and background/optimization processes except the LGS WFS processing and the computation of the LGSF FSM commands.
- Stop the LGS WFS processing.

Discussion: The LGS AO stopping sequence is orchestrated by the Observatory Control System, the AO Sequencer, the TCS and the Instrument Sequencer. It includes additional steps, which are not described in the list given above.

[REQ-3-NRTC-0750] The RTC shall implement the following steps of the NGS acquisition sequence as individual commands:

- Init the RTC, which includes configuring the RTC for NGS operations, defining which instrument is used, whether the 2x2 OIWFS is used and setting the WFS parameters
- Check for spots on the NGS WFS, and report the status and spot brightness .
- Adjust the NGS WFS integration time
- Calibrate the NGS WFS (sky background measurement).
- Close the higher order and tip/tilt/focus loops with the NGS WFS measurements. This includes the NGS WFS gradient computation, NGS WFS gradient algorithm parameter optimization, updating the NGS WFS reference vector, and NGS wavefront reconstruction without removing the tip/tilt/focus modes, and control of the DM0 and the TTS, the offload to the telescope and the atmospheric parameter computation.

- Start offloading the DM0 and TTS commands to the telescope.
- Check for images on the 2x2 OIWFS
    - Report for missing spots and spot brightness to the AO Sequencer
    - Compute centroids and report centroid offsets to the AO Sequencer
- Start filtering (removing) the tip/tilt/focus modes from the NGS wavefront reconstruction, and close the tip/tilt/focus loop using the 2x2 OIWFS measurements. This includes the 2x2 OIWFS gradient computation using the matched filter algorithm, optimizing the parameters for the 2x2 OIWFS gradient algorithm, OIWFS mode computation, OIWFS mode temporal filtering and the OIWFS mode rotation and projection onto DM0.
- Start the OIWFS ellipticity computation
- Start the temporal filter update

Discussion: The NGS AO mode acquisition sequence is orchestrated by the Observatory Control System, the AO Sequencer, the TCS and the Instrument Sequencer. It includes additional steps, which are not described in the list given above.

[REQ-3-NRTC-0755] The RTC shall be able to stop all loops and background/optimization processes of the NGS AO mode at once.

[REQ-3-NRTC-0760] The RTC shall implement the following steps of a seeing limited mode acquisition sequence as individual commands:

- Init the RTC, which includes configuring the RTC for seeing limited operations, defining which instrument is used, and setting the 2x2 OIWFS parameters
- Start offloading the TWFS modes to the telescope. This includes the computation of the TWFS modes.
- Check for images on the 2x2 OIWFS
    - Report for missing spots and spot brightness to the AO Sequencer
    - Compute centroids and report centroid offsets to the AO Sequencer.
- Close the tip/tilt loop with the TTS. This includes the OIWFS gradient computation, optimizing the OIWFS gradient algorithm parameters, the tip/tilt/focus mode computation ,the rotation and the control of the TTS. .
- Start offloading the focus mode to the telescope.
- Start offloading the TTS commands to the telescope.
- Start the OIWFS ellipticity computation
- Start the temporal filter update

Discussion: The seeing limited mode acquisition sequence is orchestrated by the Observatory Control System, the AO Sequencer, the TCS and the Instrument Sequencer. It includes additional steps, which are not described in the list given above.

[REQ-3-NRTC-0765] The RTC shall be able to stop all loops and background/optimization processes of the seeing limited operation mode at once.

[REQ-3-NRTC-0770] The RTC shall be able to start and stop the accumulation of the AO PSF statistical data independently of the other AO loops in both the LGS and NGS AO modes of operation.

Discussion: AO PSF statistical data accumulation, which is required to compute the AO PSF, shall be synchronized with the science observation.

[REQ-3-NRTC-0771] The RTC shall implement individual commands to stop all the RTC processes individually.

Discussion: This includes the LGS and NGS processes, the wavefront corrector control, and the OIWFS processes. For example, before moving the telescope during a telescope

dither sequence, the tip/tilt anisoplanatism loop is turned off as well as the focus estimation and the rotator angle offset update.

[REQ-3-NRTC-0775] The RTC shall generate a heartbeat signal (e.g., a square wave at 1Hz) to the LGSF Laser Interlock System.

