RETURN BIDS TO:
RETOURNER LES SOUMISSIONS À:

Bid Receiving Public Works and Government Services Canada/Réception des soumissions Travaux publics et Services gouvernementaux Canada
Pacific Region
401 - 1230 Government Street
Victoria, B.C.
V8W 3X4
Bid Fax: (250) 363-3344

REQUEST FOR PROPOSAL
DEMANDE DE PROPOSITION

Proposal To: Public Works and Government Services Canada

We hereby offer to sell to Her Majesty the Queen in right of Canada, in accordance with the terms and conditions set out herein, referred to herein or attached hereto, the goods, services, and construction listed herein and on any attached sheets at the price(s) set out therefor.

Proposition aux: Travaux Publics et Services Gouvernementaux Canada

Nous offrons par la présente de vendre à Sa Majesté la Reine du chef du Canada, aux conditions énoncées ou incluses par référence dans la présente et aux annexes ci-jointes, les biens, services et construction énumérés ici sur toute feuille ci-annexée, au(x) prix indiqué(s).

Comments - Commentaires

Vendor/Firm Name and Address
Raison sociale et adresse du fournisseur/de l'entrepreneur

Issuing Office - Bureau de distribution

Public Works and Government Services Canada - Pacific Region
401 - 1230 Government Street
Victoria, B. C.
V8W 3X4

Title - Sujet TMT-NFIRAOS ISM	
Solicitation No. - N° de l'invitation 31034-141412/A	**Date** 2014-10-30
Client Reference No. - N° de référence du client 31034-141412	
GETS Reference No. - N° de référence de SEAG PW-$VIC-250-6582	
File No. - N° de dossier VIC-4-37143 (250)	**CCC No./N° CCC - FMS No./N° VME**
Solicitation Closes - L'invitation prend fin **at - à 02:00 PM** **on - le 2014-11-21**	**Time Zone / Fuseau horaire** Pacific Standard Time PST
F.O.B. - F.A.B. Specified Herein - Précisé dans les présentes **Plant-Usine:** ☐ **Destination:** ☐ **Other-Autre:** ☑	
Address Enquiries to: - Adresser toutes questions à: Sole, Mike	**Buyer Id - Id de l'acheteur** vic250
Telephone No. - N° de téléphone (250) 363-8444 ( )	**FAX No. - N° de FAX** (250) 363-3344
Destination - of Goods, Services, and Construction: **Destination - des biens, services et construction:** NATIONAL RESEARCH COUNCIL HERZBERG INST. OF ASTROPHYSICS 5071 W. SAANICH RD. VICTORIA, BC V9E2E7 CANADA	

Instructions: See Herein

Instructions: Voir aux présentes

Delivery Required - Livraison exigée See Herein	**Delivery Offered - Livraison proposée**
Vendor/Firm Name and Address **Raison sociale et adresse du fournisseur/de l'entrepreneur** **Telephone No. - N° de téléphone** **Facsimile No. - N° de télécopieur**	
Name and title of person authorized to sign on behalf of Vendor/Firm (type or print) **Nom et titre de la personne autorisée à signer au nom du fournisseur/ de l'entrepreneur (taper ou écrire en caractères d'imprimerie)** **Signature**	**Date**

Canada

--- Ce blanc intentionnellement laissé de page ---

TABLE OF CONTENTS

List of Annexes:

Annex "A" Statement of Work
Annex "B" Basis of Payment
Annex "C" Contractor Disclosure of Foreground Information
Annex "D" Non-disclosure Agreement
Annex "E" Mandatory and Point Rated Technical Criteria
Annex "F" Task Authorization Form
Annex "G" Claim for Progress Payment Form PWGSC 1111

Due to the highly technical nature of the design documents, they are only available in English. Some documents will only be available on written request (email) to the Contracting Authority specified herein, including submission of the completed Annex D Non-disclosure agreement.

PART 1 - GENERAL INFORMATION

1. Introduction

The bid solicitation document is divided into six parts plus attachments and annexes as follows:

Part 1 General Information: provides a general description of the requirement;

Part 2 Bidder Instructions: provides the instructions, clauses and conditions applicable to the bid solicitation;

Part 3 Bid Preparation Instructions: provides bidders with instructions on how to prepare their bid;

Part 4 Evaluation Procedures and Basis of Selection: indicates how the evaluation will be conducted, the evaluation criteria that must be addressed in the bid, and the basis of selection;

Part 5 Certifications: includes the certifications to be provided;

Part 6 Resulting Contract Clauses: includes the clauses and conditions that will apply to any resulting contract.

The Annexes include the Statement of Work, the Basis of Payment and other annexes.

2. Background / Summary

Background

As a part of the Canadian contribution towards the Thirty Meter Telescope (TMT) project, staff at NRC Herzberg in collaboration with various academic and industry partners are development the Narrow Field InfraRed Adaptive Optics System (NFIRAOS). NFIRAOS represents a key element within the TMT optical system. In essence, NFIRAOS removes the blurring effect inherent to light passing through a dynamic medium such as our atmosphere. The value NFIRAOS brings to the TMT project is in its ability to produce images as would be taken by telescopes in space where seeing is unencumbered by the atmosphere, yet maintain all the accessibility advantages presented by having an observatory on the ground. Once this light is “corrected” NFIRAOS will interface with the InfraRed Imaging Spectrograph (IRIS), a client instrument.

The Government of Canada’s (GoC) National Research Council (NRC) Herzberg Astronomy Technology Programs (referred to as NRC Herzberg) is currently involved in pre-construction design and development of the Adaptive Optics (AO) system for the TMT project. TMT will be located on the Big Island of Hawaii atop Mauna Kea where it will join many of the worlds’ premier Observatories. For more information about the TMT project please refer to www.tmt.org

Summary

National Research Council (NRC) requires engineering and design support services in support of the Thirty Metre Telescope (TMT) Near Field Infra Red Adaptive Optics System (NFIRAOS) subsystems indicated below.

- NFIRAOS Instrument Selection Mirror Subsystem .

Due to the highly technical nature of the design documents, they are only available in English. The documents will be available on written request (email) to the Contracting Authority specified herein, including submission of the completed Annex D Non-disclosure agreement.

Lists of Attachments is included in Annex 1 – Statement of Work .

Contractors bidding on this requirement must meet the required delivery dates as these are essential towards Canada meeting its deliverables towards the set timelines of the TMT project office.

Task Authorization Contract
The work required in this solicitation is limited to the defined **Phase 1 only.** Any subsequent work (if approved) will be conducted under a separate task authorization within the contract.

Note 1: . It is the intent of this project to continue subsequent phases with the successful bidder for Phase 1. However, Canada at its discretion may choose to either:

(i) issue a task authorization to include the work under Phase 2 ,
or
(ii) competitively tender the works for Phase 2

Note 2: Bidders in responding to this solicitation are agreeing they have the capabilities and capacity to execute the work.

3. Not Used

4. Debriefings
After contract award, bidders may request a debriefing on the results of the bid solicitation process. Bidders should make the request to the Contracting Authority within 15 working days of receipt of the results of the bid solicitation process. The debriefing may be in writing, by telephone or in person.

5. Communications
As a courtesy and in order to coordinate any public announcements pertaining to this contract, the Government of Canada requests that successful Bidders notify the Contracting Authority 5 days in advance of their intention to make public an announcement related to the recommendation of a contract award, or any information related to the contract. The Government of Canada retains the right to make primary contract announcements.

6. Conflict of Interest
The Work described herein and the deliverable items under any resulting Contract specifically exclude the development of any statement of work, evaluation criteria or any document related to a bid solicitation. The Contractor, its subcontractor(s) or any of their agent(s) directly or indirectly involved in the performance of the Work and/or in the production of the deliverables under any resulting Contract will not be precluded from bidding on any potential future bid solicitation related to the production or exploitation of any concept or prototype developed or delivered under any resulting Contract.

PART 2 - BIDDER INSTRUCTIONS

1. Standard Instructions, Clauses and Conditions

All instructions, clauses and conditions identified in the bid solicitation by number, date and title are set out in the *Standard Acquisition Clauses and Conditions Manual* (*https://buyandsell.gc.ca/policy-and-guidelines/standard-acquisition-clauses-and-conditions-manual)* issued by Public Works and Government Services Canada.

Bidders who submit a bid agree to be bound by the instructions, clauses and conditions of the bid solicitation and accept the clauses and conditions of the resulting contract.

The 2003 (2014-03-01) Standard Instructions - Goods or Services - Competitive Requirements, are incorporated by reference into and form part of the bid solicitation.

1.1 *SACC Manual* Clauses

A7035T (2007-05-25) List of Proposed Subcontractors
A9033T (2012-07-16) Financial Capability

2. Submission of Bids

Bids must be submitted only to Public Works and Government Services Canada (PWGSC) Bid Receiving Unit by the date, time and place indicated on page 1 of the bid solicitation.

3. Former Public Servant

Contracts awarded to former public servants (FPS) in receipt of a pension or of a lump sum payment must bear the closest public scrutiny, and reflect fairness in the spending of public funds. In order to comply with Treasury Board policies and directives on contracts awarded to FPS, bidders must provide the information required below before contract award. If the answer to the questions and, as applicable the information required have not been received by the time the evaluation of bids is completed, Canada will inform the Bidder of a time frame within which to provide the information. Failure to comply with Canada's request and meet the requirement within the prescribed time frame will render the bid non-responsive.

Definitions

For the purposes of this clause,"former public servant" is any former member of a department as defined in the *Financial Administration Act*, R.S., 1985, c. F-11, a former member of the Canadian Armed Forces or a former member of the Royal Canadian Mounted Police. A former public servant may be:

a. an individual;
b. an individual who has incorporated;
c. a partnership made of former public servants; or
d. a sole proprietorship or entity where the affected individual has a controlling or major interest in the entity.

"lump sum payment period" means the period measured in weeks of salary, for which payment has been made to facilitate the transition to retirement or to other employment as a result of the implementation of various programs to reduce the size of the Public Service. The lump sum payment period does not include the period of severance pay, which is measured in a like manner.

"pension" means a pension or annual allowance paid under the *Public Service Superannuation Act* (PSSA), R.S., 1985, c.P-36, and any increases paid pursuant to the *Supplementary Retirement Benefits Act*, R.S., 1985, c.S-24 as it affects the PSSA. It does not include pensions payable pursuant to the *Canadian Forces Superannuation Act*, R.S., 1985, c.C-17, the *Defence Services Pension Continuation Act*, 1970, c.D-3, the *Royal Canadian Mounted Police Pension Continuation Act* , 1970, c.R-10, and the *Royal Canadian Mounted Police Superannuation Act*, R.S., 1985, c.R-11, the *Members of Parliament*

Retiring Allowances Act , R.S., 1985, c.M-5, and that portion of pension payable to the *Canada Pension Plan Act*, R.S., 1985, c.C-8.

Former Public Servant in Receipt of a Pension
As per the above definitions, is the Bidder a FPS in receipt of a pension?

Yes ( ) **No** ( )

If so, the Bidder must provide the following information, for all FPS in receipt of a pension, as applicable:

a. name of former public servant;
b. date of termination of employment or retirement from the Public Service.

By providing this information, Bidders agree that the successful Bidder's status, with respect to being a former public servant in receipt of a pension, will be reported on departmental websites as part of the published proactive disclosure reports in accordance with Contracting Policy Notice: 2012-2 and the Guidelines on the Proactive Disclosure of Contracts.

Work Force Adjustment Directive
Is the Bidder a FPS who received a lump sum payment pursuant to the terms of the Work Force Adjustment Directive?

Yes ( ) **No** ( )

If so, the Bidder must provide the following information:

a. name of former public servant;
b. conditions of the lump sum payment incentive;
c. date of termination of employment;
d. amount of lump sum payment;
e. rate of pay on which lump sum payment is based;
f. period of lump sum payment including start date, end date and number of weeks;
g. number and amount (professional fees) of other contracts subject to the restrictions of a work force adjustment program.

For all contracts awarded during the lump sum payment period, the total amount of fees that may be paid to a FPS who received a lump sum payment is $5,000, including Applicable Taxes.

4. Communications - Solicitation Period

All enquiries must be submitted to the Contracting Authority no later than 5 calendar days before the bid closing date. Enquiries received after that time may not be answered.

Bidders should reference as accurately as possible the numbered item of the bid solicitation to which the enquiry relates. Care should be taken by bidders to explain each question in sufficient detail in order to enable Canada to provide an accurate answer. Technical enquiries that are of a "proprietary" nature must be clearly marked "proprietary" at each relevant item. Items identified as proprietary will be treated as such except where Canada determines that the enquiry is not of a proprietary nature. Canada may edit the question(s) or may request that the Bidder do so, so that the proprietary nature of the question(s) is eliminated and the enquiry can be answered to all bidders. Enquiries not submitted in a form that can be distributed to all bidders may not be answered by Canada.

5. Applicable Laws

Any resulting contract must be interpreted and governed, and the relations between the parties determined, by the laws in force in British Columbia.

Bidders may, at their discretion, substitute the applicable laws of a Canadian province or territory of their choice without affecting the validity of their bid, by deleting the name of the Canadian province or territory specified and inserting the name of the Canadian province or territory of their choice. If no change is made, it acknowledges that the applicable laws specified are acceptable to the bidders.

6. Improvement of Requirement During Solicitation Period

Should bidders consider that the specifications or Statement of Work contained in the bid solicitation could be improved technically or technologically, bidders are invited to make suggestions, in writing, to the Contracting Authority named in the bid solicitation. Bidders must clearly outline the suggested improvement as well as the reason for the suggestion. Suggestions that do not restrict the level of competition nor favour a particular bidder will be given consideration provided they are submitted to the Contracting Authority at least 5 days before the bid closing date. Canada will have the right to accept or reject any or all suggestions.

7. Maximum Funding

The maximum funding available for the contract(s)resulting from the bid solicitation is:

Instrument Selection Mirror (ISM) subsystems CAD $89,000.00

(Applicable Taxes extra, as appropriate). Bids valued in excess of this amount will be considered non-responsive. This disclosure does not commit Canada to pay the maximum funding available.

PART 3 - BID PREPARATION INSTRUCTIONS

1. Bid Preparation Instructions

Canada requests that bidders provide their bid in separately bound sections as follows:
Section I : Technical Bid (1hard copies)
Section II : Financial Bid (1 hard copies)
Section III : Certifications (1 hard copies)

If there is a discrepancy between the wording of the soft copy and the hard copy, the wording of the hard copy will have priority over the wording of the soft copy.

Prices must appear in the financial bid only. No prices must be indicated in any other section of the bid.

Canada requests that bidders follow the format instructions described below in the preparation of their bid:
(a) use 8.5 x 11 inch (216 mm x 279 mm) paper; and
(b) use a numbering system that corresponds to the bid solicitation.

In April 2006, Canada issued a policy directing federal departments and agencies to take the necessary steps to incorporate environmental considerations into the procurement process Policy on Green Procurement (http://www.tpsgc-pwgsc.gc.ca/ecologisation-greening/achats-procurement/politique-policy-eng.html). To assist Canada in reaching its objectives, bidders should:
(1) use paper containing fibre certified as originating from a sustainably-managed forest and containing minimum 30% recycled content; and
(2) use an environmentally-preferable format including black and white printing instead of colour printing, print double sided/duplex, using staples or clips instead of cerlox, duotangs or binders.

Section I : Technical Bid

In their technical bid, bidders should demonstrate their understanding of the requirements contained in the bid solicitation and explain how they will meet these requirements. Bidders should demonstrate their capability and describe their approach in a thorough, concise and clear manner for carrying out the work.

The technical bid should clearly address and in sufficient depth the points that are subject to the evaluation criteria against which the bid will be evaluated. Simply repeating the statement contained in the bid solicitation is not sufficient.

In order to facilitate the evaluation of the bid, Canada requests that bidders address and present topics in the order of the evaluation criteria under the same headings. To avoid duplication, bidders may refer to different sections of their bids by identifying the specific paragraph and page number where the subject topic has already been addressed.

Section II : Financial Bid

1.1 Bidders must submit their financial bid in accordance with the following :
a) Bidders must submit a firm all-inclusive price for the work.
b) The information must be provided in accordance with the Basis of Payment in Annex B.

Section III : Certifications
Bidders must submit the certifications required under Part 5.

PART 4 - EVALUATION PROCEDURES AND BASIS OF SELECTION

1. Evaluation Procedures

(a) Bids will be assessed in accordance with the entire requirement of the bid solicitation including the technical and financial evaluation criteria.

(b) An evaluation team composed of representatives of Canada will evaluate the bids.

(c) The evaluation team will determine first if there are two (2) or more bids with a valid Canadian Content certification. In that event, the evaluation process will be limited to the bids with the certification; otherwise, all bids will be evaluated. If some of the bids with a valid certification are declared non-responsive, or are withdrawn, and less than two responsive bids with a valid certification remain, the evaluation will continue among those bids with a valid certification. If all bids with a valid certification are subsequently declared non-responsive, or are withdrawn, then all the other bids received will be evaluated.

1.1 Technical Evaluation

In their technical bid, bidders should demonstrate their understanding of the requirements contained in the bid solicitation and explain how they will meet these requirements. Bidders should demonstrate their capability and describe their approach in a thorough, concise and clear manner for carrying out the work.

The technical bid should address clearly and in sufficient depth the points that are subject to the evaluation criteria against which the bid will be evaluated. Simply repeating the statement contained in the bid solicitation is not sufficient. In order to facilitate the evaluation of the bid, Canada requests that bidders address and present topics in the order of the evaluation criteria under the same headings. To avoid duplication, bidders may refer to different sections of their bids by identifying the specific paragraph and page number where the subject topic has already been addressed.

The technical bid consists of the following:

All the information required to demonstrate its conformity with the Point Rated Technical Criteria described in Annex E.

The solicitation package contains electronic documents that are essential for bidders to understand the technical nature of the work and must be requested from the PWGSC Contracting Authority in writing.

1.1.1 Supporting Information

In the event that the Bidder fails to submit any supporting information pursuant to technical evaluation criteria, the Contracting Authority may request it thereafter in writing, including after the closing date of the bid solicitation. It is mandatory that the Bidder provide the supporting information within three (3) business days of the written request or within such period as specified or agreed to by the Contracting Authority in the written notice to the Bidder.

1.1.2 Mandatory and Point Rated Technical Evaluation

Mandatory and Point Rated Technical Evaluation Criteria are included in Annex E.

1.2 Financial Evaluation

1.2.1 Mandatory Financial Criteria

Proposals which exceed the following financial limits will be deemed non-responsive.
ISM – Instrument Selection Mirror Subsystem CAD$89,000.00

1.2.2 Evaluation of Price

The price of the bid will be evaluated in Canadian dollars, Applicable Taxes excluded, Canadian customs duties and excise taxes included.

2. Basis of Selection

2.1 Basis of Selection - Highest Rated Within Budget

To be declared responsive, a bid must:

(a) comply with all the requirements of the bid solicitation;

(b) meet all mandatory technical evaluation criteria;

(c) obtain the required minimum points for **each** criterion with a pass mark; and

(d) obtain the required minimum points overall for the technical evaluation criteria which are subject to point rating.

Bids not meeting (a) or (b) or (c) or (d) will be declared non responsive. The responsive bid with the highest number of points will be recommended for award of a contract, provided that the total evaluated price does not exceed the budget available for this requirement. In the event that the highest number of points is obtained by more than one responsive bid, the responsive bid with the lowest evaluated price will be recommended for award of a contract.

PART 5 - CERTIFICATIONS

Bidders must provide the required certifications and documentation to be awarded a contract.

The certifications provided by bidders to Canada are subject to verification by Canada at all times. Canada will declare a bid non-responsive, or will declare a contractor in default, if any certification made by the Bidder is found to be untrue, whether made knowingly or unknowingly, during the bid evaluation period or during the contract period.

The Contracting Authority will have the right to ask for additional information to verify the Bidder's certifications. Failure to comply and to cooperate with any request or requirement imposed by the Contracting Authority may render the bid non-responsive or constitute a default under the Contract.

1. Certifications Required Precedent to Contract Award

1.1 Integrity Provisions – Associated Information

By submitting a bid, the Bidder certifies that the Bidder and its Affiliates are in compliance with the provisions as stated in Section 01 Integrity Provisions - Bid of Standard Instructions 2003. The associated information required within the Integrity Provisions will assist Canada in confirming that the certifications are true.

1.2 Federal Contractors Program for Employment Equity - Bid Certification

By submitting a bid, the Bidder certifies that the Bidder, and any of the Bidder's members if the Bidder is a Joint Venture, is not named on the Federal Contractors Program (FCP) for employment equity "FCP Limited Eligibility to Bid" list (http://www.labour.gc.ca/eng/standards_equity/eq/emp/fcp/list/inelig.shtml) available from Employment and Social Development Canada (ESDC) - Labour's website

Canada will have the right to declare a bid non-responsive if the Bidder, or any member of the Bidder if the Bidder is a Joint Venture, appears on the "FCP Limited Eligibility to Bid"list at the time of contract award.

2. Additional Certifications Required Precedent to Contract Award

The certifications listed below should be completed and submitted with the bid but may be submitted afterwards. If any of these required certifications is not completed and submitted as requested, the Contracting Authority will inform the Bidder of a time frame within which to provide the information. Failure to comply with the request of the Contracting Authority and to provide the certifications within that time frame provided will render the bid non-responsive.

2.1 Canadian Content Certification

This procurement is subject to a preference for Canadian goods and/or services.

The Bidder certifies that:

( ) the service(s) offered is (are) a Canadian service as defined in paragraph 2 of clause A3050T.

2.1.1 Canadian Content Definition

1. **Canadian good**: A good wholly manufactured or originating in Canada is considered a Canadian good. A product containing imported components may also be considered Canadian for the purpose of this policy when it has undergone sufficient change in Canada, in a manner that satisfies the definition specified under the *North American Free Trade Agreement* (NAFTA) Rules of Origin. For the purposes of this determination, the reference in the NAFTA Rules of Origin to "territory", is to be replaced with "Canada". (Consult Annex 3.6(9) of the *Supply Manual*.)

For photocopiers, computers and office equipment within Federal Supply Classification (FSC) groups 36, 70 and 74, see paragraph 6.(a)).

2. **Canadian service**: A service provided by an individual based in Canada is considered a Canadian service. Where a requirement consists of only one service, which is being provided by more than one individual, the service will be considered Canadian if a minimum of 80 percent of the total bid price for the service is provided by individuals based in Canada.

3. **Variety of goods**: When requirements consist of more than one good, one of the two methods below is applied:
    a. aggregate evaluation: no less than 80 percent of the total bid price must consist of Canadian goods; or,
    b. item by item evaluation: in some cases, the bid evaluation may be conducted on an item-by-item basis and contracts may be awarded to more than one supplier. In these cases, suppliers will be asked to identify separately each item that meets the definition of Canadian goods.

4. **Variety of services**: For requirements consisting of more than one service, a minimum of 80 percent of the total bid price must be provided by individuals based in Canada.

5. **Mix of goods and services**: When requirements consist of a mix of goods and services, no less than 80 percent of the total bid price must consist of Canadian goods and services (as defined above).
   For more information on how to determine the Canadian content for a mix of goods, a mix of services or a mix of goods and services, consult Annex 3.6.(9), Example 2, of the *Supply Manual*.

6. **Other Canadian goods and services**:

    a. For photocopiers, computers and office equipment within FSC groups 36, 70 and 74, only the products of the following firms are considered Canadian goods:
        i. MERIT Partner under the MERIT Partnership Program (administered by Industry Canada [IC] and Public Works and Government Services Canada [PWGSC]);
        ii. Companies which, on March 31, 1992, were allocated to Priority Group 1 under the Priority Groups Policy in effect at that time; or
        iii. CIRCLE Canada companies as agreed on by IC and PWGSC.

    b. Textiles: Textiles are considered to be Canadian goods according to a modified rule of origin, copies of which are available from the Clothing and Textiles Division, Commercial and Consumer Products Directorate.

2.2 Status and Availability of Resources

The Bidder certifies that, should it be awarded a contract as a result of the bid solicitation, every individual proposed in its bid will be available to perform the Work as required by Canada's representatives and at the time specified in the bid solicitation or agreed to with Canada's representatives. If for reasons beyond its control, the Bidder is unable to provide the services of an individual named in its bid, the Bidder may propose a substitute with similar qualifications and experience. The Bidder must advise the Contracting Authority of the reason for the substitution and provide the name, qualifications and experience of the proposed replacement. For the purposes of this clause, only the following reasons will be considered as beyond the control of the Bidder: death, sickness, maternity and parental leave, retirement, resignation, dismissal for cause or termination of an agreement for default.

If the Bidder has proposed any individual who is not an employee of the Bidder, the Bidder certifies that it has the permission from that individual to propose his/her services in relation to the Work to be performed and to submit his/her résumé to Canada. The Bidder must, upon request from the Contracting Authority, provide a written confirmation, signed by the individual, of the permission given to the Bidder and of his/her availability. Failure to comply with the request may result in the bid being declared non-responsive.

2.3 Education and Experience

The Bidder certifies that all the information provided in the résumés and supporting material submitted with its bid, particularly the information pertaining to education, achievements, experience and work history, has been verified by the Bidder to be true and accurate. Furthermore, the Bidder warrants that every individual proposed by the Bidder for the requirement is capable of performing the Work described in the resulting contract.

2.4 Language Capability

The Bidder certifies that it has the language capability required to perform the Work, as stipulated in the Statement of Work.

PART 6 - RESULTING CONTRACT CLAUSES

The following clauses and conditions apply to and form part of any contract resulting from the bid solicitation.

1. Statement of Work

The Contractor must perform the Work in accordance with the Statement of Work at Annex A.

1.1 Task Authorization

The Work or a portion of the Work to be performed under the Contract will be on an "as and when requested basis" using a Task Authorization (TA). The Work described in the TA must be in accordance with the scope of the Contract.

1.1.1 Task Authorization Process

1. The Project Authority will provide the Contractor with a description of the task using the Task Authorization form specified in Annex F. .

2. The Task Authorization (TA) will contain the details of the activities to be performed, a description of the deliverables, and a schedule indicating completion dates for the major activities or submission dates for the deliverables. The TA will also include the applicable basis(bases) and methods of payment as specified in the Contract.

3. The Contractor must provide the Project Authority, within 14 calendar days of its receipt, the proposed total estimated cost for performing the task and a breakdown of that cost, established in accordance with the Basis of Payment specified in the Contract.

4. The Contractor must not commence work until a TA authorized by the Project Authority has been received by the Contractor. The Contractor acknowledges that any work performed before a TA has been received will be done at the Contractor's own risk.

1.1.2 Task Authorization Limit

The Project Authority may authorize individual task authorizations up to a limit of $40,000.00, Applicable Taxes included, inclusive of any revisions.

Any task authorization to be issued in excess of that limit must be authorized by the Project Authority and Contracting Authority before issuance.

1.1.3 Portion of the Work - Task Authorizations

Canada's obligation with respect to the portion of the Work under the Contract that is performed through task authorizations is limited to the total amount of the actual tasks performed by the Contractor.

2. Standard Clauses and Conditions

All clauses and conditions identified in the Contract by number, date and title are set out in the *Standard Acquisition Clauses and Conditions* Manual (https://buyandsell.gc.ca/policy-and-guidelines/standard-acquisition-clauses-and-conditions-manual) issued by Public Works and Government Services Canada.

2.1 General Conditions

2040 (2014-03-01), General Conditions - Higher Complexity - Services, apply to and form part of the Contract.

2.1.1 Canada to Own Intellectual Property Rights in Foreground Information

1. The general conditions 2040 are amended by deleting the sections entitled "Records and Disclosure of Foreground Information", Ownership of Intellectual Property Rights in Foreground Information", "Licenses to Intellectual Property Rights in Foreground and Background Information", "Contractor's Rights to Grant Licenses", "Waiver of Moral Rights", "License to Intellectual Property Rights in Canada's Information", "Transfer or License of Contractor's Rights", "Transfer of Intellectual Property Rights upon Termination of the Contract for Default", and "Products Created Using the Foreground Information" in their entirety. This section applies in lieu of those sections.

2.

   a. During and after the performance of the Contract, the Contractor must keep detailed records of the Foreground Information, including details of its creation. The Contractor must report and fully disclose to Canada all Foreground Information as required by the Contract. If the Contract does not specifically state when and how the Contractor must do so, the Contractor must provide this information if requested by the Contracting Authority, whether before or after the completion of the Contract.

   b. Before and after final payment to the Contractor, the Contractor must provide Canada with access to all records and supporting data that Canada considers pertinent to the identification of Foreground Information.

   c. For any Intellectual Property that was developed or created in relation to the Work, Canada will be entitled to assume that it was developed or created by Canada, if the Contractor's records do not list that Intellectual Property or do not indicate that it was created by the Contractor, or by someone on behalf of the Contractor, other than Canada.

3.

   a. All Intellectual Property rights in the Foreground Information belong to Canada as soon as they come into existence. The Contractor has no right in or to any such Intellectual Property Rights in the Foreground Information, except any right that may be granted in writing by Canada.

   b. The Contractor must incorporate the copyright symbol and one of the following notices, as appropriate into all Foreground Information that is subject to copyright regardless of the form or medium upon which it is recorded: © Her Majesty the Queen in Right of Canada (year), or © Sa Majesté la Reine du chef du Canada (year).

   c. The Contractor must execute any documents relating to the Intellectual Property Rights in the Foreground Information as Canada may require. The Contractor must, at Canada's expense, provide Canada all reasonable assistance in the preparation of applications and in the prosecution of any applications for registration of any Intellectual Property Rights in any jurisdiction, including the assistance of the inventor in the case on inventions.

4.

   a. The Contractor grants to Canada a license to use the Background Information to the extent that it is reasonably necessary for Canada to exercise fully all its rights in the deliverables and in the Foreground Information. This license is non-exclusive, perpetual, irrevocable, worldwide, fully-paid and royalty-free. The license cannot be restricted in any way by the Contractor providing any form of notice to the contrary, including the wording on any shrink-wrapped license attached to any deliverable.

b. For greater certainty, Canada's license in the Background Information includes, but is not limited to:

   i. the right to disclose the Background Information to third parties bidding on or negotiating contracts with Canada and to sublicense or otherwise authorize the use of that information by any contractor engaged by Canada solely for the purpose of carrying out such contracts. Canada will require these third parties and contractors not to use or disclose that information except as may be necessary to bid, negotiate or carry out those contracts;

   ii. the right to disclose the Background Information to other governments for information purposes;

   iii. the right reproduce, modify, improve, develop or translate the Background Information or have it done by a person hired by Canada. Canada, or a person designated by Canada, will own the Intellectual Property Rights associated with reproduction, modification, improvement, development or translation.

   iv. without restricting the scope of any license or other right in the Background Information that Canada may otherwise hold in relation to any custom-designed or custom-manufactured part of the Work, the right to use and disclose to a contractor engaged by Canada the Background Information for the following purposes:

      A. For the use, operation, maintenance, repair or overhaul of the custom-designed or custom-manufactured parts of the Work;

      B. In the manufacturing of spare parts for maintenance, repair or overhaul of any custom-designed or custom-manufactured part of the Work by Canada if those parts are not available on reasonable commercial terms to enable timely maintenance, repair or overhaul.

c. The Contractor agrees to make the Background Information, including in the case of Software, the source code, promptly available to Canada for any purpose mentioned above. The license does not apply to any Software that is subject to detailed license conditions that are set out elsewhere in the Contract. Furthermore, in the case of commercial off-the-shelf software, the Contractor's obligation to make the source code promptly available to Canada applies only to source code that is within the control of or can be obtained by the Contractor or any subcontractor.

5. The Contractor represents and warrants that it has the right to grant to Canada the license and any other rights to use the Background Information. If the Intellectual Property Rights in any Background Information are owned by a subcontractor or any other third party, the Contractor must have a license from that subcontractor or third party that permits compliance with paragraph 4 or arrange, without delay, for the subcontractor or third party to grant promptly the required license directly to Canada.

6. If requested by Canada, during and after the Contract, the Contractor must provide a written permanent waiver of moral rights, as defined in the *Copyright Act*, R.S., 1985, c. C-42, from every

author that contributes to any Foreground Information subject to copyright protection that is a deliverable to Canada under the Contract. If the Contractor is an author of the Foreground Information, the Contractor permanently waives the Contractor's moral rights in that Foreground Information.

2.1.2 License to Intellectual Property Rights in Foreground Information

1. Subject to subsection 2, if the Contractor wishes to make use of the Foreground Information for purposes of its commercial exploitation or further development, then the Contractor may make a written request for a license to the minister for whose department or agency the Work is being or was carried out. Such a request should be made within thirty (30) working days following completion of the Work. The Contractor shall give that minister an explanation as to why such a license is required. That minister shall respond in writing to any request for such a license within a reasonable period of time. If the request is refused the response shall provide an explanation for the refusal. Should the minister for whose department the work is being or was carried out agree to grant such a license, it shall be on terms and conditions to be negotiated between the Contractor and that minister.

2. Where the Work under the Contract involves the preparation of a database or other compilation using information or data supplied by Canada, or personal information (as this term is defined in the Privacy Act (R.S.C., c. P-21)) collected by the Contractor as part of the Work, then the license referred to in subsection 1 shall be restricted to the Intellectual Property Rights in Foreground Information that are capable of being exploited without the use of such information or data or personal information.

2.2 Non-disclosure Agreement

The Contractor must obtain from its employee(s) or subcontractor(s) the completed and signed non-disclosure agreement, attached at Annex D, and provide it to the Contracting Authority before they are given access to information by or on behalf of Canada in connection with the Work.

3. Security Requirement

There is no security requirement applicable to this Contract.

4. Term of Contract

4.1 Period of Contract

The period of the Contract is from date of Contract to 31 March 2015 inclusive.

4.2 Option to extend the Contract

The Contractor grants to Canada the irrevocable option to extend the term of the Contract by up to two (2) additional one (1) year period(s) under the same conditions. The Contractor agrees that, during the extended period of the Contract, it will be paid in accordance with the applicable provisions as set out in the Basis of Payment.

Canada may exercise this option at any time by sending a written notice to the Contractor at least 30 calendar days before the expiry date of the Contract. The option may only be exercised by the Contracting Authority, and will be evidenced for administrative purposes only, through a contract amendment.

5. Authorities

5.1 Contracting Authority

The Contracting Authority for the Contract is:

Name: Mike Sole
Title: Supply Specialist

Public Works and Government Services Canada
Acquisitions Branch
Telephone: 250-363-8444
E-mail address: Mike.Sole@pwgsc.gc.ca

The Contracting Authority is responsible for the management of the Contract and any changes to the Contract must be authorized in writing by the Contracting Authority. The Contractor must not perform work in excess of or outside the scope of the Contract based on verbal or written requests or instructions from anybody other than the Contracting Authority.

5.2 Technical Authority

The Technical Authority for the Contract is: ______ *(to be provided on award)*

The Technical Authority is the representative of the department or agency for whom the Work is being carried out under the Contract and is responsible for all matters concerning the technical content of the Work under the Contract. Technical matters may be discussed with the Technical Authority; however, the Technical Authority has no authority to authorize changes to the scope of the Work. Changes to the scope of the Work can only be made through a contract amendment issued by the Contracting Authority.

5.3 Contractor's Representative

Contact for:	Name	Telephone	Email
Contracting issues			
Technical issues			
Invoicing issues			

5.4 Procurement Authority

The Procurement Authority for the Contract is: ______ *(to be provided on award)*

The Procurement Authority is the representative of the department or agency for whom the Work is being carried out under the Contract. The Procurement Authority is responsible for the implementation of tools and processes required for the administration of the Contract. The Contractor may discuss administrative matters identified in the Contract with the Procurement Authority however the Procurement Authority has no authority to authorize changes to the scope of the Work. Changes to the scope of Work can only be made through a contract amendment issued by the Contracting Authority.

6. Proactive Disclosure of Contracts with Former Public Servants

By providing information on its status, with respect to being a former public servant in receipt of a *Public Service Superannuation Act* (PSSA) pension, the Contractor has agreed that this information will be reported on departmental websites as part of the published proactive disclosure reports, in accordance with Contracting Policy Notice: 2012-2 of the Treasury Board Secretariat of Canada.

7. Payment

7.1 Basis of Payment

The Contractor will be reimbursed for the costs reasonably and properly incurred in the performance of the Work as determined in accordance with the Basis of Payment in Annex B, to a ceiling price of $ (**insert the amount at contract award)** . Customs duties are included and Applicable Taxes are extra.

The ceiling price is subject to downward adjustment so as not to exceed the actual costs reasonably incurred in the performance of the Work and computed in accordance with the Basis of Payment.

7.1.1 Basis of Payment – Limitation of Expenditure – Task Authorizations

The Contractor will be reimbursed for the costs reasonably and properly incurred in the performance of the Work specified in the authorized Task Authorization (TA), as determined in accordance with the Basis of Payment in the Task Authorization to the limitation of expenditure specified in the authorized TA.

Canada's liability to the Contractor under the authorized TA must not exceed the limitation of expenditure specified in the authorized TA. Customs duties are excluded and Applicable Taxes are extra.

No increase in the liability of Canada or in the price of the Work specified in the authorized TA resulting from any design changes, modifications or interpretations of the Work will be authorized or paid to the Contractor unless these design changes, modifications or interpretations have been authorized, in writing, by the Contracting Authority before their incorporation into the Work.

7.2 Limitation of Price

SACC Manual Clause C6000C (2011-05-16), Limitation of Price

7.3 Method of Payment

7.3.1 Milestone Payments

Canada will make milestone payments in accordance with the Schedule of Milestones detailed in the Contract and the payment provisions of the Contract if:

(a) an accurate and complete claim for payment using form PWGSC-TPSGC 1111 (http://www.tpsgc-pwgsc.gc.ca/app-acq/forms/documents/1111.pdf)), Claim for Progress Payment, and any other document required by the Contract have been submitted in accordance with the invoicing instructions provided in the Contract;

(b) all the certificates appearing on form PWGSC-TPSGC 1111 have been signed by the respective authorized representatives;

(c) all work associated with the milestone and as applicable any deliverable required has been completed and accepted by Canada.

7.3.2 Schedule of Milestones

The schedule of milestones for which payments will be made is in accordance with the Annex B.

7.3.3 SACC Manual Clause H1001C (2008-05-12), Multiple Payments

7.4 SACC Manual Clauses

A9117C (2007-11-30), T1204 - Direct Request by Customer Department
H4500C (2010-01-11), Lien - Section 427 of the *Bank Act*

8. Invoicing Instructions – Progress Payment Claim

1. The Contractor must submit a claim for payment using form PWGSC-TPSGC 1111, Claim for Progress Payment (attached at Annex G).

Each claim must show:

a. all information required on form PWGSC-TPSGC 1111;

b. all applicable information detailed under the section entitled "Invoice Submission" of the general conditions;

c. a list of all expenses;

d. the description and value of the milestone claimed as detailed in the Contract.

Each claim must be supported by:

a. a copy of time sheets to support the time claimed;

b. a copy of the invoices, receipts, vouchers for all direct expenses, travel and living expenses;

c. a copy of the monthly progress report.

2. Applicable Taxes must be calculated on the total amount of the claim before the holdback is applied. At the time the holdback is claimed, there will be no Applicable Taxes payable as it was claimed and payable under the previous claims for progress payments.

3. The Contractor must prepare and certify one original and two (2) copies of the claim on form PWGSC-TPSGC 1111, and forward it to the Procurement Authority identified under the section entitled "Authorities" of the Contract for appropriate certification after inspection and acceptance of the Work takes place.

   The Procurement Authority will then forward the original and two (2) copies of the claim to the Contracting Authority for certification and onward submission to the Payment Office for the remaining certification and payment action.

4. The Contractor must not submit claims until all work identified in the claim is completed.

9. Certifications

9.1 Compliance

Compliance with the certifications and related documentation provided by the Contractor in its bid is a condition of the Contract and subject to verification by Canada during the entire contract period. If the Contractor does not comply with any certification, provide the related documentation or if it is determined that any certification made by the Contractor in its bid is untrue, whether made knowingly or unknowingly, Canada has the right, pursuant to the default provision of the Contract, to terminate the Contract for default.

9.2 SACC Manual Clauses

A0285C (2007-05-25) Workers Compensation
A3060C (2008-05-12) Canadian Content Certification

10. Applicable Laws

The Contract must be interpreted and governed, and the relations between the parties determined, by the laws in force in (to be inserted at contract award).

11. Priority of Documents

If there is a discrepancy between the wording of any documents that appear on the list, the wording of the document that first appears on the list has priority over the wording of any document that subsequently appears on the list.

a) the Articles of Agreement;
b) the general conditions 2040 (2011-05-16), General Conditions – Research and Development, as amended in Section 2.1 above;
c) Annex A, Statement of Work;
d) Annex B, Basis of Payment / Schedule of Milestones;
e) Annex D, Non-disclosure Agreement;
f) the signed Task Authorizations (including all of its annexes, if any) (if applicable);
g) the Contractor's bid dated ______ (insert date of bid) (If the bid was clarified or amended, insert at the time of contract award: "as clarified on _______" ***or*** ", as amended on _______" and insert date(s) of clarification(s) or amendment(s))

12. Insurance

The Contractor is responsible for deciding if insurance coverage is necessary to fulfill its obligation under the Contract and to ensure compliance with any applicable law. Any insurance acquired or maintained by the Contractor is at its own expense and for its own benefit and protection. It does not release the Contractor from or reduce its liability under the Contract.

13. Shipping Instructions – Delivery at Destination

Goods must be consigned to the destination specified in the Contract and delivered DDP (Delivered Duty Paid) to National Research Council of Canada, 5071 West Saanich Road, Victoria , British Columbia Canada V9E2E7, Inco terms 2000 for shipments from a commercial contractor.

14. Government Site Regulations

The Contractor must comply with all regulations, instructions and directives in force on the site where the Work is performed.

ANNEX A - STATEMENT OF WORK

Phased Contract

The work required in this solicitation is limited to the following **Phase 1 o**nly.

Note 1: Canada at its discretion may choose to either:

(i) competitively tender the works for Phase 2 or
(ii) amend the contract issued for Phase 1, to include the work under Phase 2

Note 2: Bidders in responding to this solicitation are agreeing they have the capabilities and capacity to execute the work required for Phase 1 and 2**.**

PHASE 1: Final design of NFIRAOS Instrument Selection Mirror Subsystem

Phase 1 of the work to be performed is the final design of NFIRAOS Instrument Selection Mirror Subsystem including mirror and cell assembly and the rotation mechanism that sends NIR light between the three client science instrument positions, top, side and bottom. Specifically, the work includes:

1. Advance the Instrument Selection Mirror Subsystem from Preliminary Design Review (PDR) level development to Final Design Review (FDR) level design in context with the Thirty Meter Telescope Project Office (TMTPO) design review level definitions[1].
   - PDR design has demonstrated a design and defined the outline of associated processes resulting in the subsystem. Major design tasks verified by the review are:
     - Sufficiently detailed design to demonstrate that (i) the majority of design and interface requirements are met and (ii) significant design choices are made at the subsystem assembly level
     - Enabling technologies established
     - Major technical risks retired
     - Outline of assembly, integration, and verification of overall NFIRAOS system integration at NRC Herzberg and TMT observatory sites
     - Long lead time procurement plans for optics
     - Associated schedule and cost of final design phase
     - Bottom-up fabrication and construction cost estimate for subsystems
     - Integrated fabrication and construction schedule with the overall TMT project schedule
     - Initial FMEA and Hazard Risk Assessment

   - FDR design development work supplied by Contractor shall demonstrate the detailed subsystem design can be realized as well as the realization processes. Major subsystem design tasks that the contractor is responsible for advancing are:
     - Final, construction/production ready design and work scopes for fabrication and procurements
     - Key technologies industrialized
     - Compliance with requirements and interfaces
     - Vendor QA/QC plans
     - Failure Mode and Effects Analysis (FMEA) and reliability prediction
     - Operations/maintenance procedures
     - Refined fabrication and construction plan, budget and schedule

[1] TMT Reviews: Definitions, Guidelines, And Procedures,TMT.SEN.SPE.12.002

2. Provide final design documentation set for the subsystem listed according to the Deliverables list in Annex A. Statement of Work.
3. Develop a binding fixed-price quote for the fabrication, integration and verification of the subsystem to be delivered to NRC Herzberg, according to the design and interface requirements, with the systems engineering documents and project control documents listed in Annex A. Statement of Work.
    - For the binding fabrication cost, this deliverable shall require the cost breakdown for labour. materials, freight etc., and shall include quotations from any sub-trades and suppliers confirming time frames and costing.
    - For the optics, NRC-Herzberg will provide the supplier information such as specifications and price quotes collected at Preliminary Design Review and subsequent cost reviews. The Contractor shall include detailed optics cost breakdown in the fixed-price quote along with specific information on their cost and schedule contingency associated with the performance risks of the optics procurement. This information will allow NRC to access the most cost effective procurement strategy for optics, i.e. Contractor procured vs. NRC supplied, for the NFIRAOS project.
    - The Contractor is required to independently inspect and verify all procured optics.

Description of Work:

1. Subsystems Final Design activities
    a. Develop final design, including documentation of design description and engineering analysis, according to the design documents supplied
    b. Tabulate compliance matrix according to design and interface requirements and document how the requirements are fully met by the design developed including FMEA, reliability prediction and spare list
    c. Produce fabrication drawings, bill-of-materials with long lead-time items
    d. Develop fabrication and assembly plan with vendor QA/QC plans that ensure production compliance
    e. Document maintenance procedures of the proposed design to meet the design life requirement
2. Binding Fixed-Price Quote Development Activities
    a. The fixed-price quote development should be based on the cost to advance the final design to the final product and include the labour effort to perform systems engineering, project management and control activities such QA/QC reports, verification & testing plans, and verification & testing reports to demonstrate full requirement compliance.
    b. The fixed-price quote shall include shipping containers, special tools, assembly fixtures, handling jigs and spare parts required for the subsystems.

Deliverables:

- Deliverables pertaining to documentation, designs and drawings shall be delivered in English and in a format determined by the NRC Project Authority.
- Telecon kickoff meeting[2] with project plan
    - The Project plan shall contain sufficient information to define the work breakdown for all engineering, systems engineering and project control tasks required to execute the project. Each scheduled task shall contain its associated: resource assignments; duration; labour,

[2] NRC-Herzberg reserves the option to hold the kickoff meeting at the Contractor’s site.

material and procurement costs; predecessor and successor link-logic for the workflow. In addition, key milestones shall be clearly identified in the project plan according to the milestone schedule in the Schedule of Key Activities section.
  - The Project plan shall be provided in the native file format of the applicable project management software as well as in PDF format.
- Telecon bi-weekly progress meetings with progress reports
  - Progress reports shall be available two days prior to the bi-weekly progress meeting. This is a concise summary of the current status of the work in progress according to the project plan including descriptions of the results achieved in the current period and planned work for the next period. In addition, the progress report shall identify unresolved issues and problems which may be: technical; programmatic and financial, that could potentially impact the project schedule and budget. The Contractor will further propose corrective actions to mitigate and/or resolve the issues so that the project may advance in a timely manner.
  - The progress report shall be in MS Word or PDF format.
    - For the first bi-weekly report of each month, up-to-date program information such as % complete, labour costs and procurement expenses shall be available for reporting. This should extend to each scheduled task in the project plan at the progress meeting for the purpose of earned-value calculations by the NRC Project Authority.
- Design description report
  - The Design description report is a document that outlines the form and function of the final design in context with the subsystem design and interface requirements
  - The report shall include schematic and block diagrams to illustrate subsystem decomposition and functionalities.
  - The report shall be in MS Word format.
- Engineering analysis report
  - The Design analysis report shall contain sufficient engineering information for a technical reader to understand the design assumptions, engineering theories and analytical tools used to realize the design. The report shall state the achieved design margin, e.g. safety factor as well as the limitations and uncertainties of the analysis with respect to the design requirements.
  - The design analysis shall be calculated in SI Units and the design analysis report shall be provided in the native file format of the analytical software as well as in PDF format.
- Compliance matrix, verification and test plan
  - The Compliance matrix is a tabulated list of all design and interface requirements and the corresponding justifications of how the requirements are fully met by the final design as developed.
  - The Verification and test plan documents the test setup and procedures of those requirements that must be tested in order to verify their compliances. Verification and test plan shall outline the timeline of the tests to be performed in the fabrication phase.
  - The compliance matrix, and verification and test plan shall be in MS Word or MS Excel file format.
- Downtime prediction document set
  - This is a document set including FMEA, reliability prediction, repair time estimate and a list of spares for all critical components to demonstrate the proposed subsystem meets the required downtime budget.
    - The downtime prediction shall be provided in the native file format of the analytical software as well as in PDF format.

- Fabrication drawings, bill-of-materials with long lead-time items identified
  - This is a document set which supports component and material procurements, and fabrication of the subsystem.
  - The drawing set shall include fabrication information for optical, mechanical, electrical and control systems, shipping containers, special tools, assembly fixtures and handling jigs.
  - The fabrication drawings shall follow established Canadian drawing standards and provided in the native CAD software format as well as in PDF format.
  - The bill-of-materials shall be provided in MS Excel format or PDF format.
- Fabrication and assembly plan with vendor QA/QC plans
  - This is a document set to outline the contractor's plan to implement the production of the subsystem and the associated procedures to ensure quality assurance and control.
  - The plan shall be provided in MS Word or PDF format.
- Maintenance procedures
  - This is a document that outlines the inspections and preventive maintenance required to ensure the proposed design meets the design life requirement.
  - The Contractor shall identify all spare/replacement parts required for the design life of the subsystem.
  - The Contractor shall identify all special tools, assembly fixtures and handling jigs for the maintenance process required.
  - The procedure shall be provided in MS Word format.
- Binding Fixed-Price Quote
  - The fixed-price quote shall include the cost of supplying: fabrication, schedule estimates, verification and testing plan as well as the corresponding verification test report in order to deliver fully verified subsystems to NRC-Herzberg.
    - The verification & test plan shall tabulate the pass-or-fail methodology to verify the design and interface requirements, as supplied by NRC, and outline the proposed equipment and test setup to verify performance. Ancillary information such as calibration certificates, equipment specifications and accuracy of the test equipment shall also be provided.
    - The verification & test plans shall be provided in MS Word or MS Excel format.
  - The fixed-price quote shall contain cost breakdown at the component level such as optics, cell, framework, mechanism, actuator, sensors, switches, cabling and utilities, shipping containers, special tools, assembly fixtures, handling jigs and spare parts etc.
  - The fixed-price quote shall include documentation list, shipping containers, special tools, assembly fixtures and handling jigs required for the subsystems
  - The fixed-price quote shall identify the cost and schedule contingencies assumed.
  - The quote shall be in tabulated in MS Word or MS Excel file format.
  - The design verification and test plan must be in MS Word or MS Excel format.