[REQ-3-NRTC-0780] The RTC shall boot up from a cold start in less than 30s.

[REQ-3-NRTC-0785] The RTC shall initialize itself with a default configuration when booting.

[REQ-3-NRTC-0790] The RTC shall include automated diagnostic test functions.

[REQ-3-NRTC-0795] The RTC shall implement a high-level simulation mode, where the interface with the AO Sequencer is simulated.

Discussion: This simulation mode shall provide a way for the AO Sequencer to check command flow and sequencing. The commands from the AO Sequencer are received by the RTC, accepted or rejected but not executed.

[REQ-3-NRTC-0796] The RTC shall implement a low-level simulation mode, where WFS input streams are simulated.

Discussion: Predefined WFS spots images are generated by the RTC and used to test the wavefront reconstruction algorithms.

[REQ-3-NRTC-0800] The RTC shall be able to operate as a standalone system and shall work without the need for interfaces to other TMT sub-systems.

3.6 OTHER REQUIREMENTS

[REQ-3-NRTC-0810] The load of each processing unit shall not exceed 70%.

[REQ-3-NRTC-0815] The RTC shall implement a modular design to allow the system to be modified or upgraded for other AO systems.

Discussion: TMT plans to implement four additional instrumentation capabilities during the first decade of TMT. These instruments will include sophisticated AO systems:

- *An upgraded version of NFIRAOS (NFIRAOS Upgrade), which will implement order 120x120 LGS WFS and order 120x120 deformable mirrors. This system will require an upgraded version of the NFIRAOS RTC.*
- *A Mid IR AO (MIRAO) system, which will include 3 LGS WFS and either an order 30x30 deformable mirror or an adaptive secondary mirror. In both case, the dimension of this system should be well within the capacity of the NFIRAOS RTC.*
- *A Ground Layer Adaptive Optics (GLAO) system, which will implement 5 LGS WFS and an adaptive secondary mirror. The dimension of this system should be well within the capacity of the NFIRAOS RTC.*
- *A Multi Object Adaptive Optics (MOAO) System, which will implement 8 LGS WFS and between 10 and 20 order 60x60 MEMs wavefront correction. This system will require an upgraded version of the NFIRAOS RTC or a complete new design depending on the number of MEMs to control.*

4. APPENDIX: LIST OF REQUIREMENTS

REQ-3-NRTC-0005	Environmental constraints
REQ-3-NRTC-0010	LGS AO operation mode
REQ-3-NRTC-0015	NGS AO operation mode
REQ-3-NRTC-0020	Seeing limited operation mode
REQ-3-NRTC-0025	Configure RTC
REQ-3-NRTC-0030	Initialize LGS WFS geometry
REQ-3-NRTC-0035	Input LGS WFS pixel intensities
REQ-3-NRTC-0040	Calibrate LGS WFS pixel intensities
REQ-3-NRTC-0041	Clip LGS WFS calibrated pixel intensities
REQ-3-NRTC-0045	Estimate LGS WFS gradients
REQ-3-NRTC-0050	Null LGS WFS gradients due to telescope obscuration
REQ-3-NRTC-0055	Compute LGS WFS sub-aperture intensities and detect additional unusable sub-apertures
REQ-3-NRTC-0060	LGS WFS loss of signal: generate interlock to LGSF and stop all AO loops
REQ-3-NRTC-0065	Monitor low or highly variable LGS WFS sub-apertures
REQ-3-NRTC-0070	Update LGS WFS constrained matched filter coefficients
REQ-3-NRTC-0075	Compute LGS WFS gradient noise covariance matrices
REQ-3-NRTC-0076	Compute LGS T/T/F drift terms from the reference LGS WFS pixel intensity vector
REQ-3-NRTC-0077	Output the focus drift terms to NFIRAOS CC for control of LGS zoom corrector mechanisms
REQ-3-NRTC-0080	Compute LGSF TTF modes
REQ-3-NRTC-0081	Update LGS gradient-to-TTF matrices
REQ-3-NRTC-0082	Combine LGS TT drift terms with LGS TT modes and apply low pass filter
REQ-3-NRTC-0085	Apply temporal filter to LGS pointing commands and modulate by dither component
REQ-3-NRTC-0090	Subtract LGS WFS reference vector
REQ-3-NRTC-0095	Input LGS WFS reference vector
REQ-3-NRTC-0105	Initialize NGS WFS geometry
REQ-3-NRTC-0110	Input NGS WFS pixel intensities
REQ-3-NRTC-0120	Calibrate NGS WFS pixel intensities
REQ-3-NRTC-0121	Clip NGS WFS calibrated pixel intensities
REQ-3-NRTC-0125	Estimate NGS WFS gradients
REQ-3-NRTC-0130	Null NGS WFS gradients due to telescope obscuration