Additional considerations

- The Contractor shall identify cost and design drivers in the design and interface requirements for discussion at the bi-weekly progress meeting as soon as they are discovered in the final design phase.
- Unless explicit written permission is granted, the Contractor designs shall adhere to advancing the design developed for the Preliminary Design Review as stated in the design report [AD4] and requirement documents [AD1, AD2, AD3].

- The proposed final design work is the preamble for the fabrication and construction phase of the NFIRAOS subsystem. The Contractor who is selected for this phase and meets the stated performance requirements shall be required to supply the subsystem.

Schedule of key activities (following Date of Contract Award - Estimated)

a.	Kickoff meeting	**2** weeks
b.	Design description report	**1-1/2** months
c.	Engineering analysis report	**2** months
d.	Compliance matrix and downtime prediction	**2-1/2** months
e.	Verification and test plans	**2-1/2** months
f.	Fabrication drawings and bill-of-materials	**3** months
g.	Fabrication, assembly, QA/QC plans	**3** months
h.	Maintenance procedures	**3-1/2** months
i.	Binding fixed price quote	**3-1/2** months

LIST OF ATTACHMENTS: **<u>Non-Disclosure Agreement (ANNEX D) Required</u>**

AD1 - TMT.AOS.DRD.14.018.REL01 NFIRAOS Instrument Selection Mirror Design Requirements DocumentThe subsystem design requirements document for the Instrument Selection Mirror Subsystem.

AD2 -TMT.AOS.ICD.14.007.REL01 Interface Control Document NFIRAOS to Instrument Selection Mirror Subsystem The interface requirements for the Instrument Selection Mirror Subsystem.

AD3 - TMT.AOS.SPE.14.002.REL04 NFIRAOS Common Design Standard Document
This document defines the common elements and their design requirements among the NFIRAOS opto-mechanical subsystems to facilitate servicing and maintenance.

AD4 -TMT.AOS.PDD.11.005.REL01 NFIRAOS PDUR Book
This report documents the NFIRAOS subsystems design at the Preliminary Design Review level.
.

LIST OF REFERENCE INFORMATION: (Appended)

RD1 – NFIRAOS Design Requirements Document, (TMT.AOS.DRD.07.002)

RD2 – NFIRAOS Operations Concept Document (TMT.AOS.CCD.05.001)

The following additional phases are for **<u>information only</u>**: It is the intent of this project to continue subsequent phases with the successful bidder for Phase 1.

PHASE 2: Instrument Selection Mirror Subsystem Fabrication, Assembly and Verification

As NRC's option, the Contractor shall fabricate and deliver a fully qualified subsystem to NRC-Herzberg according to the work, cost and schedule, outlined the fixed-price quote. Delivery shall be to the National Research Council of Canada, 5071 West Saanich Road Victoria, British Columbia Canada.

Estimated expenditure for this Phase is $94,000.00.

ANNEX B - BASIS OF PAYMENT / SCHEDULE OF MILESTONES (Phase 1)

BIDDERS MUST COMPLETE TABLE FOR EACH STREAM FOR WHICH THEY ARE BIDDING

TABLE B1 - – ISM

Mile-stone No.	Description	% of total Bid price	Firm Amount CAD$	Due Date
1	**Completion of activities a,b**	**35%**		On or before 2 months following contract award (estimated) or Contractor's best Date of _______.
2	**Completion of Activities c, d, e, f** Note: NRC is responsible for all costs to travel to Contractor's site to review Contractor's Factory acceptance test results and inspect deliverables	**35%**		On or before 3 months following contract award (estimated) or Contractor's best Date of _______.
3	**Completion of activities: g, h, i, j, k** **Note: bid price includes** Includes all delivery and insurance costs	**30%**		On or Before March 31 2015 (Mandatory).
			Total EVALUATED BID PRICE (GST Extra as applicable) STREAM 1 - OAP	

Additional Expenses

i) Travel

Travel for additional services beyond the scope of the tender and requested by NRC, shall be invoiced as per the following.

The Contractor will be reimbursed for the authorized travel and living expenses reasonable and properly incurred in the performance of the work, at cost without any allowance for overhead or profit, in accordance with the meal, private vehicle and incidental expense allowances specified in Appendix B, C, D of the Treasury Board Travel Directive, and with the other provisions of the directive referring to "travellers", rather than those referring to "employees". http://www.tbs-sct.gc.ca/pubs_pol/hrpubs/tbm_113/menu-travel-voyage-eng.asp

All Travel must have the prior authorization of the Project Authority. All Payments are subject to government audit.

ii) Additional Labour

Labour for additional services beyond the scope of the tender and requested by NRC, shall be invoiced as per the following rates:

Project Man $_________/ hourly

Sen Engineer $_________/ hourly

Engineer $_________/ hourly

Technologist $_________/ hourly

Note: The cost for additional expenses as per i) and ii) above shall **not** be included in the Financial Evaluation.

ANNEX C - Contractor Disclosure of Foreground Information

CONTRACTOR DISCLOSURE OF FOREGROUND INFORMATION

Please refer to **Article 1 - Interpretation of 2040 General Conditions** for the definition of Foreground Information to determine what information must be disclosed.

The Contractor must provide the following information:
1. Contract No.:
2. What is the descriptive title of the FIP (Foreground Intellectual Property)?
3. Abbreviated description of the FIP and, if applicable, of the different systems and subsystems.
4. What is or was the objective of the project?
5. Explain how the FIP meets the objective of the project (for example: the advantage of the new solution, what problem did the FIP resolve or what benefits did the FIP deliver).
6. Under which category(ies) would you best describe the FIP and why: Patents, Inventions,Trade Secrets, Copyright, Industrial Designs, Rights in Integrated Circuit Topography, Know-how, Other?
7. Describe the features or aspects of the FIP that are novel, useful and not obvious.
8. Has the FIP been tested or demonstrated? If yes, please summarise the results.
9. Has any publication or disclosure to others been made? If so, to whom, when, where and how?
10. Provide names and addresses of the inventors.
11. Provide an explicit and detailed description of the FIP developed during the contract (Refer to pertinent section of the technical report, if necessary).

Please specify name and position of person approving / authorizing this disclosure. This person is to sign and date the disclosure.

Signature Date
Name Title

- -

Signature Date

Name Title (Technical authority)

ANNEX D - NON - DISCLOSURE AGREEMENT

I_____________________,(*Print Name)* recognize that in the course of my work as an employee or

subcontractor of _____________________,(*Print Firm Name)*

I may be given access to information by or on behalf of Canada in connection with the Work, pursuant to **Solicitation No 31034-141412/A** between Her Majesty the Queen in right of Canada, represented by the Minister of Public Works and Government Services and National Research Council, including any information that is confidential or proprietary to third parties, andinformation conceived, developed or produced by the Contractor as part of the Work.
For the purposes of this agreement, information includes but not limited to: any documents, instructions, guidelines, data, material, advice or any other information whether received orally, in printed form, recorded electronically, or otherwise and whether or not labeled as proprietary or sensitive, that is disclosed to a person or that a person becomes aware of during the performance of the Contract.

I agree that I will not reproduce, copy, use, divulge, release or disclose, in whole or in part, in whatever way or form any information described above to any person other than a person employed by Canada on a need to know basis. I undertake to safeguard the same and take all necessary and appropriate measures, including those set outin any written or oral instructions issued by Canada, to prevent the disclosure of or access to such information in contravention of this agreement.

I also acknowledge that any information provided to the Contractor by or on behalf of Canada must be used solely for the purpose of the Contract and must remain the property of Canada or a third party, as the case may be.

I agree that the obligation of this agreement will survive the completion of the solicitation

No 31034-149492/A and any resultant Contract(s).

_______________________________________ _____________

Signature **Date**

NOTE:
Once the information is in the custody of the identified firm, ALL employees or subcontractors of the identified firm given access to the information MUST sign and return a non-disclosure agreement PRIOR to release of that information to the individual by the identified firm.

ANNEX E - TECHNICAL EVALUATION CRITERIA

Bidders who do not meet these mandatory criteria will be deemed non-responsive.

Technical Evaluation Criteria is applicable to provide the work required under Phase 1 and may be considered acceptable for subsequent phases.

Substantial Information:

Bidders must demonstrate their compliance with EACH AND EVERY section of the evaluation criteria by providing substantial information describing completely and in detail how the requirement is met or addressed. Bidders must provide with their technical bid, a page reference indicating clearly where the substantial information for each of the sections identified below can be found *(example, fill in right hand column of evaluation tables)*

Mandatory Technical Criteria	Evaluation Scale	Notes:	Page #
1.0 Equipment/Infrastructure Bidders must demonstrate they have the **appropriate equipment and facilities** to complete the design, fabrication and testing * of the elements detailed in **the NRC Documents list** *Testing at room temperature TMT.AOS.DRD.14.018.REL01 TMT.AOS.ICD.14.007REL01 TMT.AOS.SPE.14.002.REL04 TMT.AOS.PDD.11.005.REL01	**Mandatory**	**Bidders are to include a comprehensive list of equipment / facilities in their proposal.**	
2.0 Equipment/Infrastructure for cold temperature testing Since NFIRAOS operates at -30°C and must survive at lower temperature, bidders must show that they have **secured access** to a cold temperature facility to complete the testing* of the elements detailed in **the NRC Documents list** *Costs associated with cold	**Mandatory**	**The bidder's proposal must include a full description of the cold temperature facility, arrangement of usage, availability and logistics of transportation between bidder's own facility and cold test facility.**	

testing shall be included in the total proposal price.			
3.0 RESOURCES PROPOSED Provide a list of the **key personnel** (and CVs) that will be assigned to the project.	**Mandatory**	The CVs must clearly demonstrate that the proposed resources can perform the requirements called for in the statement of work. Bidders shall include an estimated breakdown of resources proposed. (I.e Project Manager 20% , Senior Engineer 20%, Engineer 40%, technologist 20%)	

POINT RATED TECHNICAL CRITERIA

Max = maximum number of points; Min = mandatory passing mark; Page # = the page number in your bid that references the required substantiating documentation.

Bidders must obtain the required minimum points for **EACH** criterion with a pass mark. Bids not meeting this criteria will be declared non-responsive and not evaluated further.

Point Rated Technical Criteria	Evaluation Scale	Max	Min	Page #
1.0 Technical Proposal				
1.1 Understanding of the 'Statement of Work' The bidder should demonstrate its understanding of the 'Statement of Work' by providing in its own words a convincing demonstration of its understanding of the context, scope and objectives of the resulting contract. The demonstrated understanding of the context, scope and objectives should be complete and should not be limited to the description of the statement of work. The understanding of the three elements (context, scope and objectives) will be evaluated independently. The score given will be the average of the individual scores for the three elements. Example of calculation : The score of the bidder is as follows : - 15 points for context - 12 points for scope - 6 points for objectives The total score of the bidder is (15+12+6)/3 = 11 points	EXCELLENT – 15 pts VERY GOOD – 12 pts GOOD – 9 pts ACCEPTABLE – 6 pts WEAK – 3 pts INADEQUATE – 0 point Please note that the definition of each element of the evaluation scale is available at the end of this attachment.	**15**	**9**	
2.0 Bidder's Experience The bidder should demonstrate its experience by describing past projects **(e.g. design, fabrication assembly and testing of large precision opto-mechanical systems that operate at low temperature)** which pertains to the following information: a. the topic, the context, the objectives and the scope of the project, b. the project periods (exact month and year of the beginning and exact month and year of the end), c. the exact dates of the involvement of the bidder in the project, d. the role(s) of the bidder in the project (prime contractor, subcontractor, etc.), e. the budget, f. the name of the client , g. the number of resource (equivalent of full-time employee)involved in the project for each year of the project, h. any other relevant information. A project will be considered by the evaluation team only if the bidder demonstrates that the project involved the equivalent of at least one full time employee working on the project for at least one year and meet the related criterion.				
2.1 Bidder's experience in performing projects in a field related to the statement of work.				

2.1.1 Bidder Design Experience Bidder's experience in performing projects in a field related to: ***The design of large mirror cell, mount and rotation mechanism or equivalents*** To be awarded Points in this section, requires a minimum of 2 and up to 3 recent projects , within the last **5** years and at a minimum shall outline the following: At a minimum, examples should outline the mechanical design elements and materials selected, analytical and CAD tools used, describe any relevant load, deflection, seismic or thermal analysis performed corresponding to the overall operating and survival conditions such as temperature, range and rate, earthquake; mechanical stability and repeatability etc.; and or relevant design features applicable to the subsystems	EXCELLENT – 5 pts VERY GOOD – 4 pts GOOD – 3 pts ACCEPTABLE – 3 pts WEAK – 1 pts INADEQUATE – 0 point Please note that the definition of each element of the evaluation scale is available at the end of this attachment. **Bidders shall be scored for each example up to a maximum of 3.**	**15**	**6**	
2.1.1.1 (no minimum score) The dollar value of each project referenced in 2.1.1, shall be stated separately. Points will be calculated based on the total dollar value of the projects (up to a maximum of 3 projects) Example of calculation : The score of the bidder is as follows : • >$300K = 5pts, • $225K - $300K = 4pts • $150K - $225K = 3pts • $75K - $150K = 2pts • $25K - $75K = 1pts • <$25K = 0pts		5	**No min**	
2.2.1 Bidder Construction Experience Bidder's experience in performing projects in a field related to: ***The design of large mirror cell, mount and rotation mechanism or equivalents*** To be awarded Points in this section, requires a minimum of 2 and up to a maximum of 3. Project must be recent, i.e. within the last **5** years and at a minimum shall outline the following: At a minimum, examples should demonstrate the materials used; fabrication equipment, fabrication processes and techniques in context with the precision required; testing and metrology equipment; overall QA/QC process, the procedure and precision required in assembly work as well as the end performance, etc.	EXCELLENT –5 pts VERY GOOD – 4 pts GOOD – 3 pts ACCEPTABLE – 2 pts WEAK – 1 pts INADEQUATE – 0 point Please note that the definition of each element of the evaluation scale is available	**15**	**6**	

	at the end of this attachment. **Bidders shall be scored for each example up to a maximum of 3.**			
2.2.1.1 (no minimum score) The dollar value of each project referenced in 2.2.1, shall be stated separately. Points will be calculated based on the total dollar value of the projects (up to a maximum of 3 projects) Example of calculation : The score of the bidder is as follows : >$300K = 5pts, $225K - $300K = 4pts $150K - $225K = 3pts $75K - $150K = 2pts $25K - $75K = 1pts <$25K = 0pts		**5**	**No min**	
3.0 Management proposal				
3.1 Personnel and task management method The bidder should describe the method and tools to be used to manage its personnel, in terms of contingency management, availability of resources, and work overload in the context completing the work under the contract.				
3.1.1 Management method: The management method described by the bidder should be realistic and take into account each of the following elements: contingency management, availability of proposed resources, work overload, and the potential unpredictable context specific to research and development contracts.	EXCELLENT – 8 pts VERY GOOD – 6 pts GOOD – 4 pts ACCEPTABLE – 2 pts WEAK – 1 pt INADEQUATE – 0 Pt Please note that the definition of each element of the evaluation scale is available at the end of this attachment.	**8**	**4**	
3.1.2 Tools used: The bidder should describe the planning and control tools that will used to enable an efficient management methodology.	EXCELLENT – 8 pts VERY GOOD – 6 pts GOOD – 4 pts ACCEPTABLE – 2	**8**	**2**	

	pts WEAK – 1 pt INADEQUATE – 0 Pt Please note that the definition of each element of the evaluation scale is available at the end of this attachment.			
3.2 Work plan and schedule development method The bidder should describe its proposed work plan and schedule development method and demonstrate its effectiveness.				
3.2.1 Work plan and schedule development method **The bidder should describe its proposed work** plan and schedule development method. The bidder should describe how its work plan and schedule development method take into account the risk elements of the project and the unpredictable nature of a research and development contract.	EXCELLENT – 8 pts VERY GOOD – 6 pts GOOD – 4 pts ACCEPTABLE – 2 pts WEAK – 1 pt INADEQUATE – 0 pt Please note that the definition of each element of the evaluation scale is available at the end of this attachment.	**8**	**2**	
3.2.2 Demonstration of Effectiveness: **The bidder should clearly demonstrate that its** work plan and schedule development method has been successfully applied and tested in previous projects. To be awarded Points in this section, requires a minimum of 1 project and up to a maximum of 2. Project must be recent, i.e. within the last 5 years	EXCELLENT – 4 pts VERY GOOD – 3 pts GOOD – 2 pts ACCEPTABLE – 1 pts WEAK – 0 pt INADEQUATE – 0 pt Please note that the definition of each element of the evaluation scale is available at the end of this attachment.	**8**	**4**	

<table>
<tr><td></td><td>Bidders shall be scored for each example up to a maximum of 2.</td><td></td><td></td><td></td></tr>
<tr><td colspan="4">3.3 Quality control Process and Workflow management method.
The bidder should describe its management method for overseeing the progress of the work and compliance with deadlines. It should also describe its quality control process and the tools to be used to ensure that deliverables meet requirements. Furthermore, it should demonstrate clearly and beyond a reasonable doubt that this method has been tested and shown to be effective in previous projects.</td><td></td></tr>
<tr><td>3.3.2 Quality control process:
The bidder should describe its quality control process that should at least include:

1. Verification and validation of work performed
2. Validation of compliance with the client's requirements
3. Identification of future elements requiring improvement

The bidder should clearly demonstrate that quality control process have been successfully applied and tested in previous projects.</td><td>EXCELLENT – 8 pts
VERY GOOD – 6 pts
GOOD – 4 pts
ACCEPTABLE – 2 pts
WEAK – 1 pt
INADEQUATE – 0 pt

Please note that the definition of each element of the evaluation scale is available at the end of this attachment.</td><td>8</td><td>4</td><td></td></tr>
<tr><td>4.1 Packaging for Shipping Methodology
Bidder should demonstrate methodology to ensure large heavy fragile opto-mechanical components can be assembled and handled safety during fabrication and assembly, and with adequate packaging / crating to protect the contents from damage in the course of handling/shipping. Bidder should include examples of special tools, assembly fixtures, handling jigs, packaging/crating design used in previous projects and should include photos of examples packaging/crating used in previous shipments.</td><td>EXCELLENT – 8 pts
VERY GOOD – 6 pts
GOOD – 4 pts
ACCEPTABLE – 2 pts
WEAK – 1 pt
INADEQUATE – 0 pt

Please note that the definition of each element of the evaluation scale is available at the end of this attachment.</td><td>8</td><td>4</td><td></td></tr>
</table>

Evaluation grid for qualitative criteria

INADEQUATE	WEAK	ACCEPTABLE	GOOD	VERY GOOD	EXCELLENT
Did not submit information which could be evaluated or inadequate information submitted.	Lacks complete or almost complete understanding of the requirements.	Has some understanding of the requirements.	Demonstrates a good understanding of the requirements.	Demonstrates a very good understanding of the requirements.	Demonstrates expert understanding of the requirements
…..........	Weaknesses cannot be corrected or doubtful that weaknesses can be corrected.	Generally, there is a good chance that weaknesses can be easily corrected.	Weaknesses can be easily corrected.	No significant weaknesses.	No apparent weaknesses
…...........	Poor; insufficient to meet performance requirements or little capability to meet performance requirements.	Minimum acceptable capability, should meet minimum performance.	Satisfactory capability, should ensure effective results.	Very satisfactory capability, should ensure very effective results.	Superior capability, should ensure superior results

DESIGN REQUIREMENTS DOCUMENT

FOR

NFIRAOS

TMT.AOS.DRD.07.002.REL07

November 4, 2011

TABLE OF CONTENTS

TABLE OF FIGURES

LIST OF TABLES

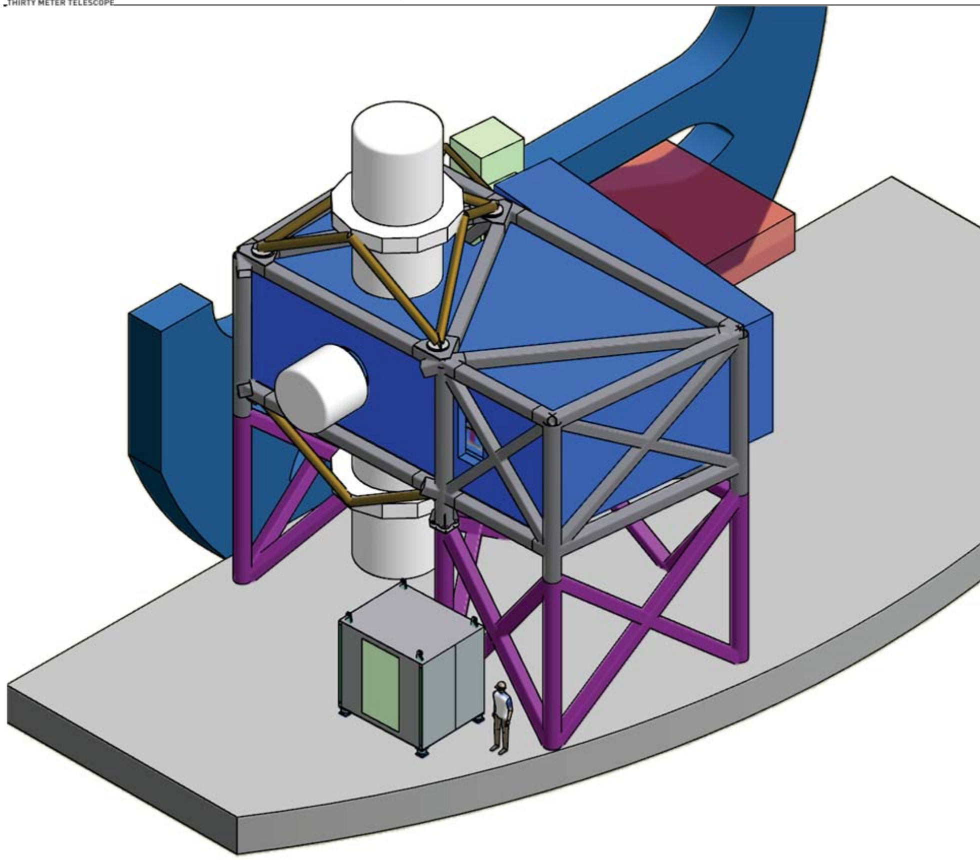

Figure 1 NFIRAOS on Nasmyth Platform with two client instruments

1. INTRODUCTION

1.1 INTRODUCTION

This document contains the design requirements for the Narrow Field InfraRed Adaptive Optics System (NFIRAOS) on the Thirty Meter Telescope (TMT). These requirements flow down from the Level 1 Requirements in the Observatory Architecture Document (OAD), the Observatory Requirements Document (ORD) and the Operational Concept Document (OCD). Requirements from the OAD and ORD which are specific to NFIRAOS are included in this document, and given NFIRAOS requirement numbers.

1.2 PURPOSE

The purpose of this design requirements document (DRD) is to provide a comprehensive list of the NFIRAOS functional and performance requirements. This document is to be used by the designer and fabricator of NFIRAOS and any of its elements. As well it will be used as a checklist during acceptance and verification testing of NFIRAOS.

The requirements documented in the NFIRAOS DRD are intended to fully describe the top level engineering requirements and functional concepts to satisfy the criteria of the ORD, OCD and OAD and by reference the Science Requirements Document, and the detailed Science Case for the Observatory.

The NFIRAOS DRD replaces the FPRD (Functional and Performance Requirements Document) that was written during the NFIRAOS Conceptual Design. Many specifications from the FPRD were later promoted into the OAD and ORD – these are repeated and/or expanded in this DRD.

1.3 SCOPE

This document includes the Level 2 Requirements for NFIRAOS.

Section 1 describes this document. Section 2 describes the overall NFIRAOS System and Section 3 lists the requirements for NFIRAOS. Paragraphs in Section 3 marked as "*Discussion*" are for information only and are not requirements.

The decomposition of NFIRAOS is presented in § 3.1.2 [REQ-2-NFIRAOS-0050].

This document does not include the external interfaces' specific requirements. Instead compliance to each external ICD is an individual, numbered NFIRAOS requirement.

1.4 APPLICABLE DOCUMENTS

Applicable documents contain information that shall be applied in the context of current document.

AD1 – Operations Concept Document (OCD), (TMT.OPS.MGT.07.002)

AD2 – Observatory Requirements Document, (TMT.SEN.DRD.05.001)

AD3 – Observatory Architecture Document, (TMT.SEN.DRD.05.002)

1.5 REFERENCE DOCUMENTS

Reference documents contain information complementing, explaining, detailing, or otherwise supporting the information included in the current document.

RD1 – NFIRAOS Error Budget, (TMT.AOS.TEC.10.005)

RD2 – Laser Guide Star Facility Conceptual Design Report, (TMT.AOS.CDD.06.035)

RD3 – NFIRAOS Preliminary Design Report, (TMT.AOS.PDD.08.020)

RD4 – Gemini Seismic Hazard Analysis (GSM.FAC.TEC.94.001)

RD5 – STR to NFIRAOS ICD (TMT.AOS.ICD.07.004)

RD6 – TCS to NFIRAOS ICD (TMT.SEN.ICD.07.037)

RD7 – NFIRAOS to LGSF ICD (TMT.SEN.ICD.07.027)

RD8 – NFIRAOS to AOESW ICD (TMT.SEN.ICD.XX.XXX)

RD9 – NFIRAOS to IRIS ICD (TMT.SEN.ICD.07.039)

RD10 – NFIRAOS to IRMS ICD (TMT.SEN.ICD.07.036)

RD11 – NFIRAOS to DMS ICD (TMT.SEN.ICD.XX.XXX)

RD12 – NFIRAOS to NSCU ICD (TMT.SEN.ICD.XX.XXX)

RD13 – NFIRAOS to Side-Mounted Instrument ICD (TMT.SEN.ICD.XX.XXX)

RD14 – NFIRAOS Space Envelope Drawing TMT.INS.NFIRAOS.ENV

RD15 – Observation workflow for the TMT (TMT.AOS.TEC.07.013)

RD16 – NFIRAOS Operational Concepts (TMT.AOS.CDD.05.001)

RD17 – NFIRAOS Operating Temperature (TMT.AOS.TEC.09.005), D. Andersen 2009

RD18 – NSCU Design Requirements Document (TMT.INS.DRD.08.001)

RD19 – NFPA 780 Standard for the Installation of Lightning Protection Systems (http://www.nfpa.org/catalog/product.asp?category%5Fname=&pid=78004&target%5Fpid=78004&order_src=A292)

RD20 – Interface with the Summit Facilities (SUM) (TMT.SEN.ICD.xx.xxx)

RD21 – Software Management Plan (TMT.SEN.SPE.08.002)

RD22 – TMT Interface N2 diagram (TMT.SEN.TEC.05.035)

RD23 – Environment, Safety, and Health Plan (TMT.PMO.MGT.08.040)

RD24 – Gemini Planet Imager Functional and Performance Requirements Document (FPRD) GPI_FPRD.doc 2009-07-15, Version 7.2 Leslie Saddlemyer, Dave Palmer, Bruce Macintosh

RD25 – Pupil Stability Error Budget (TMT.SEN.CCD.07.001.DRF01)

RD26 – Field rotation and distortion in TMT/NFIRAOS (TMT.AOS.TEC.09.002.DRF01)

1.6 CHANGE RECORD

Revision	Date	Section	Modifications
DRF01	29 November, 2007	All	Initial draft GH
DRF02	2 May, 2008	All	Revisions by DA, GH, CB, BE
DRF03	15 March, 2009	All	Revisions by JR, GH
DRF04	11 August, 2009	All	Revisions by CB, BE, GH, JR, DA
REL05	12 August, 2009	All	Release for ingestion into DOORS by GH
REL06	1 June, 2011	All	4 OAP Design; Cost reductions, GH

1.7 ABBREVIATIONS & ACRONYMS

ACQ Acquisition Camera
ACRS Azimuth Coordinate Reference System
ADC Atmospheric Dispersion Compensator
AHU Air Handling Unit
AO Adaptive Optics
AODP US National Science Foundation AO development program
AOESW Adaptive Optics Executive Software
AOSQ Adaptive Optics Sequencer
BTO Beam Transfer Optics
CC Component Controller
CCD Charge Coupled Device
CFD Computational Fluid Dynamics
CIS Communication and Information System
CW Continuous Wave
DC Detector Controller
DM Deformable Mirror
DM0 Deformable Mirror conjugate to 0 km
DM11 Deformable Mirror conjugate to 11.2
DMS Data Management System
DRD Design Requirements Document
FOV Field of View

FPRD	Functional and Performance Requirements Document
FSM	Fast Steering Mirror
GLAO	Ground Layer Adaptive Optics
HFC	Hydro-FluoroCarbon
HOL	High order, low bandwidth (TWFS)
HRWFS	High Resolution WFS
ICD	Interface Control Document
IFU	Integral Field Unit
IR	InfraRed
IRIS	Infrared Integral-field Spectrograph
IRMS	Infrared Imaging Spectrograph
IRMOS	Infra-Red Multi-Object Spectrograph
ISFM	Instrument Selection Fold Mirror
IST	Instrument Support Tower
LGS	Laser Guide Star
LGSF	Laser Guide Star Facility
LIS	Laser Interlock System
LLT	Laser Launch Telescope
M1	Telescope primary mirror
M2	Telescope secondary mirror
M3	Telescope tertiary mirror
MCAO	Multi Conjugate Adaptive Optics
MIRAO	Mid InfraRed Adaptive Optics
MOAO	Multi Object Adaptive Optics
MOR	Moderate Order, Radially Symmetric modes (TWFS)
NFIRAOS	Narrow Field Infrared Adaptive Optics System
MTBF	Mean Time Between Failures
NCPA	Non-Common Path Aberrations
NFPA	National Fire Protection Association
NGS	Natural Guide Star
NIRES-b	Near Infrared Echelle Spectrograph – blue wavelengths
NSCU	NFIRAOS Science Calibration Unit
OAD	Observatory Architecture Document
OAP	Off axis parabola
OCD	Operational Concept Document
OCS	Observatory Control System

OIWFS	On-Instrument Wavefront Sensor
ORD	Observatory Requirements Document
OSS	Observatory Safety system
PSF	Point Spread Function
PI	Principal Investigator
RMS	Root Mean Square
RPG	Reconstructor Parameter Generator
RTC	Real Time Controller
SMI	Side-Mounted Instrument
STR	Telescope Structure
SMP	Software Management Plan
SUM	Summit Facilities
TBC	This item still needs to be confirmed
TBD	This item still needs to be determined
TCS	Telescope Control System
TMT	Thirty-Meter Telescope
TTF	Tip/Tilt/Focus
TTS	Tip/tilt stage
TWFS	Truth Wavefront Sensor
WBS	Work Breakdown Structure
WFS	Wavefront Sensor
WFOS	Wide-Field Optical Spectrograph
WIRC	Wide field Infrared Camera
N/A	Not Applicable

Units:

asec – arcsecond

mas – milliarcsecond

nm – nanometer

μm – micrometer

μRad – microradian

2. OVERALL DESCRIPTION

2.1 PERSPECTIVE

NFIRAOS is an order 60x60 Laser Guide Star, Multi-conjugate Adaptive Optics System (LGS MCAO) system that accepts the telescope beam and provides atmospheric turbulence compensation in the near IR over a 2' FOV for up to three instruments on the TMT Nasmyth platform. Near-diffraction-limited performance is provided over the central 10-30" FOV. Its adaptive optics control functions are integrated with the Laser Guide Star Facility, and with on-instrument wavefront sensors included within science instruments. To maximize sky coverage, these WFSs are near infra-red natural guide star tip/tilt and focus wavefront sensors. NFIRAOS will be designed to be upgradeable to an order 120x120 system to improve image quality.

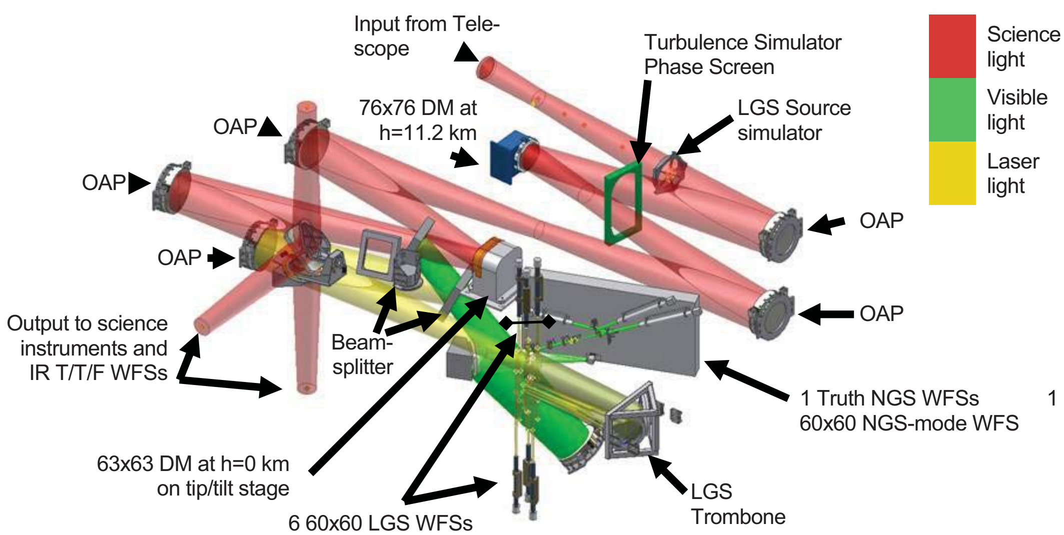

Figure 2: NFIRAOS optical paths showing components

NFIRAOS includes an optical support system, 6 LGS WFSs, 1 NGS WFS, 1 TWFS, 2 DMs and a tip/tilt stage (TTS), a source simulator (for natural objects and laser beacons) and all associated entrance windows, beamsplitters, fore-optics, opto-mechanical devices, cooling, electronics and computing systems. It also includes test equipment, which is composed of an external high-resolution wavefront sensor, and near-IR acquisition camera, a turbulence simulator and miscellaneous fixtures. Excluded from NFIRAOS are instrument rotators, cable wraps, science ADCs, on-instrument Tip/Tilt/Focus (TTF) WFSs, rotating lip seals and windows at NFIRAOS exit ports; these are included in the NFIRAOS-fed instruments and not in NFIRAOS. Also excluded are instrument wavelength and flat field calibration sources.

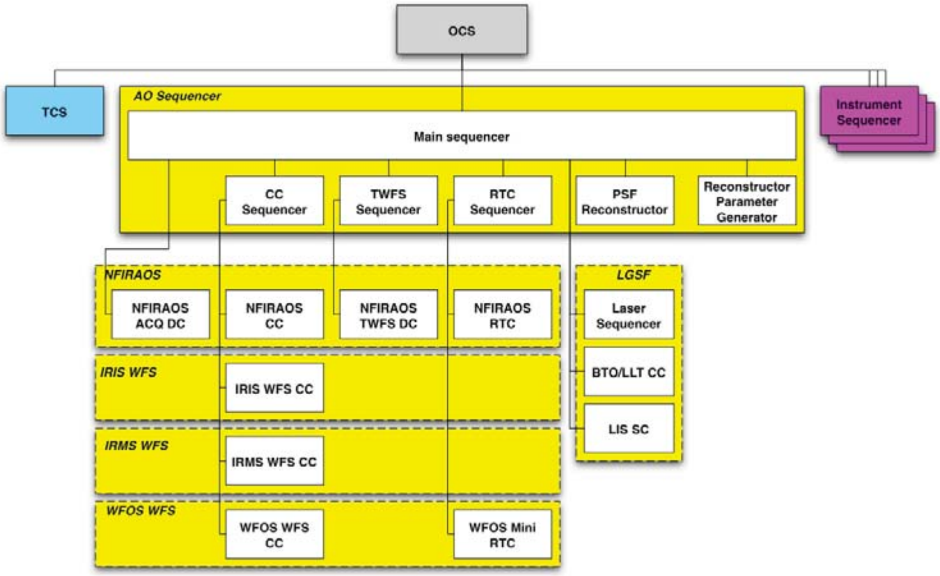

Figure 3 Context for NFIRAOS command and control

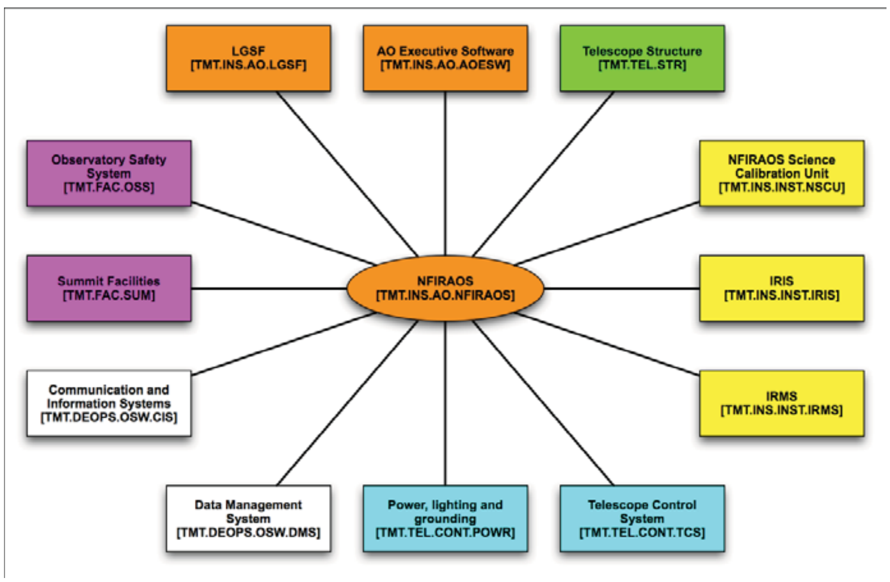

Figure 4: NFIRAOS context for communication and services.

NFIRAOS' software and control interfaces are illustrated in Figure 3. NFIRAOS is set-up, controlled and coordinated by the AO Executive Software. As well, as shown in Figure 4 it has direct data communications with the Laser Guide Star Facility, the client instrument Wavefront Sensors, the Telescope Control System, the Data Management System and the Observatory Safety System.

2.2 SYSTEM FUNCTIONS

NFIRAOS has three astronomical observing modes:

1. Laser guide star mode. High order correction using six laser guide stars.
2. Natural Guide Star mode. High order correction using a natural guide star.
3. Seeing Limited Mode. Fast guiding via NFIRAOS' tip/tilt stage, together with sending (to the telescope control system) slow speed measurements of telescope aberrations from a Truth WFS within NFIRAOS.

NFIRAOS has four daytime calibration modes:

1. Closed loop operation on internal point sources simulating natural and laser guide stars at varying range distance.
2. Feeding internal natural star simulated sources to client instruments, especially to calibrate non-common path errors and pointing models for OIWFSs.
3. Passing Flat field and Wavelength standard light from an external calibrator in front of NFIRAOS through to client instruments.
4. Closed loop operation, correcting artificial turbulence from a turbulence simulator in NFIRAOS.

2.3 USER AND OPERATOR CHARACTERISTICS

NFIRAOS will be designed for highly-automated operation in order to maximize observing efficiency. All interactions and interfaces with other subsystems will be optimized to remove observing bottlenecks and reduce the risk of operator error during both classical and queue modes of observing.

2.4 CONSTRAINTS

Command and control interfaces shall follow the rules and standards developed by the TMT Observatory software.

2.5 ASSUMPTIONS AND DEPENDENCIES

The NFIRAOS design concept assumes the availability of the following AO component technologies:

- 6 Sodium laser guidestars with a minimum total power of ~150 W, good coupling to the sodium layer and good beam quality (on the sky)
- WFS detector geometries, and/or other features to adequately compensate for sodium LGS elongation
- DMs of order at least 60^2 ("Baseline") to 120^2 ("Upgrade") within a 0.3 m pupil
- DM mechanical stroke of at least 9 μm
- Robust tomographic wavefront reconstruction algorithms and signal processing hardware for a system with ~17000 LGS WFS subapertures, 3 TT/(F) WFS and an update rate of 800 Hz.

Some of the requirements in this document depend on the physical location of the telescope. The following environmental conditions vary with observatory location: altitude, humidity, wind and temperature. The Mauna Kea 13-North site has now been selected for TMT and the requirements in this document were derived from the OAD and ORD, which assume a remote mountain at an elevation of ~4000 meters: Mauna Kea, Hawai'i.

There are no facility guiders in TMT. If an instrument or AO system needs guiding, it must supply it. During science exposures, all Natural Guide star tip/tilt/focus sensing, science light atmospheric dispersion compensation, pupil and image rotation will be performed internally within client instruments. (Certain of these functions are associated with the NFIRAOS RTC.)

The NFIRAOS electronics enclosure will be designed to accommodate the first light order 60x60 version. The technology of the upgraded 120x120 real time computer and upgraded DM drive electronics are too uncertain to forecast the space, power and cooling required. We assume that these upgrades will reside in an additional cabinet mounted above the baseline electronics enclosure.

2.5.1 Baseline Design

The electronics are in a separate enclosure on the Nasmyth platform. The opto-mechanical components are mounted on a space frame table, inside a cooled enclosure. Figure 5 shows a block diagram of the NFIRAOS optics and Figure 2 shows these components in an isometric view.

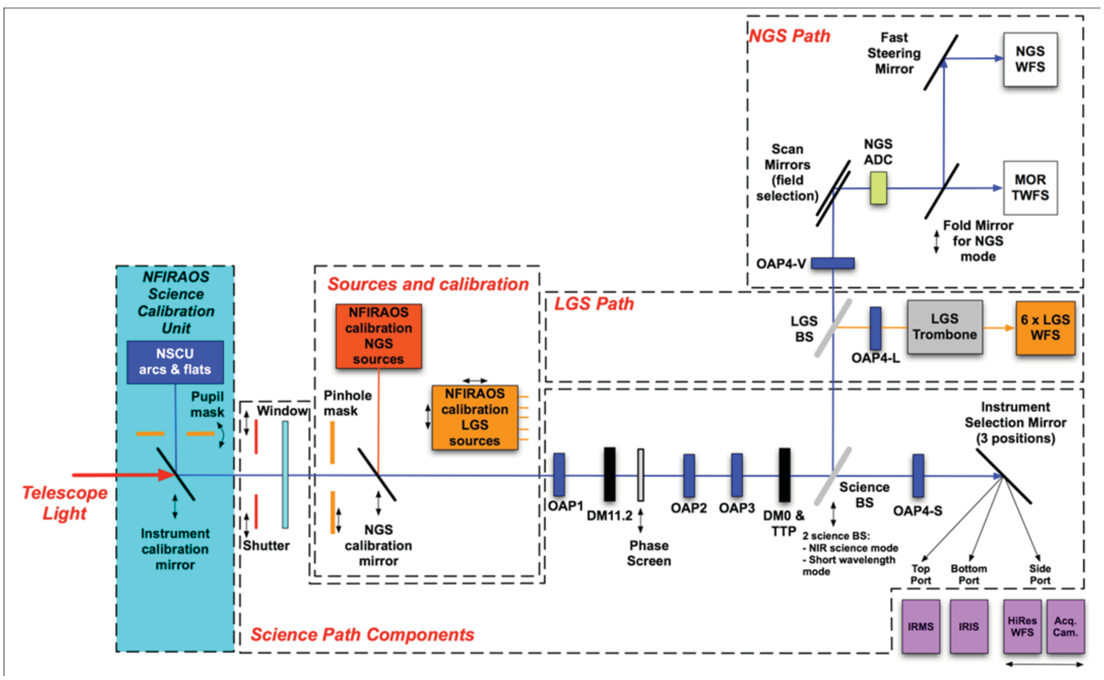

Figure 5 Optical Block Diagram NFIRAOS

3. SPECIFIC REQUIREMENTS

3.1 GENERAL CONSTRAINTS

3.1.1 Governing specifications

[REQ-2-NFIRAOS-0010] NFIRAOS shall be compliant with all Observatory Level 1 requirements given in the ORD, OCD and OAD. In the case of disagreement with this DRD, the Level 1 requirements apply unless specifically waived.

Discussion: The user of this NFIRAOS DRD is assumed to be familiar with these three level 1 requirements documents The reader is invited to refer to the relevant Level 1 requirements before reading section 3 of this DRD.

[REQ-2-NFIRAOS-0020] NFIRAOS shall be a multi-conjugate adaptive optics system utilizing laser guide stars, and shall feed near-diffraction limited images to TMT instruments working in the near infrared.

Discussion: This is a direct flow down of requirement [REQ-1-ORD-3500]. It implies multiple high-order deformable mirrors in series, multiple guide stars, tomography; and DM fitting optimized for the science field of view.

[REQ-2-NFIRAOS-0030] The NFIRAOS design shall accommodate the AO components to be developed by the TMT project: tip/tilt stage, deformable mirrors, LGS and NGS WFS detector CCDs, and Real Time Controller.

Discussion: Derived from the Observatory Decomposition in [REQ-1-OAD-0194].

3.1.2 Decomposition

[REQ-2-NFIRAOS-0040] The NFIRAOS system decomposition element is defined as follows:

Associated WBS element(s):
TMT.INS.AO.NFIRAOS, TMT.INS.AO.COMP.PCVWFS.NFIRAOS,
TMT.INS.AO.COMP.RTC.NFIRAOS, TMT.INS.AO.COMP.WC.NFIRAOS

NFIRAOS is a Laser Guide Star, Multi-conjugate Adaptive Optics System (LGS MCAO) system intended to provide atmospheric turbulence compensation in the near IR over a 2' FOV for up to 3 instruments working in the near IR. Near-diffraction-limited performance is provided over the central 10-30" FOV. NFIRAOS includes optics and supports, 6 LGS WFS, 1 NGS WFS, 1 TWFS, 2 DMs and a tip/tilt stage (TTS), a source simulator (for natural objects and laser beacons), a turbulence simulator and all associated entrance windows, beamsplitters, fore-optics, opto-mechanical devices, cooling, electronics and computing systems. It also includes local and global e-stops and any sensors and wiring that interface with the Observatory Safety System. It also includes test equipment, which is composed of a high-resolution wavefront sensor an acquisition camera, and miscellaneous fixtures. Instrument rotators, cable wraps, Science ADCs, on-instrument TTF WFSs, rotating lip seals and windows at NFIRAOS exit ports are included in the NFIRAOS-fed instruments and not in NFIRAOS. Also excluded are instrument wavelength and flat field calibration sources.

Discussion: This requirement is a traceable to [REQ-1-OAD-0194]

[REQ-2-NFIRAOS-0050] NFIRAOS shall be decomposed into the following subsystems given in Table 1.

Subsystem Code	WBS elements TMT.INS.AO….	Description
NIST	NFIRAOS.IST	Instrument Support Tower
NENCL	NFIRAOS.ENCL	Optics Enclosure
NTABL	NFIRAOS.TABL	Optical Tables & support in cold
NOPT	NFIRAOS.OPT.SCI NFIRAOS.OPT.VIS NFIRAOS.OPT.LGS	Optics up to 1) science exit 2) NGS gimbals 3) LGS fold; inclusive
NSS	NFIRAOS.SS	Source Simulators
NVNW	NFIRAOS.VNW NFIRAOS.VNW.NGS NFIRAOS.VNW.TWFS	Visible Natural Wavefront sensing. Field stop, Collimators, ADC, Beamsplitters, MOR Truth, NGS SH barrels; detectors & readout
NDME	NFIRAOS.WC.DME	DM electronics
NDM	COMP.WC.NFIRAOS.DM0 COMP.WC.NFIRAOS.DM11	DM0, DM11
NTTS	COMP.WC.NFIRAOS.TTS	Tip Tilt Stage
NLGS	NFIRAOS.LGS.ZOOM NFIRAOS.LGS.OPTSH NFIRAOS.LGS.AR NFIRAOS.LGS.AC COMP.PCVWFS.NFIRAOS	LGS Zoom corrector, fixed lenses through moving barrels to plane in front of lenslets, LGS WFS Optics Barrel LGS WFS Polar Coordinate Detectors and readout electronics
NACQ	NFIRAOS.EQT.SEN.ACQ.OPT NFIRAOS.EQT.SEN.ACQ.CAM	Acquisition Camera optics and camera
NTWAQC	NFIRAOS.EL.DC.CTRL NFIRAOS.EL.DC.SW	Processing Computer for TWFSs and Acquisition Camera and HRWFS
NMMEL	NFIRAOS.EL.MMEL	Conventional Electronics (motion and monitoring)
NELENC	NFIRAOS.EL.ENC	Electronics Enclosure
NCC	NFIRAOS.EL.CC	Component Controller
NRTC	COMP.RTC.NFIRAOS	RTC
NHRWFS	NFIRAOS.EQT.SEN.HRWFS	High-Res Wavefront Sensor (test fixture on side output port)
NTG	NFIRAOS.TG	Turbulence generator
NJIGS	NFIRAOS.EQT.JIGS	Misc Jigs and Fixtures

Table 1 NFIRAOS Subsystems Decomposition

Discussion: Expansion of [REQ-1-OAD-0194]. The subsystem codes are used to denote level 3 subsystems within NFIRAOS for detailing requirements and internal interfaces. In general these codes map onto (groups of) WBS elements.

3.1.3 Volume, Mass, and Positioning Constraints

[REQ-2-NFIRAOS-0060] NFIRAOS shall not exceed the volumes, and shall meet the focal plane position requirements given in [RD14] drawing TMT.INS.NFIRAOS.ENV

Discussion: This is a direct flow down of requirement [REQ-1-OAD-1425]

[REQ-2-NFIRAOS-0070] The mass of NFIRAOS shall not exceed 46.5 tonnes and the electronics cabinet mass shall not exceed 2.8 tonnes

Discussion: This is a direct flow down of requirement [REQ-1-OAD-0764] to be amended

[REQ-2-NFIRAOS-0080] The centre of gravity of NFIRAOS shall be at x = 20.9 m, y = 3.2 m, z = 19.1 m in the ACRS

Discussion: This is a direct flow down of requirement [REQ-1-OAD-0764]

[REQ-2-NFIRAOS-0082] The moment of inertia of NFIRAOS about its centre of gravity shall be (TBD) $kg \cdot m^2$.