REQ-3-NRTC-0135	Compute NGS WFS sub-aperture intensities and detect additional unusable sub-apertures
REQ-3-NRTC-0140	NGS WFS loss of signal: stop all AO loops
REQ-3-NRTC-0145	Monitor low or highly variable NGS WFS sub-apertures
REQ-3-NRTC-0150	Update NGS WFS gradient estimation algorithm coefficients
REQ-3-NRTC-0151	Output NGS FSM commands to NGS FSM mirror
REQ-3-NRTC-0155	Compute NGS WFS gradient noise covariance matrix
REQ-3-NRTC-0160	Subtract NGS WFS reference vector
REQ-3-NRTC-0165	Input NGS WFS reference vector
REQ-3-NRTC-0170	Detect spots in NGS WFS during NGS AO acquisition sequence
REQ-3-NRTC-0175	Input OIWFS pixel intensities
REQ-3-NRTC-0185	Calibrate OIWFS pixel intensities
REQ-3-NRTC-0186	Clip OIWFS calibrated pixel intensities
REQ-3-NRTC-0190	Estimate OIWFS gradients
REQ-3-NRTC-0191	Estimate OIWFS sub-aperture image peak pixel
REQ-3-NRTC-0192	Use standard thresholded centroid algorithm
REQ-3-NRTC-0195	Compute OIWFS sub-aperture intensities and detect unusable sub-apertures
REQ-3-NRTC-0205	Update OIWFS gradient estimation algorithm coefficients
REQ-3-NRTC-0210	Compute OIWFS gradient noise covariance matrices
REQ-3-NRTC-0211	Subtract OIWFS reference vector
REQ-3-NRTC-0212	Initialize OIWFS reference vector
REQ-3-NRTC-0215	Detect spots in OIWFS during acquisition sequence
REQ-3-NRTC-0220	Compute residual field rotation
REQ-3-NRTC-0226	Compute OIWFS ellipticity
REQ-3-NRTC-0230	Reconstruct LGS WFS gradients into DMs commands
REQ-3-NRTC-0236	Compute the M1 scalloping mode and output to TCS
REQ-3-NRTC-0235	Compute LGS pseudo open loop gradients
REQ-3-NRTC-0240	Remove tip/tilt modes from LGS pseudo open loop gradients
REQ-3-NRTC-0245	Perform LGS tomography step
REQ-3-NRTC-0250	Perform LGS fitting step
REQ-3-NRTC-0251	Subtract clipped DM commands from fitting outputs
REQ-3-NRTC-0255	Init LGS wavefront reconstruction parameters
REQ-3-NRTC-0260	Update LGS wavefront reconstruction parameters
REQ-3-NRTC-0265	Remove tip/tilt and tilt anisoplanatism modes from DMs commands after LGS fitting step
REQ-3-NRTC-0270	Reconstruct NGS WFS gradients into DM0 commands