Discussion: This is a direct flow down of requirement [REQ-1-OAD-0764]

[REQ-2-NFIRAOS-0090] NFIRAOS shall be designed to be located at the 174.5 degree position on the –X Nasmyth platform

Discussion: This requirement flows down from [REQ-1-OAD-1410].

The Nasmyth sides are designated –X and +X corresponding to directions in the Elevation Coordinate System. This coordinate system is located above the vertex of the primary mirror, on the elevation axis, defined by +Z pointing towards the stars, and +Y pointing towards zenith when the telescope is pointed at the horizon. The foci locations are designated by their angular position, where 0 degrees is on the elevation axis of the +X platform, increasing counter clockwise as viewed from above.

Discussion: At the 174.5 degree position, the beam to NFIRAOS clears the primary mirror by 100 mm when the telescope is pointed 65 degrees off zenith.

[REQ-2-NFIRAOS-0100] NFIRAOS shall be designed to support the next generation of NFIRAOS instruments: This includes but is not limited to NIRES-b and WIRC, as defined in the ORD, each at their own foci and with their required field of view.

Discussion: This is a flowdown of requirement [REQ-1-OAD-1415]. NIRES-b and WIRC will be supported by NFIRAOS. IRMS is expected to be decommissioned when IRMOS is commissioned.

3.2 EXTERNAL INTERFACES

[REQ-2-NFIRAOS-0110] NFIRAOS shall comply with the external interfaces listed in Table 2:

Table 2 External Interfaces

Requirement Number	External Interfaces	ICD	Description
[REQ-2-NFIRAOS-0120]	Interface with the telescope structure	STR to NFIRAOS ICD [RD5]	Structural and mechanical interfaces with the TMT Nasmyth platform
[REQ-2-NFIRAOS-0130]			Access and handling interfaces with the telescope structure
[REQ-2-NFIRAOS-0140]			Services and cooling interfaces with the telescope structure
[REQ-2-NFIRAOS-0150]			Thermal interfaces with the telescope structure
[REQ-2-NFIRAOS-0160]			Safety interfaces with the telescope structure
[REQ-2-NFIRAOS-0170]	Interface with the Telescope Control System (TCS)	TCS to NFIRAOS ICD [RD6]	Software and control interface between the TCS and the NFIRAOS RTC: actual zenith angle
[REQ-2-NFIRAOS-0180]			Software and control interface between the TCS and the NFIRAOS CC: destination zenith angle and NGS WFS/TWFS positions
[REQ-2-NFIRAOS-0190]	Interface with the Laser Guide Star Facility (LGSF)	NFIRAOS to LGSF ICD [RD7]	Software and control interface between the NFIRAOS RTC and the LGSF BTO/LLT Component Controller: Fast Steering Mirror commands/positions

[REQ-2-NFIRAOS-0200]			Software and control interface between the NFIRAOS RTC and the LGSF Laser Interlock System: RTC interlock event
[REQ-2-NFIRAOS-0210]	Interface with the AO Executive Software (AOESW)	NFIRAOS to AOESW ICD [RD8]	Software and control interface between the AO Executive Software and the NFIRAOS RTC: commands, status and telescope modes.
[REQ-2-NFIRAOS-0220]			Software and control interface between the AO Executive Software and the NFIRAOS CC: commands and status.
[REQ-2-NFIRAOS-0230]			Software and control interface between the AO Executive Software and the TWFS & ACQ Camera DC: commands and status.
[REQ-2-NFIRAOS-0240]			Software and control interface between the RPG and the NFIRAOS RTC: RTC reconstructors, tomography matrices and parameters, temporal filter optimization parameters, noise covariance matrices, turbulence parameters, LGS/NGS WFS unusable sub-apertures.
[REQ-2-NFIRAOS-0250]			Software and control interface between the NFIRAOS RTC and the PSF Reconstructor: PSF statistical data
[REQ-2-NFIRAOS-0260]	Interface with IRIS	NFIRAOS to IRIS ICD [RD9]	Optical interface between NFIRAOS and IRIS

[REQ-2-NFIRAOS-0270]			Structural and Mechanical interface between NFIRAOS and IRIS
[REQ-2-NFIRAOS-0280			Access and handling interface between NFIRAOS and IRIS
[REQ-2-NFIRAOS-0290]			Thermal interface between NFIRAOS and IRIS
[REQ-2-NFIRAOS-0300]			Software and control interface between the NFIRAOS RTC and IRIS OIWFS array controllers: pixels and controls
[REQ-2-NFIRAOS-0310]			Software and control interface between the NFIRAOS RTC and IRIS OIWFS CC: rotator angle, detectors' rotation w.r.t rotator, OIWFS reference vectors, OIWFS ellipticities and rotator angle update
[REQ-2-NFIRAOS-0320]	Interface with IRMS	NFIRAOS to IRMS ICD [RD10]	Optical interface between NFIRAOS and IRMS
[REQ-2-NFIRAOS-0330]			Structural and Mechanical interface between NFIRAOS and IRMS
[REQ-2-NFIRAOS-0340]			Access and handling interface between NFIRAOS and IRMS
[REQ-2-NFIRAOS-0350]			Thermal interface between NFIRAOS and IRMS
[REQ-2-NFIRAOS-0360]			Software and control interface between NFIRAOS RTC and IRMS OIWFS array controllers: pixels and controls

[REQ-2-NFIRAOS-0370]			Software and control interface between the NFIRAOS RTC and IRMS OIWFS CC: rotator angle, detector rotation w.r.t rotator, OIWFS reference vector, OIWFS ellipticities
[REQ-2-NFIRAOS-0380]	Interface with Side-Mounted Instrument (SMI) *Discussion: WIRC is a placeholder name for side port client*	NFIRAOS to Side-Mounted Instrument ICD [RD13]	Optical interface between NFIRAOS and Side Mounted Instrument
[REQ-2-NFIRAOS-0382]			Structural and Mechanical interface between NFIRAOS and SMI
[REQ-2-NFIRAOS-0384]			Access and handling interface between NFIRAOS and SMI
[REQ-2-NFIRAOS-0386]			Thermal interface between NFIRAOS and SMI
[REQ-2-NFIRAOS-0388]			Software and control interface between NFIRAOS RTC and SMI OIWFS array controllers: pixels and controls
[REQ-2-NFIRAOS-0390]			Software and control interface between the NFIRAOS RTC and SMI OIWFS CC: rotator angle, detector rotation w.r.t rotator, OIWFS reference vector, OIWFS ellipticities
[REQ-2-NFIRAOS-0400]	Interface with the NFIRAOS Science Calibrator	NFIRAOS to NSCU interface [RD12]	Optical interface between NFIRAOS and the Science Calibration Unit
[REQ-2-NFIRAOS-0410]			Structural and Mechanical interface between NFIRAOS and the Science Calibration Unit

[REQ-2-NFIRAOS-0420]			Access, servicing and handling interface between NFIRAOS and the Science Calibration Unit
[REQ-2-NFIRAOS-0430]			Safety interface between NFIRAOS and the Science Calibration Unit
[REQ-2-NFIRAOS-0440]	Interface with the Data Management System (DMS)	NFIRAOS to DMS ICD [RD11]	Software and control interface between the NFIRAOS sub-systems (RTC, CC, TWFS DC, ACQ DC) and the DMS: engineering data
[REQ-2-NFIRAOS-0450]	Interface with the Summit Facilities (SUM)	TBD document	Structural, power, cooling and Mechanical Interface with computer room (volume in U within computer room – The NFIRAOS RTC telemetry storage is located in the computer room)
[REQ-2-NFIRAOS-0460]	Interface with Observatory Safety System	TBD document	
[REQ-2-NFIRAOS-0470]	Interface with Power, Lighting and Grounding System	TBD document	
[REQ-2-NFIRAOS-0480]	Interface with Communication and Information Systems	TBD document	
REQ-2-NFIRAOS-0482	Interface with Common Software	TBD document	Interface necessary for observatory-wide configuration, command, control, status reporting, and data management
REQ-2-NFIRAOS-0484	Interface with Test Equipment	TBD document	Location of GMS targets

Discussion: The interface requirements above flow down from [REQ-1-OAD-xxxx] TBD that specifies ICDs shall be defined as per the TMT N^2 diagram [RD22]

3.3 ENVIRONMENTAL CONSTRAINTS

[REQ-2-NFIRAOS-0490] NFIRAOS shall be able to operate and meet the requirements at altitudes varying between 0 meters and 4050 meters.

Discussion: This requirement flows down from [REQ-1-ORD-1050]. The altitude of 4050 meters corresponds to the altitude of the Mauna Kea 13-North site.

[REQ-2-NFIRAOS-0500] NFIRAOS shall operate with its enclosure cooled to the operating temperature, as well as at 20 C and at the ambient temperature of the TMT dome.

Discussion: NFIRAOS has no other special environmental constraints beyond those in the Level 1 documents.

[REQ-2-NFIRAOS-0510] NFIRAOS shall not emit electromagnetic radiation at any frequency that significantly interferes with itself or the operation of any other current astronomical facility, or TMT first-decade instrument.

Discussion: This requirement flows down from [REQ-1-ORD-7410]. This requirement applies to both summit and support facilities.

[REQ-2-NFIRAOS-0520] In seeing limited and adaptive optics operating modes, NFIRAOS shall be able to carry out astronomical observations under the conditions listed in Table 3 below.

Discussion: This requirement is quoted directly from [REQ-1-ORD-1200]

[REQ-2-NFIRAOS-0530] Unless otherwise stated, all requirements shall be met over the range of the Observing Performance Conditions listed in Table 3.

Discussion: This requirement is traceable to [REQ-1-ORD-1210]

Table 3 Observing Performance Conditions

Ambient temperature range	268 K to 282 K (approx. -5ºC to +9ºC)
Median night time temperature	275.3 K (2.15 ºC)
Temperature temporal gradients	0-100% of ORD § 4.3
Ambient air pressure range	600 hPa to 618 hPa
Ambient relative air humidity	All non-condensing conditions
External mean wind velocity range at 20 m above ground, all directions relative to the telescope azimuth.	0 m/s to 18 m/s

Discussion: Median temperature is traceable to ORD Appendix 4, §4.1.1, Meteorological Parameters, Ground level median nighttime temperature T = 275.3° and is included in this table for the purpose of quantifying a standard telescope whose background degradation by NFIRAOS is specified in [REQ-1-ORD-3660]. NFIRAOS will meet the requirement to not degrade the sky and telescope inter-OH background emission when the telescope is at median temperature or higher.

[REQ-2-NFIRAOS-0550] NFIRAOS shall be able to operate in Calibration Mode, under the conditions listed in Table 4.

Table 4 Facility Performance Conditions

Ambient temperature range	263 K to 286 K (-10ºC to +13ºC)
Ambient air pressure range	600hPa to 618hPa (TBC)
Ambient relative air humidity	All non-condensing conditions
External Wind Speed	up to 30 m/s (3 s gust at 20m elevation)

Discussion: This requirement flows down directly from [REQ-1-ORD-1300] except rainfall, which is not relevant to NFIRAOS when dome is closed.

Discussion: Condensing conditions are defined as occurring when the air temperature is within 2K of the dew point. During servicing and maintenance or other facility activities condensing conditions or rainfall can occur external to the enclosure. However under condensing conditions internal to the enclosure, such activities would be suspended.

[REQ-2-NFIRAOS-0555] All mechanical and electrical components of the system shall be designed to function over the range of the component functional conditions listed in

Table 5 Component Functional Conditions

Ambient air temperature range	260 K to 298 K (approx. -13ºC to +25ºC)
Ambient air pressure range	600 hPa to 1015 hPa (TBC)
Ambient air relative humidity	All non-condensing conditions

Discussion: The intent of this section is to define the range of conditions over which any subcomponent of NFIRAOS can be expected to function. For example motors, pumps, mechanisms, computers, valves, actuators, hydraulics and electronics all must function over this range. In principle any removed subcomponent should be capable of functioning over this range. This does not imply that any system requirements are met over this range.

3.3.1.1 Survival Conditions

[REQ-2-NFIRAOS-0557] NFIRAOS' Survival Conditions occur when any of the following conditions occur and they exceed the facility operation conditions listed in Table 4 Facility Performance ConditionsTable 4

Discussion: This requirement flows down directly from [REQ-1-ORD-1415]

[REQ-2-NFIRAOS-0560] NFIRAOS shall be designed to survive without damage repeated survival conditions listed in Table 6.

Discussion: No prior warning is available for these conditions and it cannot assume that equipment will have been manually switched to an off or standby state prior to arrival of these conditions. No damage may be caused by onset of the Survival conditions in any operating state.

Discussion: This requirement flows down directly from [REQ-1-ORD-1400]. The system will be designed to survive these conditions without damage and without the need for optical re-alignment etc. Consumable or one time safety measures are not permitted.

Table 6 Operational Basis Survival Conditions

Ambient temperature range	257 K to 303 K (-16ºC to +30ºC)
Ambient air pressure range	590hPA o 1025hPa (TBC)
Ambient relative air humidity	0% to 100%, condensing

[REQ-2-NFIRAOS-0570] The normal observatory operations staff shall be able to perform an inspection of NFIRAOS in 6 hours. The inspection shall be sufficient to ensure it is in a safe condition to allow astronomical observations or regular maintenance operations to take place.

Discussion: This requirement flows down directly from [REQ-1-ORD-1410], inspection after operational basis survival event, or after frequent (10 year return) earthquake [REQ-1-ORD-1502]. Inspection would be expected to start after any potentially damaging event once the danger has passed and staff has returned to work. Such inspection of NFIRAOS will consist of motor torque and positioning tests and feeding light from source simulators to client instruments and NFIRAOS WFSs. Warming and opening NFIRAOS is not part of this inspection.

[REQ-2-NFIRAOS-0580] NFIRAOS shall be designed to withstand operational basis survival conditions when there is no power to the observatory.

Discussion: This requirement flows down directly from [REQ-1-ORD-1420]

[REQ-2-NFIRAOS-0590] NFIRAOS shall be designed such that loss of power will not cause damage to NFIRAOS or the observatory.

Discussion: Flowed down from [REQ-1-ORD-1425].

3.3.1.2 Frequent Earthquakes

[REQ-2-NFIRAOS-0600] NFIRAOS and all its subsystems shall withstand earthquakes up to the levels of the 10-year return period earthquake with no damage. Inspection by the normal operations staff, as described in [REQ-2-NFIRAOS-0570] shall be sufficient to ensure that the observatory can be returned to normal operations after such an earthquake.

Discussion: Flowed down from [REQ-1-ORD-1502]. The observatory shall be designed such that earthquakes of this size cause no damage and the observatory can continue to operate without interruption. This implies that inspection should not be necessary. However the observatory must also be designed to allow for easy inspection so that the normal operations staff can conduct an inspection in less than six hours to ensure that in fact no significant damage has occurred. The levels of a 10-year period return earthquake have a 10% probability of being exceeded in a one year period.

3.3.1.3 Infrequent Earthquakes

[REQ-2-NFIRAOS-0610] After exposure to an earthquake up to the levels of the 200-year return period earthquake, once the observatory staff has resumed regular duty, NFIRAOS shall be able to resume normal operations within two weeks using assuming the availablility of staff and regularly available equipment.

Discussion: Flowed down from [REQ-1-ORD-1510]. The levels of a 200-year return period earthquake have a 22% probability of being exceeded in a 50 year period

[REQ-2-NFIRAOS-0620] An earthquake up to and including the severity of the 200 year return period, in some servicing modes, may result in extensive damage to NFIRAOS, or danger to personnel. Any operation that falls under this description shall be specifically identified in the NFIRAOS safety plan, and the operational procedure shall be designed to minimize the time spent in this state.

Discussion: Flowed down from [REQ-1-ORD-1550].

3.3.1.4 Very Infrequent Earthquakes

[REQ-2-NFIRAOS-0630] NFIRAOS' enclosure, structure, instrument support structure, optical mounts, optics, and interfaces to its client instruments shall be designed to withstand the loads resulting from an earthquake up to the levels of the 1000-year return period earthquake. Optics must survive and be re-useable (after recoating), but structure is allowed to yield as long as it maintains sufficient structural integrity to protect optics, client instruments and personnel.

Discussion: This requirement is traceable to [REQ-1-ORD-1560]. The telescope needs to limit loads to the telescope mounted subsystems resulting from such an earthquake to the values specified in the OAD. The primary structure of all telescope mounted subsystems and their optics must be designed to withstand these same specified loads imparted by the telescope. This requirement is a structural design requirement only and no expectation is made about either the time or cost to repair other damage to the observatory. The following are not required to be designed against this level of earthquake provided they do not pose a hazard to optics: Structure whose failure would not cause a hazard to personnel safety; fluid and electrical services; computers and other ancillary systems:

The levels of a 1000-year return period earthquake have a 5% probability of being exceeded in a 50 year period.

[REQ-2-NFIRAOS-0640] Non-structural sub-system components shall be designed so as to not damage the optics (except for coatings) in the event of their failure.

Discussion: Enclosure failure may cause humid air to condense on optics and damage coatings. This requirement is traceable to [REQ-1-ORD-1565]. Any sub-systems, components, hoses, etc. that may fail under the conditions resulting from a 1000-year return period earthquake and whose failure could cause damage to the optics shall be identified. The failure modes will be identified and where necessary measures shall be put in place to prevent or reduce the probability of failures causing damage to the optics.

[REQ-2-NFIRAOS-0642] NFIRAOS shall limit earthquake loads transmitted to its client instruments and to the NSCU. Accelerations and displacements shall not be amplified more than xx% TBD relative to those that would be transmitted during an earthquake by a rigid body having the mass, moment, centre of gravity and dimensions of NFIRAOS.

3.4 REQUIREMENTS

3.4.1 Top Level Requirements

[REQ-2-NFIRAOS-0650] NFIRAOS shall reduce the effects of the atmospheric turbulence and residual system misalignments, with the residuals included in the NFIRAOS error budget.

Discussion: This requirement flows down from [REQ-1-ORD-2525] and [REQ-2-OAD-2760]. It is quantified in more detail in the following requirements in this section.

This implies requirements upon both the AO system and the other observatory subsystems introducing these disturbances. The telescope and instrument requirements include specifications on the amplitude of these wavefront errors, and the allowable residual wavefront errors for an idealized (linear, noise-free) AO system with order 60x60 wavefront compensation and a -3dB error rejection bandwidth of 30 Hz.

[REQ-2-NFIRAOS-0660] NFIRAOS throughput shall exceed 80% over the 1 - 2.5 micron wavelength range, and 78% over 0.8 – 1 microns, with a goal of 90% from 0.6 to 2.5 microns. Only one of Z, J, H, K bands must be observed at one time.

Discussion: Derived from [REQ-1-ORD-3655] to be amended. This requirement is partitioned in [REQ-2-NFIRAOS-3380]. NFIRAOS may include a provision for at least two different spectral pass bands, e.g. by incorporating a beamsplitter changer: For example, the second beamsplitter might be designed with a bluer short wave cutoff to enable observations at shorter wavelengths with reduced sky coverage.

[REQ-2-NFIRAOS-0670] NFIRAOS shall meet its requirements for image quality, sky coverage, throughput, and background simultaneously over a wavelength range of 1.0 to 2.5 μm, with a strong goal to simultaneously meet these requirements down to 0.8 μm.

Discussion: Quoted from [REQ-1-ORD-3505]. Extending the short wave cutoff from 1.0 μm to 0.8 μm may reduce sky coverage, since a brighter natural guide star will be required for real-time calibration of the LGS WFS measurement errors arising due to sodium layer variability and Rayleigh backscatter variability. Observations at 0.8 μm will definitely be possible, (see [REQ-1-ORD-3655]) even if the sky coverage requirement is not met. This agrees with SAC thinking, and it is technically feasible in the current NFIRAOS design.

[REQ-2-NFIRAOS-0680] NFIRAOS shall provide a transmitted technical field with a focal ratio of f/15

Discussion: This requirement is quoted directly from [REQ-1-ORD-3510].

[REQ-2-NFIRAOS-0690] NFIRAOS shall pass an unvignetted field of view of at least 2 arcminutes diameter to the science instruments.

Discussion: This requirement is quoted directly from [REQ-1-ORD-3515].

[REQ-2-NFIRAOS-0700] NFIRAOS shall enable 50% sky coverage at the galactic pole.

Discussion: This requirement is quoted directly from [REQ-1-ORD-3525], and is qualified by [REQ-2-NFIRAOS-3530], a specification on tip/tilt residual with median turbulence and 70th percentile windshake.

[REQ-2-NFIRAOS-0710] NFIRAOS will deliver images at the science instrument focal plane, with an RMS wavefront error of 187 nanometers (nm) on axis and 191 nm over a 10 arcsec FOV under reference atmospheric seeing conditions (see Appendix § 4.1 in ORD) with 50% sky coverage at the galactic pole.

Discussion: This requirement is quoted directly from [REQ-1-ORD-3530]. The wavefront error values must include allocations for the uncorrectable and uncalibrated errors in the *science instruments themselves. The reference atmospheric seeing conditions correspond to a 0 degree zenith angle, and off-zenith performance will degrade with the changing atmospheric profile. The post early-light upgraded version of NFIRAOS shall achieve on the order of 120 nm high order RMS wavefront image quality on-axis.*

[REQ-2-NFIRAOS-0720] NFIRAOS will deliver diffraction-limited images at the science instrument focal plane, with an RMS wavefront error of 208 nm over a 30 arcsec diameter FOV under reference atmospheric seeing conditions (see Appendix in § 4.1 ORD) with 50% sky coverage at the galactic pole.

Discussion: This requirement is quoted directly from [REQ-1-ORD-3532]. This is about 82 nm RMS worse (in quadrature) than the 191 nm RMS error on a 10" square FOV.

[REQ-2-NFIRAOS-0730] NFIRAOS shall operate at zenith angles from 1 to 65 degrees.

Discussion: This requirement is quoted directly from [REQ-1-ORD-3535].

[REQ-2-NFIRAOS-0740] NFIRAOS shall operate with values of r_0 (in the direction of the observation) as small as 0.10 m, measured at $\lambda = 0.5\ \mu$m.

Discussion: This requirement is quoted directly from [REQ-1-ORD-3540] and flows down to the stroke of DM actuators.

[REQ-2-NFIRAOS-0750] NFIRAOS shall enable measurement of differential photometry at the 2% level for 10 minute integrations at 1 μm wavelength over a 30" field of view assuming a single standard star is in each image.

Discussion: This requirement is quoted directly from [REQ-1-ORD-3645]. It flows down to the decrease of residual wavefront error with integration time.

[REQ-2-NFIRAOS-0760] NFIRAOS shall enable precise differential astrometry measurements, where one-dimensional time-dependent rms astrometric positional uncertainties, after fitting distortion measured with field stars, and over a 30 arcsecond field of view, shall be no larger than 50 micro-arcseconds in the H band for a 100 s integration time. Errors should fall as $t^{-1/2}$. Systematic one-dimensional rms position uncertainties shall be no more than 10 μas.

Discussion: This requirement is quoted directly from [REQ-1-ORD-3650]. It flows down to the distortion specification and the decrease of residual wavefront error with integration time. Distortion convolved with the variability of cirrus and residual correction during an exposure limits astrometric accuracy.

[REQ-2-NFIRAOS-0780] NFIRAOS shall not increase the (inter-OH) background by more than 15% over natural sky + the telescope.

Discussion: Traceable to [REQ-1-ORD-3660]. The telescope background for the purpose of this requirement shall include the emissivity computed as (1-throughput), with throughput defined in [REQ-1-ORD-2900], plus the contribution of gaps in the M1 geometry as per [REQ-1-OAD-1715], both at the median temperature as defined in Table 3*, and assuming that a cold stop within an instrument is used to mask out the telescope top end obstructions.*

3.4.2 Architecture

[REQ-2-NFIRAOS-0800] NFIRAOS shall utilize multi-conjugate adaptive optics to widen the compensated field of view.

Discussion: This is traceable to requirement [REQ-1-OAD-2720] and [REQ-1-ORD-3500]. This significantly improves sky coverage by "sharpening" the natural guide stars used for tip/tilt sensing, and also improves astrometric and photometric accuracy on the IRIS and WIRC science fields.

[REQ-2-NFIRAOS-0810] NFIRAOS shall utilize laser guide stars to improve sky coverage.

Discussion: This requirement is traceable to [REQ-1-ORD-2960] and [REQ-1-ORD-3500].

[REQ-2-NFIRAOS-0820] NFIRAOS shall incorporate laser guide star wavefront sensors to collect and analyze the returned 589 nm sodium light to provide active and adaptive optics corrections to the system.

Discussion: This requirement flows down from [REQ-1-ORD-2970].

3.4.3 Client Instruments

[REQ-2-NFIRAOS-0830] NFIRAOS shall support the IRIS and IRMS system configurations.

Discussion: This is a flow down of [REQ-1-OAD-2820]. Refer to the decomposition description [REQ-2-NFIRAOS-0040] for a list of functions such as science ADCs, which instruments are responsible for.

[REQ-2-NFIRAOS-0850] NFIRAOS shall be designed and built in a manner that supports, in the first decade of operation, the following additional client instruments: NIRES-b and WIRC.

Discussion: This requirement flows down from [REQ-1-ORD-4200] and [REQ-2-NFIRAOS-0100]. NIRES-b will replace IRMS. It is expected that WIRC will reside on the top port, NIRES-b will reside on the side port, IRIS will remain on the bottom port. IRMS and the Acquisition camera will be retired.

[REQ-2-NFIRAOS-0860] NFIRAOS shall provide mounting for three separate instrument focal planes.

Discussion: This requirement is quoted directly from [REQ-1-ORD-3520].

[REQ-2-NFIRAOS-0870] NFIRAOS shall provide a common mechanical, thermal and optical interface at each of the three instrument interface ports.

Discussion: The intent of this requirement is to allow any on the NFIRAOS client instruments to be mounted to any of the three output ports without significant modification to either NFIRAOS or the instrument. Minor changes including modification or replacement of the client instrument support truss would be permitted to allow relocation from the side port to either the top or bottom port of NFIRAOS.

[REQ-2-NFIRAOS-0872] The interface ports for all three instruments shall be optically identical.

Discussion: This requirement covers f/ratio, exit pupil, field curvature, beam diameter, field tilt.

REQ-2-NFIRAOS-0880] NFIRAOS shall permit instrument rotation at the instrument mounting points.

Discussion: This requirement is traceable to [REQ-1-ORD-3523] and [REQ-1-ORD-3825]. It is the responsibility of the instrument to provide rotation, but a requirement on NFIRAOS to permit this. E.g. by allowing space for rotating seals outside the beam.

[REQ-2-NFIRAOS-0900] NFIRAOS shall accept OIWFS pixel intensities from instruments with three OIWFSs and maintain image position, focus and plate scale.

Discussion: [REQ-1-ORD-1-3810], [REQ-1-ORD-1-3725] IRIS includes three NGS on-instrument wavefront sensors (OIWFSs). WIRC will include 3 OIWFS to provide guide star position feedback to maintain plate scale. The quantity of WFS in NIRES-b is three.[REQ-1-ORD-4615]

[REQ-2-NFIRAOS-0910] For instruments with a single OIWFS, NFIRAOS shall accept OIWFS pixel intensities and maintain image position and focus.

Discussion: [REQ-1-ORD-1-3810] IRMS includes only one OIWFS. The IRMS OIWFS will be similar to the IRIS OIWFS

3.4.4 Operating Functions

[REQ-2-NFIRAOS-0930] NFIRAOS shall have a standby mode.

Discussion: In standby mode, high-voltage supplies are turned off, shutters are closed, and light sources turned off. Returning from standby mode is included in the 10 minutes allowed to switch TMT instruments [REQ-2-NFIRAOS-3460].

[REQ-2-NFIRAOS-0950] NFIRAOS shall support classical observing.

Discussion: This requirement is quoted directly from [REQ-1-ORD-1700]. Classical Observing defines the operational mode where the observatory is made available to a particular astronomer (PI) or group of astronomers for a definite time period. The PI has real-time control over target specification & acquisition and AO/instrument configuration during the assigned time period. Therefore, NFIRAOS will comply with this specification by exposing acquisition and configuration functionality to the AO Executive software and will not have internal sequencers automating functions that a PI needs direct control over for classical observing.

[REQ-2-NFIRAOS-0960] NFIRAOS shall be upgradeable to support queue mode observations.

Discussion: This requirement is quoted directly from [REQ-1-ORD-1705]. It is expanded in requirements on optical path stability (especially for NIRES calibrations) and in requirements on a fully automated interface to the AOESW.

[REQ-2-NFIRAOS-0970] NFIRAOS shall monitor its own status to enable the assessment of whether a particular function can be, and has been, successfully completed.

Discussion: This requirement flows down from [REQ-1-ORD-1720]

[REQ-2-NFIRAOS-0990] The NFIRAOS Control System shall be configured, controlled and coordinated by the AO executive software, for all scheduled science observations, calibrations, and engineering modes.

[REQ-2-NFIRAOS-0993] It shall be possible to build, run, control, and monitor each NFIRAOS software subsystem in stand-alone mode, i.e. without starting the entire TMT software system or AO Executive software.

Discussion: This is traceable to [REQ-1-OAD-9303].

[REQ-2-NFIRAOS-1000] NFIRAOS shall include the following operating functions:

- [REQ-2-NFIRAOS-1010] Pre-observation calibration of sensors, mirrors, and actuators
- [REQ-2-NFIRAOS-1020] Initialization of sensors, mirrors, actuators, and software systems/interfaces at the beginning of nightly operation
- [REQ-2-NFIRAOS-1030] Interface with, the laser guide star facility (LGSF) for LGS projection, and real-time optimization algorithms
- [REQ-2-NFIRAOS-1040] NGS WFS deployment at the beginning of each observation. †
- [REQ-2-NFIRAOS-1050] Instrument selection at the beginning of each observation
- [REQ-2-NFIRAOS-1060] NGS and LGS acquisition on the corresponding WFSs at the start of each observation

- [REQ-2-NFIRAOS-1070] Operation and real-time optimization of tip/tilt and higher-order AO control loops, together with any required offloads to telescope mirrors, LGS launch system, etc.
- [REQ-2-NFIRAOS-1080] Data acquisition as needed for PSF estimation and similar calibration tasks
- [REQ-2-NFIRAOS-1090] Opening loops at the end of each observation
- [REQ-2-NFIRAOS-1100] Opening loops, parking mechanisms, closing shutters and powering down subsystems at the end of nightly operations
- [REQ-2-NFIRAOS-1110] Interrupting closed loop operations to suspend, and if possible resume, operations in the event of a safety fault or laser traffic control event
- [REQ-2-NFIRAOS-1120] Interfaces to the instruments, telescope, data management system, LGSF, and safety systems as needed to implement the above functions.

Discussion: † "NGS WFS deployment" refers to deployment of the 60x60 WFS in NGS AO mode, and the TWFS in LGS AO mode. Both these sensors are deployed using a common pair of gimbal mirrors in the current design.

[REQ-2-NFIRAOS-1130] These operating functions shall be performed automatically in a predictable process, with results that are consistent with the procedures described in the Observing Scenarios document [RD15] and the NFIRAOS Operational Concepts Definition document [RD16].

[REQ-2-NFIRAOS-1140] All sequences of operations for routine daytime calibration shall be executable through the AO Executive Software and Observatory Executive Software.

Discussions: NFIRAOS shall implement all the functions above, but the responsibility to assemble these functions into observing and calibration sequences belongs to the AO Executive Software and the Observatory Executive Software. An engineering user interface is also a requirement [REQ-2-NFIRAOS-2650].

3.4.5 Observing Modes

3.4.5.1 Laser Guide Star mode

[REQ-2-NFIRAOS-1150] NFIRAOS shall utilize six Na (Sodium) laser guide stars.

Discussion: This requirement flows down from [REQ-1-OAD-2810], [REQ-1-3500], [REQ-1-2960], [REQ-1-OAD-2710] and [REQ-1-OAD-2715]. LGS are used to improve sky coverage. This implies a high-order correction system. Utilizing multiple laser guide stars in the mesospheric sodium layer and atmospheric tomography will allow minimizing the impact of the cone effect. The purpose is to meet the sky coverage requirement defined in [REQ-1-NFIRAOS-0600]

3.4.5.2 Single Natural Guide Star mode, No lasers

[REQ-2-NFIRAOS-1170] NFIRAOS shall provide a natural guide star operational mode, delivering Strehl ratios of 0.5 in K-Band with a 16th magnitude guide star.

Discussion: This requirement is quoted directly from [REQ-1-ORD-3670]. This specification includes both implementation errors and first-order (servo lag, fitting, measurement noise) AO errors, and assumes a sub-electron noise CCD.

.

3.4.5.3 Seeing Limited mode

[REQ-2-NFIRAOS-1200] NFIRAOS shall include a Seeing Limited Mode, doing fast guiding via NFIRAOS' tip/tilt stage using measurements from a science instrument OIWFS, together with sending, to the telescope control, slow speed measurements of telescope aberrations from a low order Truth WFS within NFIRAOS.

3.4.6 Daytime Calibration Modes

[REQ-2-NFIRAOS-1210] NFIRAOS shall include or make allowance for all necessary components and processes for self-calibration or calibration of the instruments that NFIRAOS feeds.

Discussion: This requirement is quoted directly from [REQ-1-ORD-3665]

[REQ-2-NFIRAOS-1220] NFIRAOS shall feed internal natural star simulated sources to client instruments, especially to calibrate non-common path errors and pointing models for OIWFSs.

[REQ-2-NFIRAOS-1230] NFIRAOS shall pass Flat Field and Wavelength standard light from an external calibrator in front of NFIRAOS through to client instruments.

[REQ-2-NFIRAOS-1240] NFIRAOS shall perform closed loop operation on internal point sources simulating natural stars and laser guide stars at varying range distance.

[REQ-2-NFIRAOS-1250] NFIRAOS shall perform closed loop correction of artificial turbulence from a turbulence simulator in NFIRAOS.

[REQ-2-NFIRAOS-1260] In both of the above closed loop modes, NFIRAOS shall be able to feed the output beam to the HRWFS test instrument on the side port, without tip/tilt/focus feed back.

Discussion: In these cases, there is no tip/tilt/focus available from an OIWFS, but the image must be stable on the HRWFS. The intent is that the MOR TWFS will be used as the zero-point reference for image position. This requirement flows down to the RTC architecture.

[REQ-2-NFIRAOS-1270] Closed loop modes shall be operable in the absence of any HRWFS or instrument on an output port.

Discussion: This requirement flows down to the RTC architecture.

[REQ-2-NFIRAOS-1280] NFIRAOS' engineering user interface shall allow at a minimum to set patterns of DM actuators and to read WFS images and slopes.

Discussion: This requirement flows down to the RTC architecture. See §3.5.13 for details.

3.4.7 Control Optimization

[REQ-2-NFIRAOS-1290] The optical, wavefront sensing, and control subsystems of NFIRAOS shall be adjustable and/or adaptive to optimize performance as seeing, the sodium layer profile, and other atmospheric parameters vary during an observation.

3.5 SUBSYSTEM REQUIREMENTS

3.5.1 Instrument Support Tower

[REQ-2-NFIRAOS-1300] NFIRAOS shall include an instrument support tower that interfaces with the telescope structure and carries the loads of the NFIRAOS optics and enclosure, the three client instruments and the NFIRAOS Science Calibration unit.

[REQ-2-NFIRAOS-1310] Two of the client instruments shall have a vertical orientation (on the top and bottom face of NFIRAOS) with identical mechanical interfaces to the instrument support tower.

[REQ-2-NFIRAOS-1320] The third instrument port shall be on the side of NFIRAOS.

[REQ-2-NFIRAOS-1330] The design of the interfaces to the three client instruments shall take into account the mass and centre of gravity as defined in the ICDs [RD9, RD10 and RD13].

Discussion: The assumption is that the centre of gravity of each of the client instruments will be on the optical axis. The mass, moment of inertia and centre of gravity of the three instruments is also defined in the OAD (requirements [REQ-1-OAD-0768], [REQ-1-OAD-0770], [REQ-1-OAD-0778]).

3.5.2 Enclosures - optics

Discussion: As described in [REQ-2-NFIRAOS-0780], NFIRAOS shall not increase the (inter-OH) background by more than 15% over natural sky + the telescope.

[REQ-2-NFIRAOS-1340] NFIRAOS shall have a light-tight optics enclosure, cooled to meet the specification in [REQ-2-NFIRAOS-0780] for emissive background.

[REQ-2-NFIRAOS-1350] The operating temperature of the optics enclosure shall be -30 C.

Discussion: Derived from [REQ-1-ORD-3660] and optical throughput [REQ-2-NFIRAOS-3380]. See [RD17]. NFIRAOS plans to use a refrigerant system to cool the optics enclosure.

[REQ-2-NFIRAOS-1360] The NFIRAOS optics enclosure initial cool-down shall be using forced air.

[REQ-2-NFIRAOS-1370] NFIRAOS optics shall cool to operating temperature after <15 hours, starting from the median dome temperature on the selected site.

Discussion: This requirement, together with the downtime allocation in Table 12 feed into to MTBF calculations for NFIRAOS.

[REQ-2-NFIRAOS-1380] NFIRAOS shall warm up from operating temperature to median dome temperature in <12 hours.

[REQ-2-NFIRAOS-1390] The optics enclosure forced air shall be shut off after reaching operating temperature, or at sunset, or during sensitive daytime calibrations.

[REQ-2-NFIRAOS-1395] Operating temperature shall be maintained by active cold panels buried in insulated walls, both during operation and during standby mode.

Discussion: Refrigerant cooling to intercept heat leakage within walls and at support legs for optical tables and of sources like high-duty cycle motors and CCD cameras is acceptable, and will provide temperature uniformity within the enclosure.

[REQ-2-NFIRAOS-1400] The forced air within NFIRAOS shall be cooled using Refrigerant-507, at flow rate, temperature and pressure TBD.

Discussion: R-507 is a modern Hydro-fluorocarbon refrigerant, without ozone damaging chlorine.

Discussion: This requirement flows down from [REQ-1-OAD-4705]. Compressed refrigerant (e.g. Hydro-fluorocarbon (HFC) shall be provided to the Nasmyth areas for removal of heat from instrumentation).

[REQ-2-NFIRAOS-1405] When the optics enclosure is closed and the cooling system is operating, NFIRAOS shall keep the frost point of the air in the optics enclosure at least 5 kelvin below the temperature of all surfaces except those of the air handling unit.

Discussion: During ambient temperature operation with the enclosure open, this requirement does not apply. During cool-down, and while at operating temperature and during warm-up, NFIRAOS may use a dry air purge to lower the interior dew point (or frost point when temperature is below 0 °C). *Alternately, the air handling unit (AHU) may employ reheat cycles during cool-down to purge and drain moisture collected in the AHU, together with the slight air purge specified in [REQ-2-NFIRAOS-1406]. Note that frost point is approximately 0.90*dew point inCelsius for temperatures below freezing.*

[REQ-2-NFIRAOS-1406] During operation, NFIRAOS shall be maintained at a slight positive pressure of 5 Pascals gauge pressure, using a dry air feed of TBD litres/minute.

[REQ-2-NFIRAOS-1410] The absolute value of heat transfer between the NFIRAOS optics enclosure and the telescope dome air shall be < 1600 W.

Discussion: Since the optics are colder than the dome, NFIRAOS is a heat sink which could affect local seeing in the dome. If this level of cooling is a problem, NFIRAOS could have surface heaters on its outer metal cladding.

[REQ-2-NFIRAOS-1420] The temperature of any motor/actuator/mechanism within the opto-mechanical enclosure shall be within 0.5 °C of the enclosure temperature.

Discussion: Derived from requirement to limit seeing within the NFIRAOS enclosure. (based on Gemini GPi specification REQ-FPR-1340 in [RD24]).

[REQ-2-NFIRAOS-1422] Individual NFIRAOS mechanisms shall each have a maximum heat leakage of <0.5 W from any part exposed to the interior of the optics enclosure.

Discussion: This specification is based on experience with Altair where heat dissipation below an optical beam, of 1.8 W in a cable bundle 30 mm diameter, and 400 mm long, ruined the images. Further CFD work may in future refine this specification. Mechanisms with excessive power dissipation, e.g. LGS zoom, may require cooling.

[REQ-2-NFIRAOS-1660] The feed to instruments shall have a back focal distance (i.e. distance from the NFIRAOS exit ports' interface plane to output focus) at least 0.5 m, with a goal of +1 m.

[REQ-2-NFIRAOS-1670] To seal unused instrument ports, NFIRAOS shall use manually installed insulated, light-tight and air-tight covers.

[REQ-2-NFIRAOS-1680] NFIRAOS shall incorporate uninsulated gate valves to seal exit ports during instrument exchange.

Discussion: These gate valves will prevent intrusion of ambient-temperature air until port covers can be installed.

[REQ-2-NFIRAOS-1690] The design of NFIRAOS shall accommodate a maximum heat leakage from each of the client instruments of <0.5 W and a maximum temperature difference of 0.5 degrees Celsius between any part of the client instruments exposed to the interior of the optics enclosure and the NFIRAOS operating temperature.

Discussion: These two numbers are based on experience with Altair where heat dissipation below an optical beam, of 1.8 W in a cable bundle 30 mm diameter, and 400 mm long, ruined the images. Further CFD work may in future refine this specification.

3.5.2.1 Servicing

Discussion: For additional safety-related requirements consult § 3.7.4.

[REQ-2-NFIRAOS-1424] NFIRAOS optics enclosure shall contain provision for access of personnel while reducing contamination.

Discussion: It is planned to have removable clean vestibules for personnel access on two sides of NFIRAOS.

[REQ-2-NFIRAOS-1425] NFIRAOS optics enclosure shall have provision for removing or replacing opto-mechanical subassemblies like optics mounts, beamsplitter changers, and deformable mirrors, while minimizing contamination.

Discussion: It is planned to have deployable clean vestibules with laminar flow air knives. These would be craned among several hatches on the roof of NFIRAOS. Equipment would be lowered through these vestibules and hatches.

[REQ-2-NFIRAOS-1426] NFIRAOS optics enclosure shall have provision for moving sub-assemblies between access hatches and their destinations on the optical table.

Discussion: Internal jib cranes, and rail guided carts are planned to transfer opto-mechanical sub-assemblies.

[REQ-2-NFIRAOS-1427] NFIRAOS optics enclosure shall have internal lighting on standard ('dirty') power, and emergency lighting on backup power.

3.5.3 Optical Table

[REQ-2-NFIRAOS-1430] NFIRAOS shall use one custom space frame to support the science, visible and laser optics, the wavefront correctors, the laser zoom system and the visible natural wavefront sensors.

Discussion: All NFIRAOS opto-mechanics are supported by the table.

[REQ-2-NFIRAOS-1450] The optical table shall be connected to the Instrument support tower in such a manner that as the optics are cooled, the optics shrink isotropically about a point located within +/- 4 m of the input focus from the telescope.

3.5.4 Optics

3.5.4.1 Science Path Optics

[REQ-2-NFIRAOS-1455] NFIRAOS shall be designed to work with the TMT telescope prescription.

Discussion: This requirement is traceable to [REQ-1-OAD-1000] and [REQ-1-OAD-1050] to [REQ-1-OAD-1064].

[REQ-2-NFIRAOS-1460] The NFIRAOS science path shall be a 1:1 dual OAP relay.

[REQ-2-NFIRAOS-1465] The NFIRAOS science path shall accept and deliver an f/15 beam in and out.

[REQ-2-NFIRAOS-1470] The NFIRAOS optical design shall accept, from the Thirty Meter Telescope as input, a beam with 2.0 arcminutes diameter unvignetted field of view, with a goal of 2.6 arcminutes with ≤50% vignetting at the edge of this field of view,

Discussion: The goal for 2.6 arcminutes unvignetted field of view would impact the entrance window

[REQ-2-NFIRAOS-1480] NIFIRAOS shall deliver an unvignetted beam 2.0 arcminutes diameter. As a goal, the NFIRAOS optical design shall deliver a beam with 2.6 arcminutes diameter with ≤50% vignetting at the edge of this field.

Discussion: [REQ-1-ORD-3515] governs the unvignetted field of view delivered by NFIRAOS. The goal for 2.6 arcminutes vignetted field of view is most valuable on the upper port for the IRMS guide field, and shall not drive the cost of the entrance window, OAPs, science selection fold mirror, and affordable patrol range in the acquisition camera.

[REQ-2-NFIRAOS-1485] The worst case image distortion over the 2.0 arcminute diameter field shall be <0.05% with a goal of <0.01% of the 2.0 arcminute field.

Discussion: This requirement flows down from [REQ-1-ORD-3650]. A perfectly square array of points at the input focal plane will be delivered to the output focal plane with this tolerance, after removing magnification, translation and rotation. Differential magnification in X vs Y and other higher-order distortions are covered by this specification.

[REQ-2-NFIRAOS-1490] The beamprint on DM0 shall be at an angle of incidence of 13.75 degrees, with a dimension of 300 mm along the short (vertical) axis of the elliptical beamprint.

Discussion: For programmatic reasons, prototyping of the tip/tilt stage carrying this DM0, is underway, to meet this requirement.

[REQ-2-NFIRAOS-1500] The beamprint on DM11 shall be at an angle of incidence of 10 degrees, with a dimension of 365 mm along the short axis of the elliptical footprint.

[REQ-2-NFIRAOS-1532] The stability of the science path pointing, over a time period of one year (TBC), from input focal mask plane to output image, including the effects of moving the ISFM among its four positions, shall be <0.2" rms on the sky.

Discussion: This is an allocation from the telescope pointing budget of 1", intended to be a minor component of that budget, and intended to not impede transferring coordinates from the Acquisition Camera images to OIWFS probe offsets.

[REQ-2-NFIRAOS-1533] The stability of the science path pointing, from input focal mask plane to output image, over a time period of one day, when the ISFM remains fixed in one of its four positions, shall be <0.1 mas rms on the sky.

Discussion: This stability specification is intended to permit calibration of OIWFS probe pointing models, instrument rotator bearing runout, and optical distortions in NFIRAOS' science optics, and in instruments' science optics.

[REQ-2-NFIRAOS-1534] The optical mounts shall be supported kinematically such that each can be lifted into place and maintain optical alignment with only minor adjustments in tip and tilt needed to meet specifications.

3.5.4.2 Entrance Window

[REQ-2-NFIRAOS-1540] NFIRAOS shall have a double-paned, evacuated entrance window into the optical enclosure.

[REQ-2-NFIRAOS-1542] The temperature of the inside surface of the window, exposed to the optical enclosure, shall be within 0.5 K of the enclosure temperature.

Discussion: Since there will be temperature differences of up to 50 Celsius degrees across the window, we wish to avoid the risk of window seeing. This quantity is traceable to the error budget in the sense that meeting it causes negligible image degradation, and therefore does not appear in that budget.

[REQ-2-NFIRAOS-1550] The entrance window shall transmit >94% from 0.589 to 2.45 μm.

[REQ-2-NFIRAOS-1560] There shall be a remotely operated shutter outside the entrance window.

Discussion: For calibrating instrument backgrounds, the intent is to open the shutter and deploy the science calibrator flat field source in front of NFIRAOS. Thus, there is no requirement in NFIRAOS to present a view of a cold shutter to instruments.

[REQ-2-NFIRAOS-1570] The shutter shall operate in < 10 seconds, with a goal of 5 seconds.

Discussion: This relatively undemanding time allowance is intended to not limit design options. The time is acceptable because it occurs infrequently, mainly in parallel with the 10 minutes allowed to switch instruments.

3.5.4.3 Beamsplitter

[REQ-2-NFIRAOS-1580] NFIRAOS science path shall have a beamsplitter changer with at least two positions.

[REQ-2-NFIRAOS-1590] Each beamsplitter shall transmit science light longwards of its cutoff and reflect short wavelength light.

Discussion: This requirement specifies the polarity of the beamsplitter. The wavelength cutoff is determined by [REQ-2-NFIRAOS-0660].

3.5.4.4 Narcissus Mirror

[REQ-2-NFIRAOS-1600] As a goal, NFIRAOS may have a Narcissus mirror, parallel to the second surface of the science beamsplitter.

Discussion: The purpose of this goal is to reduce emissivity of NFIRAOS. An instrument, looking back into NFIRAOS will see its cold self in the Narcissus mirror, rather than the warmer (-30 C) NFIRAOS enclosure reflected by an imperfect antireflection coating on the tilted beamsplitter.

[REQ-2-NFIRAOS-1610] The narcissus mirror shall reflect the science wavelengths.

Discussion: cf. [REQ-2-NFIRAOS-0670] for wavelength range.

3.5.4.5 Instrument Selection Fold Mirror

[REQ-2-NFIRAOS-1620] The output beam from NFIRAOS shall be directed to three instrument ports via a steerable instrument selection mirror.

Discussion: The speed of the instrument selection fold mirror (ISFM) is specified in [REQ-2-NFIRAOS-3516].

[REQ-2-NFIRAOS-1630] The repeatability of the ISFM, when moving among its three positions, shall be <0.1" rms on the sky.

Discussion: This is an allocation from science path repeatability budget in [REQ-2-NFIRAOS-1532].

3.5.4.6 Exit ports

[REQ-2-NFIRAOS-1640] NFIRAOS shall have open port holes for feeding the science beam to client instruments.

Discussion: Exit ports do not have windows, which are the instruments' responsibility.

See [REQ-NFIRAOS-0830…0880] for closely related requirements.

3.5.5 Visible Natural Wavefront Sensing

[REQ-2-NFIRAOS-1700] NFIRAOS shall implement a natural visible optics path, split from the Laser light to feed one high speed NGS WFS and one Truth WFS.

[REQ-2-NFIRAOS-1710] The visible path shall have two pointing and centering (e.g. star selection) mirrors to select a single star in the field of view and simultaneously register DM0 actuators to WFS lenslets.

[REQ-2-NFIRAOS-1720] One of the two star selection mirrors shall move axially (in piston) to refocus the natural guide star.

[REQ-2-NFIRAOS-1725] The coordinated motion of the star selection mirrors shall map the DM0 actuators onto the TWFS lenslets.

[REQ-2-NFIRAOS-1730] The visible path shall include a 1 arcsecond diameter field stop.

[REQ-2-NFIRAOS-1740] The visible path shall include an atmospheric dispersion compensator.

[REQ-2-NFIRAOS-1750] The visible path shall include a deployable mirror to: 1) send all the available visible light to the TWFS for LGS mode and Seeing Limited mode; or 2) send all the light to the NGS WFS for NGS mode.