REQ-3-NRTC-0275	Compute NGS pseudo open loop gradients
REQ-3-NRTC-0276	Compute the M1 scalloping mode and output to TCS
REQ-3-NRTC-0280	Remove tip/tilt modes from NGS pseudo open loop gradients
REQ-3-NRTC-0285	Perform NGS tomography step
REQ-3-NRTC-0290	Perform NGS fitting step
REQ-3-NRTC-0291	Subtract clipped DM0 commands from fitting outputs
REQ-3-NRTC-0295	Init NGS wavefront reconstruction parameters
REQ-3-NRTC-0300	Update NGS wavefront reconstruction parameters
REQ-3-NRTC-0305	Remove tip/tilt/focus modes from DM0 commands after NGS fitting step
REQ-3-NRTC-0306	Resampling and gain if additional 2x2 OIWFS is utilized
REQ-3-NRTC-0310	Estimate low-rank modes from OIWFS gradients
REQ-3-NRTC-0315	Init OIWFS reconstructor
REQ-3-NRTC-0320	Update OIWFS reconstructor
REQ-3-NRTC-0325	Apply low pass filter to OIWFS modes
REQ-3-NRTC-0330	De-rotate the OIWFS modes
REQ-3-NRTC-0340	In NGS mode, transform tip/tilt/focus modes into DM0 commands
REQ-3-NRTC-0345	In LGS mode, transform tip/tilt and tilt anisoplanatism modes into DMs commands
REQ-3-NRTC-0346	During acquisition process, compute TTS commands
REQ-3-NRTC-0355	In seeing limited mode, input TWFS gradients to compute telescope modes
REQ-3-NRTC-0370	In LGS mode, estimate turbulence and AO performance parameters
REQ-3-NRTC-0371	In LGS mode, output strengths of turbulence layers to RPG
REQ-3-NRTC-0375	In NGS mode, estimate turbulence and AO performance parameters
REQ-3-NRTC-0380	Init DMs geometry
REQ-3-NRTC-0385	Apply DM commands
REQ-3-NRTC-0390	Flatten DMs
REQ-3-NRTC-0395	Apply TTS modes
REQ-3-NRTC-0400	Apply integrator to DMs commands
REQ-3-NRTC-0405	Apply woofer/tweeter to tip/tilt commands
REQ-3-NRTC-0410	Project DM command to TTS
REQ-3-NRTC-0415	Apply proportional integrator to TTS commands
REQ-3-NRTC-0416	During acquisition process, apply simple integrator to TTS commands
REQ-3-NRTC-0420	In LGS mode, update temporal filter parameters
REQ-3-NRTC-0421	In NGS mode with additional 2x2 OIWFS, update temporal filter parameters

REQ-3-NRTC-0422	In NGS mode without additional 2x2 OIWFS, update temporal filter parameters
REQ-3-NRTC-0423	In seeing limited, update temporal filter parameters
REQ-3-NRTC-0425	In LGS mode, compute PSDs
REQ-3-NRTC-0426	In NGS mode with additional 2x2 OIWFS, compute PSDs
REQ-3-NRTC-0427	In NGS mode without additional 2x2 OIWFS, compute PSDs
REQ-3-NRTC-0428	In seeing limited, compute PSDs
REQ-3-NRTC-0430	Clip DM commands
REQ-3-NRTC-0431	Input DM actuator thresholds for clipping from RPG
REQ-3-NRTC-0435	Prevent DM integrator windup
REQ-3-NRTC-0436	Prevent OIWFS integrator windup
REQ-3-NRTC-0440	Clip TTS commands
REQ-3-NRTC-0455	Feedback DM commands to LGS/NGS wavefront reconstruction process
REQ-3-NRTC-0460	Compute DM edge actuator commands
REQ-3-NRTC-0465	Calibrate DM commands
REQ-3-NRTC-0466	Input DM actuator calibration from RPG
REQ-3-NRTC-0470	In seeing limited mode, apply integrator to TTS commands
REQ-3-NRTC-0475	In seeing limited mode, clip TTS commands
REQ-3-NRTC-0480	In seeing limited mode, prevent TTS integrator windup
REQ-3-NRTC-0485	In LGS/NGS modes, offload DM and TTS commands to telescope
REQ-3-NRTC-0490	In LGS/NGS modes, telescope mode offload frequency and latency
REQ-3-NRTC-0491	In LGS mode, curvature plate scale mode offload frequency and latency
REQ-3-NRTC-0495	In seeing limited mode, offload DM and TTS commands to telescope
REQ-3-NRTC-0500	In seeing limited mode, telescope mode offload frequency and latency
REQ-3-NRTC-0505	Update offload process
REQ-3-NRTC-0510	AO loop stability
REQ-3-NRTC-0520	Estimate NGS-to-LGS focus difference
REQ-3-NRTC-0525	Input OIWFS focus term and combine all
REQ-3-NRTC-0530	Apply low pass filter to combined focus term
REQ-3-NRTC-0535	Convert filtered defocus term into LGS WFS reference vectors
REQ-3-NRTC-0540	Input common LGS WFS reference vector from TWFS
REQ-3-NRTC-0545	Compute LGS WFS reference vectors
REQ-3-NRTC-0550	RTC telemetry required storage and data rate
REQ-3-NRTC-0555	RTC telemetry storage accessibility
REQ-3-NRTC-0556	RTC telemetry storage interface requirements