[REQ-2-NFIRAOS-1761] The pupil image on the lenslets of the NGS WFS and TWFS shall be derotated to compensate for the rotation introduced by the collapsed periscope formed by the star selection mirrors.

Discussion: The expected maximum rotation is 5 degrees. Either rotating each WFS barrel (from lenslets to CCD), or rotating a common K-mirror may be employed, under remote control of the NFIRAOS CC.

3.5.5.1 Truth Wavefront Sensors

Discussion: The requirements in this section flow down from requirement [REQ-1-OAD-2840]

[REQ-2-NFRAOS-1765] NFIRAOS shall provide high spatial resolution, slow "truth" NGS wavefront sensing to prevent long term drifts in the corrected wavefront due to variations in the sodium layer profile, WFS background noise due to Rayleigh backscatter, or other system calibration errors.

[REQ-2-NFIRAOS-1790] The MOR TWFS (Moderate Order, Radially symmetric mode sensing) shall have 12x12 subapertures and frame rates of 0.1 to 10 Hz.

[REQ-2-NFIRAOS-1800] The MOR TWFS detector shall be Nyquist sampled in 95 percentile good seeing.

Discussion: The intent is to not lose AO performance when the seeing is best.

3.5.5.2 Natural Guide Star Wavefront Sensor

[REQ-2-NFIRAOS-1820] NFIRAOS shall have a NGS WFS 60x60 SH WFS for controlling the DM conjugated to the ground when LGS are not available or desirable.

Discussion: For example, the science case of guiding on a galactic nucleus, which is the science target. The galaxy halo is bright enough to blind the OIWFSs, thereby precluding using LGS.

[REQ-2-NFIRAOS-1190] The NGS mode WFS shall utilize visible light in the bandpass between the laser wavelength and the science wavelength.

[REQ-2-NFIRAOS-1830] The NGS WFS detector shall be 240x240 pixels, using quad cells of pixels with two guard rows between each subaperture.

[REQ-2-NFIRAOS-1840] The NGS WFS frame rate shall be set prior to an observation in the range of 10 Hz (TBC) to 800 Hz.

[REQ-2-NFIRAOS-1845] The NGS WFS shall include a fast steering mirror with 1 kHz -3dB bandwidth to dither the stellar images in a 50 mas radius circle on the detector.

Discussion: Dithering will be used to measure centroid gain on the undersampled detector to compensate in real time for sensitivity changes caused by seeing variations.

3.5.6 Laser Wavefront Sensors

[REQ-2-NFIRAOS-1860] NFIRAOS shall utilize LGS wavefront sensors requiring minimal extrapolation of existing detector technology in terms of read noise, pixel read rate, and number of pixels.

[REQ-2-NFIRAOS-1160] NFIRAOS shall include six high-order LGS WFS for use with the laser guide stars.

[REQ-2-NFIRAOS-1870] Five of the laser guide stars shall be in a pentagon. The pentagonal array of laser beam images at the input focal plane of NFIRAOS shall have a horizontal plane of symmetry. The pentagon shall be oriented so that the single vertex (channel B) that lies in this plane of symmetry shall be at the 9 o'clock position when facing M3.

Discussion: Channel B lies on the +X axis of the FCRS (the Focal Surface Coordinate System), as defined in the OAD. The FCRS has the Z axis pointing towards the M3, the Y axis up, with X the right hand complement. See Figure 6 for the dimensions of the asterism. One of the LGS WFS will be on axis. Note that the asterism will rotate on the sky to keep aligned with the array of LGS WFSs in NFIRAOS as described in § 3.5.17.

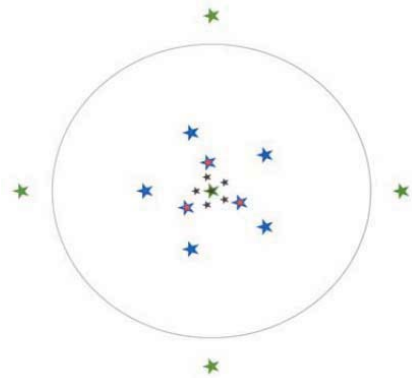

*Figure 6 LGSF asterisms supporting different AO modes: **NFIRAOS** (black) 1 on-axis, 5 on a 35 arcsec radius; MIRAO (red) 3 on a 70 arcsec radius; MOAO (blue) 3 on a 70 arcsec radius, 5 on a 150 arcsec radius; GLAO (green) 1 on-axis, 4 on a 510 arcsec radius*

[REQ-2-NFIRAOS-1880] Early light NFIRAOS shall be designed to operate with currently demonstrated guidestar laser pulse formats and conventional CCD clocking schemes. Therefore dynamic refocusing is not required at first light.

Discussion: This includes either CW or quasi-CW lasers as per [REQ-1-OAD-2925]

[REQ-2-NFIRAOS-1890] NFIRAOS shall be designed to use a Polar Coordinate CCD with radial pixel geometry.

Discussion: This CCD is under development in an AODP program.

[REQ-2-NFIRAOS-1900] The NFIRAOS LGS WFSs will be designed for a radially symmetric spot elongation pattern.

Discussion: This requirement results from [REQ-1-OAD-2935] specifying that the Laser Launch Telescope of the LGSF shall be mounted behind the secondary mirror of the telescope (M2). Note that the amount of elongation is determined geometrically by [REQ-2-NFIRAOS-1920] and [REQ-2-NFIRAOS-1930]

3.5.6.1 LGS Zoom Corrector

[REQ-2-NFIRAOS-1910] NFIRAOS shall implement a corrector for the LGS WFSs to continuously refocus on the sodium layer while correcting aberrations introduced by imaging sodium guide stars off axis and at close range through telescope and science optics designed for objects at infinity.

[REQ-2-NFIRAOS-1920] The LGS zoom optics shall be designed to operate with a mean guidestar range from 85 to 200 km, with a goal of 235 km.

Discussion: LGS Zoom image quality requirement is given in § 3.6.4

[REQ-2-NFIRAOS-1930] The LGS WFSs shall accept light from a 10 km thick sodium layer for all of the above ranges.

[REQ-2-NFIRAOS-1940] The LGS Zoom shall include an 8 arcsecond diameter field stop for each WFS.

[REQ-2-NFIRAOS-1950] The LGS Zoom shall operate at the science optics temperature.

3.5.7 Wavefront Correctors

[REQ-2-NFIRAOS-1970] NFIRAOS AO system shall have 2 deformable mirrors conjugate to 0 km and 11.2 km.

Discussion: The DM conjugate to 0 km is named DM0, and the DM conjugate to altitude is named DM11. This requirement is a direct flow down of requirement [REQ-1-OAD-2800]

[REQ-2-NFIRAOS-1980] The early light implementation of NFIRAOS shall utilize piezo-stack deformable mirrors.

Discussion: It is understood that either higher density piezo-stack mirrors or MEMS deformable mirrors may be utilized to improve image quality for the future upgrade of NFIRAOS.

Discussion: This is a direct flow down of requirement [REQ-1-OAD-2805]

[REQ-2-NFIRAOS-1990] The actuator grid on NFIRAOS DMs shall be rectangular, with a 5 mm pitch in the vertical direction, and magnified in the horizontal dimension by the secant of the angle of incidence.

[REQ-2-NFIRAOS-2000] DM0 actuator grid originates from an actuator at the centre of the beamprint.

[REQ-2-NFIRAOS-2010] DM11 actuator grid shall have the four central actuators horizontally and vertically symmetric about the centre of the beamprint.

Discussion: The deformable mirror conjugate to 11.2 km is therefore sheared half an actuator pitch with respect to the DM conjugate to the ground. Even though NFIRAOS has subapertures with d=0.5 m which are comparable to existing AO systems, shearing the second DM reduces the fitting error, since for a modest field of view, there is effectively a finer DM pitch.

[REQ-2-NFIRAOS-2020] Deformable mirrors in NFIRAOS shall have a guard ring of actuators located at a radius of one actuator pitch on all sides of the beamprint.

Discussion: This means that, including guard actuators, DM0 has a total of 63 actuators across the horizontal and vertical diameters, and DM11 has 76 actuators. The central actuator of DM0 lies at the intersection of the beamprint perimeter with the major and minor axes of the elliptical beamprint. In DM11, the intersection of the beamprint major and minor axes is surrounded by four actuators.

[REQ-2-NFIRAOS-2030] To correct higher-order wavefront errors induced by telescope aberrations, instrument aberrations, and dome/mirror seeing, wavefront corrector stroke of 2 microns peak-to-valley must be available beyond that needed to correct atmospheric turbulence.

Discussion: Derived from [REQ-1-OAD-0610]

[REQ-2-NFIRAOS-2040] Correcting the quasi-static aberrations of the NFIRAOS optics shall use ≤0.25 μm stroke on the DM.

Discussion: This requirement flows down from [REQ-1-OAD-0626]. The higher-order wavefront errors induced by NFIRAOS aberrations must be correctable to the error budget allocations listed in the NFIRAOS error budget.

[REQ-2-NFIRAOS-2050] DM stroke allocation to correct NFIRAOS quasi-static aberrations in the Common Path shall be <0.175 μm

Discussion: The common path is from the entrance window to DM0 inclusive. This requirement flows down [REQ-1-OAD-0628].

[REQ-2-NFIRAOS-2060] DM stroke allocation to correct NFIRAOS quasi-static aberrations in the Non-Common portion of the Science Path shall be <0.175 μm.

Discussion: The non-common science path is inclusively from the science beamsplitter in transmission to the instrument selection fold mirror. This requirement flows down [REQ-1-OAD-0630].

3.5.7.1 DM stray light baffle

[REQ-2-NFIRAOS-2070] There shall be a fixed, non-rotating baffle plate, parallel to, and as close as practical to, the surface of DM0, with an opening slightly oversized to clear the beam.

Discussion: This baffle does not imitate the serrated rotating illumination pattern of the telescope pupil. The NSCU does simulate the TMT pupil illumination.

3.5.7.2 Tip/Tilt Stage

[REQ-2-NFIRAOS-2080] There shall be a tip/tilt stage supporting DM0 with 20 Hz -3 db mechanical bandwidth, with a goal of 90 Hz.

Discussion: Carrying a DM on a tip/tilt stage reduces surfaces. The bandwidth requirement is intended to provide some margin to correct telescope windshake.

[REQ-2-NFIRAOS-2090] The tip/tilt stage shall have 500 μRad peak-valley range and 0.05 μRad resolution.

Discussion: This requirement is in terms of mechanical angle. For angle on the sky on the sky divide by 100, since the TMT pupil is demagnified 100x onto DM0.

3.5.8 High Resolution Wavefront Sensor

[REQ-2-NFIRAOS-2530] NFIRAOS shall have, as test equipment, a 120x120 high resolution wavefront sensor (HRWFS) mountable on the side port.

Discussion: Optionally the HRWFs may be relocatable to the top and bottom ports to satisfy [REQ-2-NFIRAOS-4082]

The HRWFS is intended as a diagnostic tool to align and (nearly) calibrate NFIRAOS. However, the measurement accuracy of the HRWFS will not become part of the NCPA error budget. The final stage of NCPA calibration will be with respect to the instrument focal plane.

[REQ-2-NFIRAOS-2540] The HRWFS shall patrol the 2 arcminute output field in XYZ.

Discussion: The Z range should be sufficient to cover the sag of the curved focal plane.

3.5.9 Acquisition Camera

[REQ-2-NFIRAOS-2100] NFIRAOS shall implement an acquisition camera to support guide star acquisition.

Discussion: [REQ-1-OAD-8710] requires an acquisition camera to locate a natural guide star for the OIWFS. This camera is sensitive to near-IR to reduce integration time from tens of minutes worst case, for a visible detector, to seconds. The chief purpose is to reduce the telescope blind pointing error so that the brightest natural guide star will land in the field of an OIWFS. The OCD says that the observations will be preplanned so that the guide star positions will be known in advance. Once the AO system is guiding on the first star, it is expected that the other two stars will automatically be within the capture range of their OIWFSs. Therefore the acquisition camera will not usually image all three guide stars.

Discussion: This requirement flows down from [REQ-1-ORD-2670], [REQ-1-OAD-2700], [REQ-1-ORD-2685] and [REQ-1-OAD-8710].

[REQ-2-NFIRAOS-2110] The NFIRAOS acquisition camera shall have a 20 arcsecond diameter instantaneous field of view.

[REQ-2-NFIRAOS-2120] The NFIRAOS acquisition camera shall patrol the 2 arcminute field of view.

[REQ-2-NFIRAOS-2122] The NFIRAOS acquisition camera shall be operate on the side port of NFIRAOS and share this port with the HRWFS.

Discussion: It is planned that one XY stage will carry both the HRWFS and the Acquisition Camera.The bottom port is earmarked for IRIS, and the top port for IRMS for early light operation. When a third instrument such as NIRES-b is commissioned, the IRMS or IRIS imager can serve as the acquisition camera.

[REQ-2-NFIRAOS-2130] The acquisition camera shall traverse the field of view in <30 seconds.

[REQ-2-NFIRAOS-2140] The NFIRAOS acquisition camera shall be sensitive to light from 1 – 1.8 μm.

[REQ-2-NFIRAOS-2142] A blocking filter between J & H bands is TBD.

Discussion: Whether blocking the OH lines between J & H is necessary to meet the sensitivity requirement is TBD.

[REQ-2-NFIRAOS-2145] The acquisition camera should be able to detect a 22nd (TBD) magnitude seeing-limited point source in 10 s integration, with 5 sigma confidence.

Discussion: This sensitivity is a relationship among sky background, read noise and dark current. Integration of 10 s is traceable to Acquisition Scenario, [REQ-2-NFIRAOS-3490].

[REQ-2-NFIRAOS-2150] The NFIRAOS acquisition camera shall have a pixel scale of ≤0.08 arcsec per pixel.

Discussion: This scale permits using a small 256x320 pixel camera, while providing some sampling margin to reject galaxies. Processing of the pixels is covered in § 3.5.15

[REQ-2-NFIRAOS-2152] The Acquisition camera should have a diffraction limited mode to examine a single object with well sampled pixels, ≥4 pixels across the FWHM in J band. This mode may be manually changeable from acquisition mode, with a goal for remotely changeable operation.

Discussion: For assessing delivered Strehl ratio accurately, much better than Nyquist sampling is needed.

[REQ-2-NFIRAOS-2153] The diffraction limited mode should have a field of view of at least the diameter of 5 Airy rings at H band and sufficient optical quality to distinguish them given a perfect image from NFIRAOS.

[REQ-2-NFIRAOS-2155] In the diffraction limited mode, the camera should patrol the NFIRAOS field of view in XYZ. It is permitted to exclude a zone beyond a single chord 0.5 arcminutes from the centre, with a goal of no exclusion zone.

Discussion: This allows designs where the detector is moved behind a separate lens barrel, without driving additional travel on the stage.

[REQ-2-NFIRAOS-2157] The diffraction limited mode should have individual filters for J & H bands. The requirement is for manual interchange, but the goal is remote operation.

Discussion: Higher Strehl ratios are achievable in H band and therefore this band is more sensitive to diagnosing high order degradations. However for assessment of the lowest *modes, a narrower FWHM in J band is more useful. The highest priority is H band. Narrow-ish filters are preferable rather than broad astronomical filters designed to maximize flux.*

3.5.10 Source Simulators

3.5.10.1 Flat Field and wavelength calibration

[REQ-2-NFIRAOS-2180] NFIRAOS shall pass light from the NSCU to client instruments.

Discussion: This is derived from requirement [REQ-1-OAD-2705] that TMT Instrumentation shall incorporate all hardware necessary for calibration. The TMT observatory will not provide a general calibration facility. Flat field and wavelength calibration sources for NFIRAOS' client instruments are the responsibility of the NSCU.

3.5.10.2 Deployable Focal Plane Mask

[REQ-2-NFIRAOS-2190] NFIRAOS shall have a deployable pinhole mask at its focal plane.

Discussion: This mask will be back-illuminated by the NSCU with both arc lamps and broadband light. Its purpose is to create reference asterisms for calibrating pointing models for the natural visible WFS gimbals, the instrument selection fold mirror, and for the client instrument OIWFSs and rotators. It also provides a reference for calibrating image distortion. Also, in conjunction with the pupil mask in the NSCU, the focal plane mask simulates pupil illumination onto the DMs, the WFSs and the instrument cold stops. This is derived from requirement [REQ-1-OAD-2705]

[REQ-2-NFIRAOS-2200] The focal plane mask shall be fixed in one location when deployed.

Discussion: Short range patrolling of the pinhole images, e.g. to calibrate distortion on OIWFS detectors or IFUs, will be done with the tip tilt stage. Focus scanning will be done with the DM.

[REQ-2-NFIRAOS-2210] When retracted, the focal plane mask shall not vignette a 2.6-arcminute diameter beam.

[REQ-2-NFIRAOS-2220] The focal plane mask shall be athermal as a goal.

Discussion: The intent is that it should not move when NFIRAOS is cooled.

[REQ-2-NFIRAOS-2230] The pinhole mask shall be curved to represent the telescope focal plane.

[REQ-2-NFIRAOS-2240] The focal plane mask shall have at least one hole of median seeing image diameter.

Discussion: The purpose of this hole is to illuminate the TWFSs as if on sky. It will be located just outside the centre of the field of view.

[REQ-2-NFIRAOS-2250] A diffraction limited central hole in the focal plane mask shall be the reference for alignment of NFIRAOS.

Discussion: All other features of NIRAOS will be surveyed into position relative to this mask. The optical axis, the interfaces to instruments, the mounting feet under the Instrument support structure, and the external survey targets will all be surveyed with respect to this mask hole.

[REQ-2-NFIRAOS-2260] The focal plane mask shall have local dense grids of diffraction limited holes covering IFU fields of view and imager fields.

Discussion: Field sizes are traceable to [REQ-ORD-3750] and [REQ-ORD-3755].

[REQ-2-NFIRAOS-2262] The dense grid of diffraction limited holes shall be accurate to 10 μas on the sky.

Discussion: This requirement is traceable to [REQ-1-ORD-3652]: NFIRAOS should provide sufficient calibration information to not degrade the astrometric capabilities beyond the limits set by the atmosphere.

[REQ-2-NFIRAOS-2270] The focal plane mask shall have an array of diffraction limited holes throughout a 2.6 arcminute field of view.

[REQ-2-NFIRAOS-2280] As a goal, the wide field grid should be at non-redundant radii.

Discussion: "This may be desirable to achieve fine pointing model via the instrument rotator". -- James Larkin.

3.5.10.3 Survey Targets

[REQ-2-NFIRAOS-2290] The exterior of NFIRAOS shall have survey targets, whose position is accurately known with respect to the input focal plane location and orientation, and which are visible from the telescope GMS (global metrology system).

Discussion: The purpose of these targets is to establish the location of NFIRAOS with respect to the telescope. The position will eventually be included in the TINS-NFIRAOS ICD

3.5.10.4 Pupil pointing calibration

[REQ-2-NFIRAOS-2300] NFIRAOS shall have a means for off-line calibration of the telescope pupil pointing.

Discussion: The location and tilt of the pupil delivered by the telescope will affect the illumination on DM0 and DM11. Pointing models for the telescope, M2 and M3 need to be calibrated. Simply observing the illumination pattern on the WFSs cannot determine the pupil position accurately on long time scales.

[REQ-2-NFIRAOS-2310] NFIRAOS shall employ the following procedure to take a reference TWFS image to establish the pupil pointing zero point:

- Deploy the pinhole mask (The NSCU will illuminate the DMs through the central hole in the deployable focal plane mask. The NSCU has a rotating pupil mask and optics to simulate the telescope illumination of DM0).
- Adjust the NGS gimbals so that the TWFS spots are centred on the CCD, and so that DM/WFS registration is verified by applying waffle to DM0.
- Then with the DM flat, take a reference image on the TWFS.

Discussion: The outer perimeter of the DM illumination will mimic the rotating, serrated telescope pupil seen from NFIRAOS at a variety of zenith distances.

[REQ-2-NFIRAOS-2320] The NFIRAOS TWFS processing computer shall measure pupil pointing with respect to the reference image.

Discussion: Pupil position is estimated on-sky based upon the difference in illumination in the left versus right edges, and top versus bottom edges on the CCD

[REQ-2-NFIRAOS-2330] The NFIRAOS TWFS processing computer shall measure pupil magnification and differential magnification at 0 and 45 degrees, with respect to the reference image.

Discussion: Pupil magnification is estimated on-sky based upon the change in illumination in three sets of opposing edges oriented at 0, 45 and 90 degrees on the TWFS CCD. It is related to plate scale and will be a useful diagnostic. Note however, that offloading of tele-

scope plate scale modes will be accomplished by projecting the DM figure onto these modes, for the purpose of maximizing DM stroke available for atmospheric correction.

3.5.10.5 Source Simulators

[REQ-2-NFIRAOS-2340] NFIRAOS shall include simulated NGS sources, and simulated LGS sources, deployable at its input focal plane.

Discussion: These devices shall be used to characterize and calibrate system performance, system alignment, deformable mirror (DM) to wavefront sensor (WFS) influence functions, WFS detectors, and non-common path aberrations between the wavefront sensing and science optical paths.

[REQ-3-NFIRAOS-2355] As a goal, the position of the central NGS pinhole(s) shall provide fine position sampling within a field of ∅25", centred on the optical axis. This may be accomplished with a fine grid, or a patrolling source. In this latter case, the location of the central pinhole shall have the following linear position specifications:

- Accuracy: ± 10 mas on the sky (±22 μm in the focal plane)
- Repeatability: ± 5 mas on the sky (±11 μm in the focal plane)

Discussion: All NGS sources, except the central NGS source, are not required to patrol within the field of the telescope focal plane. Two concepts for a patrolling source are suggested. 1. The on-axis source of may be remotely adjustable in position with a patrol field 25 asec (55.25 mm) in diameter, centered on the optical axis. 2. The central 25 arcsecond diameter contains a pinhole mask that includes the on-axis hole. The mask may be illuminated by a single common light source.

[REQ-2-NFIRAOS-2360] The LGS source simulator shall reproduce the LGS asterism of 6 guide stars at range distances from 85 to 235 km.

[REQ-2-NFIRAOS-2370] The LGS source simulator, as a goal, shall simulate the thickness of the sodium layer.

Discussion: Simulating elongated WFS spots is desirable, but shall not be a cost driver.

[REQ-2-NFIRAOS-2380] The wavelength of the LGS simulator shall be 589 ±10 nm

Discussion: The LGS zoom optics NCPA errors are optimized for a narrow bandpass, and narrowband coatings/detectors might be used in the LGS WFS. InGaAlP LEDS at 592 nm are available from several suppliers. Bandwidths typical of LEDs are acceptable.

[REQ-2-NFIRAOS-2390] The intensity of the LGS simulator shall be adjustable to cause 250 to 2000 photo-detection events per subaperture per frame on the LGS WFSs.

[REQ-2-NFIRAOS-2400] The LGS source simulator shall have wavefront errors <200 nm RMS.

[REQ-2-NFIRAOS-2410] The NGS source simulator shall have a modest number of sources, one on axis and two surrounding rings of sources.

[REQ-2-NFIRAOS-2420] The NGS source simulator shall have wavefront errors <20 nm RMS.

[REQ-2-NFIRAOS-2430] The NGS source simulator shall have broadband (0.6 – 1.6 μm) adjustable brightness sources, from the faintest mJ = 22 and increasing in brightness by at least 6 magnitudes (250x).

[REQ-2-NFIRAOS-2440] It is a requirement to use both laser and NGS sources simultaneously.

Discussion: Traceable to [REQ-1-OAD-2705]. We wish to close all loops simultaneously during test and calibration.

3.5.11 Turbulence Simulator

[REQ-2-NFIRAOS-2450] NFIRAOS shall include an atmospheric turbulence simulator (turbulator), using a phase screen.

Discussion: Phase screens are required, precluding a hot air turbulence generator. The intent is to simulate generalized isoplanatism repeatably. The plan is to simultaneously apply additional phase screens as disturbances to the DM commands.

[REQ-2-NFIRAOS-2470] The turbulator shall be employed for factory acceptance testing. As a goal, it shall be available on-line on the Nasmyth platform at the telescope.

[REQ-2-NFIRAOS-2490] The Turbulator's physical phase screen shall simulate atmospheric wavefront errors of 2.5 micrometer peak-valley.

Discussion: This includes tip-tilt and high order errors. The spec is chosen to allow using commercial phase screens.

[REQ-2-NFIRAOS-2500] The turbulator shall have a phase screen at conjugate altitudes and strengths to mimic NFIRAOS' expected θ_2 = 20 arcsec.

Discussion: θ_2 is expected to be FWHM = 20 arcseconds. I.e. the image quality at the edge of a 20 arcsecond diameter field of view is half that at the centre

[REQ-2-NFIRAOS-2510] The turbulator shall simulate a Greenwood frequency of 30 Hz, with a goal to allow adjustment from 15 to 60 Hz.

Discussion: This flows down from [REQ-1-ORD-3530], and ORD appendix §4.1. and sets the velocity required on the phase screen.

[REQ-2-NFIRAOS-2520] The turbulator shall have differential chromaticity between aberrations at 589 nm and at 1.1 μm, of < 2% of the rms wavefront.

3.5.12 Enclosures - electronics

[REQ-2-NFIRAOS-2550] The majority of the NFIRAOS electronics, to the greatest extent practical, shall be located in a cooled and insulated cabinet located on the Nasmyth platform at -7 m below the optical axis.