REQ-3-NRTC-0560	Output engineering data to DMS
REQ-3-NRTC-0565	In LGS mode, acquire PSF statistical data
REQ-3-NRTC-0570	In LGS mode, compute LGS WFS structure functions for PSF reconstruction (goal)
REQ-3-NRTC-0575	In NGS mode, acquire PSF statistical data
REQ-3-NRTC-0580	In NGS mode, compute NGS WFS structure function for PSF reconstruction (goal)
REQ-3-NRTC-0585	Calibration mode
REQ-3-NRTC-0590	In LGS mode, LGS WFS processing latency
REQ-3-NRTC-0595	In LGS mode, DM commands processing latency
REQ-3-NRTC-0600	In LGS mode, LGSF FSM commands processing latency
REQ-3-NRTC-0605	In NGS mode, NGS WFS processing latency
REQ-3-NRTC-0610	In NGS mode, DM0 commands processing latency
REQ-3-NRTC-0615	Update real time algorithms without impacting real time algorithms
REQ-3-NRTC-0620	Time to init and configure RTC
REQ-3-NRTC-0625	Time to init LGS tomographic reconstruction parameters
REQ-3-NRTC-0630	Time to init NGS tomographic reconstruction parameters
REQ-3-NRTC-0635	Time to init TTF wavefront reconstruction parameters
REQ-3-NRTC-0640	Numerical precision
REQ-3-NRTC-0645	Time for AO loop stabilization
REQ-3-NRTC-0650	Time for AO loop stabilization after a telescope dither
REQ-3-NRTC-0655	Time for AO loop stabilization after a telescope nod
REQ-3-NRTC-0660	Time for NGS spot detection during NGS AO acquisition
REQ-3-NRTC-0665	Time for TTF spot detection during acquisition sequence
REQ-3-NRTC-0670	Down time budget
REQ-3-NRTC-0675	RTC lifetime
REQ-3-NRTC-0680	RTC MTBF
REQ-3-NRTC-0685	Environmental, Health, Safety and Security Requirements
REQ-3-NRTC-0690	Preventive maintenance
REQ-3-NRTC-0695	Servicing and replacement
REQ-3-NRTC-0700	RTC maintenance performed by TMT AO staff
REQ-3-NRTC-0710	Engineering User Interface (EUI)
REQ-3-NRTC-0715	High bandwidth, flexible real time display tools (RTD)
REQ-3-NRTC-0720	Real time data to be displayed with RTD
REQ-3-NRTC-0725	Remote EUI and RTD
REQ-3-NRTC-0730	Control of RTC by AO Sequencer

REQ-3-NRTC-0731	RTC parameters initialization
REQ-3-NRTC-0735	Implement LGS AO acquisition steps as individual commands
REQ-3-NRTC-0740	Stop LGS AO mode
REQ-3-NRTC-0745	Implement LGS AO stopping steps as individual commands
REQ-3-NRTC-0750	Implement NGS AO acquisition steps as individual commands
REQ-3-NRTC-0755	Stop NGS AO mode
REQ-3-NRTC-0760	Implement seeing limited acquisition steps as individual commands
REQ-3-NRTC-0765	Stop seeing limited mode
REQ-3-NRTC-0770	Start and stop PSF statistical data accumulation
REQ-3-NRTC-0771	Stop all RTC processes individually
REQ-3-NRTC-0775	Generate heartbeat signal
REQ-3-NRTC-0780	Time to boot up from cold start
REQ-3-NRTC-0785	Init with default configuration
REQ-3-NRTC-0790	Include automated diagnostic test functions
REQ-3-NRTC-0795	Implement high level simulation mode
REQ-3-NRTC-0796	Implement low level simulation mode
REQ-3-NRTC-0800	Operate as a standalone system
REQ-3-NRTC-0810	Load of each processing unit
REQ-3-NRTC-0815	Modular and upgradeable design