Discussion: The intent is to reduce vibration from fans and heat exchangers, and to reduce wind blockage of the telescope primary mirror. Some electronics, e.g. sensor preamps for Tip/tilt stage, must operate > 0 C, but must be near to the NFIRAOS opto-mechanics.

[REQ-2-NFIRAOS-2560] No equipment whose weight is supported by the NFIRAOS instrument support tower may use fans or other vibrating machinery, including closed cycle cryo-pumps.

Discussion: Electronics on the instruments support tower (e.g. TTS sensor preamps and CCD digitizers) should be passively cooled with e.g. cold plates in private enclosures.

[REQ-2-NFIRAOS-2570] The absolute value of heat transfer from the NFIRAOS electronics directly to the telescope dome air shall be < 100 W.

[REQ-2-NFIRAOS-2580] The absolute value of heat transfer from the NFIRAOS electronics, conducted into the Nasmyth platform shall be < 100 W.

[REQ-2-NFIRAOS-2590] Power Consumption of the NFIRAOS electronics shall be no more than 15 kW, with a goal of 10 kW.

Discusssion: Flows down from [REQ-1-ORD-6400], energy efficiency.

[REQ-2-NFIRAOS-2600] The electronics shall be cooled using glycol at flow rate, temperature and pressure TBD.

Discussion: This requirement flows down from requirements [REQ-1-OAD-4700].

[REQ-2-NFIRAOS-2610] The NFIRAOS electronics enclosures shall furnish space for the Component Controller, the TWFS/ACQ Detector Controller, the motion and monitoring electronics, the Real Time Controller, the DM electronics, power supplies, network equipment, and a node of the LGSF safety system.

3.5.13 NFIRAOS Control System

[REQ-2-NFIRAOS-2620] NFIRAOS shall implement three principal control sub-systems: (i) the Component Controller (CC), (ii) the Real Time Controller (RTC), and (iii) the Truth WFS and acquisition camera Detector Controller (NTWAQ).

Discussion: The NFIRAOS control hierarchy and the NFIRAOS context diagram are shown in Figure 3 and Figure 4.

[REQ-2-NFIRAOS-2625] The NFIRAOS control sub-systems shall meet the following top-level software/control requirements:

[REQ-2-NFIRAOS-2630] The NFIRAOS control sub-systems shall be compliant with the TMT Observatory software standards.

Discussion: The overall software requirements are defined in OAD requirements [REQ-1-OAD-9000] to [REQ-1-OAD-09740]. The TMT Observatory standards are defined in the Software Management Plan [RD21].

[REQ-2-NFIRAOS-2640] The NFIRAOS control sub-systems shall be under the direct control of the AO Sequencer.

Discussion: This includes, but is not limited to, configuring the AO systems at the beginning of an observation, acquiring the guide stars, performing necessary calibrations, and managing the AO loops.

[REQ-2-NFIRAOS-2650] Each NFIRAOS control sub-system shall implement an engineering user interface.

[REQ-2-NFIRAOS-2660] Each NFIRAOS control sub-system shall support remote control via the engineering user interface.

[REQ-2-NFIRAOS-2665] The engineering user interface shall support remote control by scripts.

Discussion: During development and testing, ad hoc scripts in e.g. IDL or Matlab may be used to control NFIRAOS. The intention is that eventually coordinating all test and calibration functionality will be done by the AOESW. However, this requirement permits rapid prototyping and fast response to diagnose unforeseen problems. The plan is to migrate such temporary functionality to the AOESW, if useful.

[REQ-2-NFIRAOS-2665] All sequences of operations for NFIRAOS routine daytime calibration shall be executable though engineering operator screens, the AOESW, and also temporary control scripts.

Discussion: All NFIRAOS functions will be executable through both the NFIRAOS engineering user interfaces of the different sub-systems and the AO Executive Software.

[REQ-2-NFIRAOS-2670] The NFIRAOS control sub-systems shall be able to operate as standalone systems without the need to interface to other TMT software systems.

Discussion: Traceable to [REQ-OAD-1-9303]. Booting from remote network disc storage systems is acceptable.

[REQ-2-NFIRAOS-2675] The NFIRAOS Control System shall be operable in simulation mode.

Discussion: Traceable to [REQ-OAD-1-9303]. In simulation mode, the NFIRAOS Control System responds to the AOESW as if individual mechanisms were present and functioning. This mode assists debugging and also enables selectively taking some subsystems off-line.

[REQ-2-NFIRAOS-2680] The NFIRAOS Control System shall be able to boot and be ready in 30 seconds.

[REQ-2-NFIRAOS-2685] The NFIRAOS Control System shall be able to buffer short (TBD) duration bursts of high-speed (up to 200 Hz, TBC) of engineering data and then store them in the local observatory database.

Discussion: Traceable to [REQ-1-ORD-9100]

3.5.14 Conventional Electronics

3.5.14.1 Component Controller

[REQ-2-NFIRAOS-2690] The NFIRAOS Component Controller (CC) shall consist of computer hardware and software responsible for the control and monitoring of all the slow sensors (temperature and humidity, door status, oxygen) and mechanisms of the NFIRAOS sub-systems (shutter, WFS acquisition mechanisms, LGS zoom corrector mechanisms, instrument selection fold mirror, source simulators, pinhole mask, gate valves, beamsplitter changer, cooling system.)

Discussion: The CC does not include signal conditioning, sensors, motor controllers, power supplies. These are in the motion and monitoring electronics.

[REQ-2-NFIRAOS-2700] The NFIRAOS Component Controller shall provide a technical data stream of parameters such as temperature, humidity, mechanism status and position, DM supply voltage.

Discussion: This flows down from [REQ-1-ORD-9070] and [REQ-1-ORD-9100].

[REQ-2-NFIRAOS-2710] The positions of the NGS and Truth WFSs shall be commanded by the pointing model in the Telescope Control system.

Discussion: This requirement flows down directly from [REQ-1-OAD-8725]. The purpose is to have one central model for atmospheric refraction, field rotation, dithering, nodding, acquisition. The intent is that the gimbals will track a stream of TCS follow commands.

[REQ-2-NFIRAOS-2720] The position of the LGS zoom optics shall be driven as a function of Zenith angle, and the expected or recently-measured sodium altitude, with the addition of a correction signal produced by integrating a focus error signal from the RTC.

3.5.14.2 Motion and Monitoring Electronics

[REQ-2-NFIRAOS-2730] NFIRAOS shall incorporate signal conditioning, sensors, motor controllers, power supplies for the low speed mechanisms and environmental systems.

[REQ-2-NFIRAOS-2740] Separate grounds shall be provided for electrically sensitive (e.g. detector controllers) or noisy (e.g. motors/solenoids) components.

3.5.15 Truth Wavefront Sensor and Acquisition Camera Detector Controller

[REQ-2-NFIRAOS-2750] NFIRAOS shall have a TWFS and acquisition camera Detector Controller (NTWAQC) to acquire and process acquisition camera images, and Shack-Hartmann images from the MOR and HOL TWFSs.

Discussion: This is a separate system from the component controller system.

3.5.15.1 TWFS Processing

[REQ-2-NFIRAOS-2760] The NFIRAOS NTWAQ shall acquire Shack-Hartmann images from the MOR and HOL TWFSs, and process them to supply to the RTC, reference vectors for the LGS WFSs.

[REQ-2-NFIRAOS-2780] The absolute wavefront reference on long timescales shall be the pre-calibrated null-point of the MOR TWFS.

[REQ-2-NFIRAOS-2790] The reference vectors shall incorporate Non-common-path offsets, determined by calibration procedures in advance.

[REQ-2-NFIRAOS-2800] The Non-common-path calibration offsets shall be customized for each instrument, and observing mode (IFU, imager, band filter) and each LGS WFS versus range distance of the zoom optics.

[REQ-2-NFIRAOS-2810] The reference vectors shall be customized for each observation to minimize field-dependent aberrations over the science field of view.

Discussion: This implies that there are a different set of reference vectors for each LGS WFS.

[REQ-2-NFIRAOS-2812] In Natural Seeing Mode, the controller for the TWFS shall send pixels to the RTC.

Discussion: In Natural Seeing mode, the NTWAQ does not centroid TWFS SH spots and reconstruct wavefront to create reference vector(s) as it does for NGS and LGS mode. Instead it sends pixels to the RTC.

3.5.15.2 Acquisition Camera Processing

[REQ-2-NFIRAOS-2820] The NFIRAOS NTWAQ shall acquire images from the acquisition camera and perform basic processing on them.

[REQ-2-NFIRAOS-2830] The NFIRAOS NTWAQ shall remove bias and flat-field artifacts from the acquisition camera images.

[REQ-2-NFIRAOS-2840] The NFIRAOS NTWAQ shall pass the acquisition camera images to the Data Management System (DMS) for visualization and/or analysis during acquisition.

Discussion: Other Observatory software subsystems will be responsible for retrieving acquisition camera images from the DMS and identifying guide stars in these images.

3.5.16 DM Electronics

[REQ-2-NFIRAOS-2850] NFIRAOS shall provide high voltage electronics to accept actuator commands from the Real Time Computer and drive the DMs.

[REQ-2-NFIRAOS-2860] The electronics for the two DMs shall be separable.

Discussion: For an interval during integration it is expected that while DM0 is used in the NFIRAOS optics, DM11 will be cold tested in another building.

[REQ-2-NFIRAOS-2870] The DM electronics shall use <8 kW electrical power.

[REQ-2-NFIRAOS-2880] The DM electronics shall be remotely commanded to enter standby mode, consuming <300 W.

[REQ-2-NFIRAOS-2890] The DM electronics shall limit output voltage slew rate to a maximum of 100 kV/s, and shall also provide a minimum slew rate of > 25 kV/s.

Discussion: This voltage slew rate limit may be implemented either directly, or by means of current limit acting with the actuator capacitance. The maximum requirement comes from the DM manufacturer who specifies that the DM must not experience any higher slew rate during its operation. The minimum comes from AO performance modeling and flows from the servo lag portion of the error budget.

[REQ-2-NFIRAOS-2900] The DM electronics shall limit conducted and radiated radio-frequency interference into the NFIRAOS WFS controllers and acquisition camera to <TBD over the frequency range < TBD Hz.

3.5.17 Real Time Computer

[REQ-2-NFIRAOS-2910] NFIRAOS shall implement a Real Time Controller (RTC) to perform the real-time atmospheric turbulence compensation.

Discussion: In particular, the RTC processes signals originating in various wavefront sensors in order to compute the commands of the wavefront correctors (DMs and TTS).

[REQ-2-NFIRAOS-2920] The RTC shall implement three modes of observations (LGS, NGS and seeing limited) and calibration/engineering mode.

[REQ-2-NFIRAOS-2930] The RTC shall process: the outputs of six LGS WFSs, or at the observer's discretion, one high order NGS WFS; and up to 3 low order TT(F) WFSs, (also known as OIWFSs); together with reference vectors originating from processed Truth WFS data.

Discussion: This requirement is traceable to [REQ-1-OAD-2730], [REQ-1-OAD-2735], [REQ-1-OAD-2815], AND [REQ-1-OAD-2830].

[REQ-2-NFIRAOS-2940] From the OIWFS pixel intensities, the NFIRAOS RTC will compute: the tip-tilt modes, focus mode, and the DM Tilt anisoplanatism modes.

Discussion: This requirement flows down from [REQ-1-ORD-4820] and [REQ-1-ORD-3725] Tip/tilt is necessary to perform fast guiding. Focus mode calibrates the focus biases in the LGS WFSs induced by variations in the range to the sodium layer. DM tilt anisoplanatism modes compensate tilt anisoplanatism (plate scale distortions) over the extended FOW without introducing higher order wavefront errors.

[REQ-2-NFIRAOS-2950] The RTC shall have at first light, inputs for nine OIWFSs and select and processes up to three simultaneously.

Discussion: This requirement is traceable to [REQ-1-ORD-3720] and [REQ-1-ORD-3710] (revised to only 1 OIWFS)

[REQ-2-NFIRAOS-2970] The RTC shall compute and apply the commands to two high order DMs and one TTS using a computationally efficient implementation of minimum variance wavefront reconstructors.

[REQ-2-NFIRAOS-2980] The RTC shall operate at 800 Hz sampling rate with a 1000 μs (goal of 400 μs) end-to-end latency from end of LGS readout to end of DM commands output.

[REQ-2-NFIRAOS-2990] The RTC shall update and optimize the control algorithms in real time as observing parameters and atmospheric conditions change.

[REQ-2-NFIRAOS-3000] The RTC shall update and optimize the control algorithms to meet the delivered wavefront to specification, within 20 seconds after closing all control loops.

Discussion: This requirement is traceable to [REQ-2-NFIRAOS-3480].

[REQ-2-NFIRAOS-3010] The NFIRAOS RTC shall estimate supplementary information about atmospheric conditions included but not limited to r_0, layer strengths and sodium altitude.

Discussion: This flows down from [REQ-1-OCD-3255].

[REQ-2-NFIRAOS-3020] The RTC shall offload persistent, low spatial frequency components of the wavefront corrector commands to the telescope via the AO Executive Software.

[REQ-2-NFIRAOS-3030] The RTC shall compute the commands for the LGSF fast steering mirrors to stabilize the pointing of the LGS on the sky

Discussion: Derived from [REQ-1-OAD-2770].

[REQ-2-NFIRAOS-3040] The RTC shall store up to one night of circular buffer data for diagnostic purposes or PSF post-processing reconstruction in a dedicated storage system.

Discussion: The RTC storage system is separate from the Data Management System.

[REQ-2-NFIRAOS-3050] The RTC shall offload persistent defocus errors to the NFIRAOS components controller (CC) to adjust the LGS Zoom optics.

[REQ-2-NFIRAOS-3060] The RTC shall accept the AO reconstructor parameters generated by the AOESW Reconstructor Parameter Generator (RPG) necessary to perform the AO real time reconstruction.

Discussion: This requirement flows down from [REQ-1-OAD-3015]

[REQ-2-NFIRAOS-3070] The RTC shall acquire and store all the real time data needed to post-process the AO PSF.

[REQ-2-NFIRAOS-3080] As goal the RTC shall compute the LGS structure functions and the gradient covariance matrix from the OIWFS measurements and store them into the Data Management System for post-processing of the AO PSF.

Discussion: This requirement flows down from [REQ-1-OAD-3020]

3.5.18 Miscellaneous Jigs and fixtures

[REQ-2-NFIRAOS-4040] NFIRAOS shall include specialized handling fixtures for integration, testing, mounting and servicing, in the factory, in the Assembly Integration Facility, and at the telescope.

[REQ-2-NFIRAOS-4050] The NFIRAOS Jigs and Fixtures shall be compatible with, and make best use of Observatory cranes, lifts, scaffolding and cherry pickers etc.

[REQ-2-NFIRAOS-4060] NFIRAOS shall include necessary additional specialized temporary personnel platforms, vestibules, pulpits and kneeling boards for integration and servicing.

Discussion: The intent is that facility equipment and platforms will be used for servicing, where possible, but that in some cases NFIRAOS will supply remaining customized access equipment.

[REQ-2-NFIRAOS-4070] The NFIRAOS-supplied servicing platforms and vestibules shall

REQ-2-NFIRAOS-3100	Delivered Wavefront	187			

be removable to reduce wind blockage of the telescope.

Discussion: It may be desirable to retain a small frequently-used platform for cleaning the entrance window.

[REQ-2-NFIRAOS-4080] NFIRAOS handling and servicing fixtures and procedures shall prevent damage and injury during earthquakes up to the levels of the 200-year return period earthquake.

3.5.18.1 Optical Alignment Fixtures

[REQ-2-NFIRAOS-4082] NFIRAOS shall include a fixture to assess the output focal plane XYZ location, as well as focal plane tilt of all three exit ports.

Discussion: This requirement could be met by moving the HRWFS/Acquisition camera among all three ports, or else a separate jig could be provided for a simpler instrument.

[REQ-2-NFIRAOS-4084] NFIRAOS shall include a fixture to assess the boresighting of NFIRAOS towards the centre of the telescope M3.

Discussion: For example, an alignment telescope, with precise 180 degree reversibility, manually deployable between the entrance window and the NSCU, could sight a fiducial at the centre of M3 and then reverse and sight through the central pinhole mask to a fiducial at the centre of OAP1. It is expected that if NFIRAOS is aligned like this, that the telescope can accurately deliver a pupil onto DM0.

3.6 PERFORMANCE REQUIREMENTS

3.6.1 Error Budget

[REQ-2-NFIRAOS-3090] NFIRAOS shall compensate for wavefront distortions introduced by dome/mirror seeing, telescope optics, and instrument optics, with the residual errors included as part of the NFIRAOS error budget.

Discussion: This requirement flows down from [REQ-1-OAD-2760] (See the discussion in this OAD requirement and also refer to OAD sections 3.4.1 and 3.4.4). The budget is elaborated in Table 7.

REQ-2-NFIRAOS-3103	First-order turbulence compensation		124		
REQ-2-NFIRAOS-3106	LGS control loop			124	
REQ-2-NFIRAOS-3109	DM fitting error				72
REQ-2-NFIRAOS-3112	DM projection error				50
REQ-2-NFIRAOS-3115	LGS WFS aliasing				34
REQ-2-NFIRAOS-3118	Tomography error				65
REQ-2-NFIRAOS-3121	Servo lag				21
REQ-2-NFIRAOS-3124	LGS WFS noise				43
REQ-2-NFIRAOS-3126	Opto-mechanical implementation		79		
REQ-2-NFIRAOS-3130	* Telescope pupil misregistration			12	
REQ-2-NFIRAOS-3140	* Telescope and observatory OPD			49	
REQ-2-NFIRAOS-3150	* M1 static shape				30
REQ-2-NFIRAOS-3152	* M2 & M3 static shape				11
REQ-2-NFIRAOS-3160	* TMT pupil function				28
REQ-2-NFIRAOS-3170	* Segment dynamic misalignment				14
REQ-2-NFIRAOS-3180	* Dome seeing				16
REQ-2-NFIRAOS-3190	* Mirror seeing				14
REQ-2-NFIRAOS-3195	* Field Dependent Astigmatism				0
REQ-2-NFIRAOS-3200	NFIRAOS			53	
REQ-2-NFIRAOS-3210	* Residual Instrument			30	
REQ-2-NFIRAOS-3220	AO component errors & higher order effects		97		
REQ-2-NFIRAOS-3230	DM effects			51	
REQ-2-NFIRAOS-3240	LGS WFS & Na layer			48	
REQ-2-NFIRAOS-3245	LGS WFS non-linearity			25	
REQ-2-NFIRAOS-3250	Control algorithm			62	
REQ-2-NFIRAOS-3255	Simulation under-sampling		26		
REQ-2-NFIRAOS-3260	Tip / Tilt WFE at 50% sky coverage		48		
REQ-2-NFIRAOS-3270	* Residual telescope windshake			17	
REQ-2-NFIRAOS-3280	* Residual telescope vibration			10	
REQ-2-NFIRAOS-3285	* Residual telescope tracking jitter			17	
REQ-2-NFIRAOS-3290	Atmospheric servo lag			14	
REQ-2-NFIRAOS-3300	Atmospheric tilt anisoplanatism			8	
REQ-2-NFIRAOS-3310	NGS WFS noise			13	
REQ-2-NFIRAOS-3315	Physical Optics			35	
REQ-2-NFIRAOS-3320	NGS controlled Plate Scale Modes- 50% sky coverage		16		
REQ-2-NFIRAOS-3330	Contingency		26		

Table 7 NFIRAOS RMS wavefront error budget (60 x 60 actuators, on axis) in nm

*Discussion: Items marked * for the telescope, instrument, dome, and mirror seeing are residuals after correction by a 60x60 AO system, computed as the fitting and servo lag errors for an idealized (linear, noise free, well calibrated) AO system with a -3 dB error rejection bandwidth of 30 Hz. Thus compliance depends both on the performance of NFIRAOS and these external subsystems. Table 7 is a direct quotation of requirements from [REQ-1-OAD-0550] to [REQ-1-OAD-0548].*

Note that compliance with [REQ-1-NFIRAOS-3240] and [REQ-1-NFIRAOS-3310] depends on the LGSF and the OIWFS performance respectively.

Note that [REQ-1-OAD-0585] is in error. In Table 7, which is an on-axis budget, field dependent astigmatism has zero effect on image quality.

[REQ-2-NFIRAOS-3350] NFIRAOS shall comply with the detailed NFIRAOS Error Budget given in [RD1].

Discussion: [RD1] elaborates on the governing budget found in Table 7.

[REQ-2-NFIRAOS-3360] The on-axis performance of the upgraded NFIRAOS system shall be equal or better than 133 nm RMS on-axis.

Discussion: This requirement flows down from [REQ-1-ORD-4225]. The on-axis performance of a future NFIRAOS upgrade is estimated to be about 130 to 135 nm RMS, assuming that (i) the ground-layer order 61 by 61 DM is replaced by a 121 by 121 mirror with 2.5 mm inter-actuator pitch, (ii) an adaptive secondary mirror (AM2) is available to provide low-order, large, amplitude corrections, if 10 μm of stroke with the new DM is not feasible due to the smaller inter-actuator pitch and (iii) advanced, higher power pulsed laser systems are available to eliminate wavefront sensing errors associated with the non-zero thickness of the sodium layer.

[REQ-2-NFIRAOS-3362] Under median conditions, the goal for J band energy in a 160 mas slit is at least 30% (TBC) averaged over a 2.3 arcminute field of view.

Discussion: Flows down from [REQ-0-SRD-0835] and [REQ-0-SRD-0840]. Seeing-limited value is 6% on Mauna Kea.

[REQ-2-NFIRAOS-3364] Under median conditions, the goal for K band energy in a 160 mas slit is at least 50% (TBC) averaged over a 2.3 arcminute field of view.

Discussion: Flows down from [REQ-0-SRD-0835] and [REQ-0-SRD-0845]. Seeing-limited value is 9% on Mauna Kea.

3.6.2 Throughput Budget

[REQ-2-NFIRAOS-3380] NFIRAOS Science Light Throughput shall be apportioned as in Table 8.

		Loss per element	
Optical Element	Quantity	0.8 – 1 μm	1 – 2.5 μm
Entrance Windows	2	3%	3%
OAPs	4	1.5%	1.5%
Beamsplitter	1	5%	5%
DM	2	3%	2%
Selection Fold	1	1.5%	1.5%

Table 8 Throughput Budget

Discussion: These losses combine multiplicatively =1-product(1 - $Loss_i$) to give a total of 22% (0.8-1 μm) and 20% (1 – 2.5 μm). This requirement is apportioned from [REQ-1-ORD-3655], which also includes a throughput goal of 90% from 0.6 to 2.5 microns.

3.6.3 Integration Sensitivity Budget

[REQ-2-NFIRAOS-3390] The integration time sensitivity degradation of NFIRAOS, normalized with respect to a 30 m telescope without an atmosphere, of xxx% TBD shall be apportioned as in Table 9.

Item	PSS	Sub-section PSS
Wavefront error		
Thermal Background		
Throughput		
Stray Light #		
Ghost Images !		
Second surface reflections		
4th port of beamsplitter		
Waffle and periodicity in DM actuator print through		
Non-NFIRAOS Contributors		
Image Smearing	0.5 mas	ORD-2732
Image rotator – tracking and guiding		
Flexure of OIWFS w.r.t. science detector		
Science and OIWFS ADCs moving images w.r.t. each other		
NSCU stray light		
Telescope optics & structure scattered light		
Dome scattered light		

Table 9 Point Source Sensitivity Budget

Discussion: NFIRAOS shall provide sufficient baffling to reduce stray light to levels such that any image degradation resulting from light originating outside the technical field is an acceptable contribution to the sensitivity budget. This requirement flows down from [REQ-

1-OAD-1025] in addition to the baffle on the deformable mirror, [REQ-2-NFIRAOS-2070] other baffles may be needed TBD, in order to keep stray light out of OIWFS and TWFSs. Narrow band filters may be used in the LGS WFSs, which need not rely on baffles. A narcissus mirror may also help reduce background and increase sensitivity.

3.6.4 Non-common path slope budgets

[REQ-2-NFIRAOS-3400] NFIRAOS system shall operate off-null in order to compensate non-common path aberrations in science instruments, with a maximum offset of 0.35" slope on each wavefront sensing subaperture.

Discussion: This is a direct flow down of, requirement [REQ-1-OAD-2765]. This allocation is 70% of a pixel, and is partitioned in Table 10.

[REQ-2-NFIRAOS-3410] The worst case given in [REQ-2-NFIRAOS-3400] for slope errors in the non-common path wavefront between the LGS WFS and the Science instrument shall be apportioned as in Table 10, whose terms sum linearly.

Discussion: Individual Shack-Hartmann spots, after calibration, must lie close to nominal position on the wavefront sensors to preserve dynamic range. This table does not include the effects of meteor transients, when another 50 mas is allowed for <10 seconds.

Slope Allocation OPD across a subaperture	**mas**
Dithering	50
Input path	40
Science Exit	25
LGS Path	180
Non-common path Instrument	55

Table 10 WFS Dynamic range allocation

3.6.5 Miscellaneous performance requirements

[REQ-2-NFIRAOS-3420] NFIRAOS shall meet its requirements with a pupil amplitude profile defined by the M1 segment geometry, M2 support struts, and a maximum (single axis) pupil decentration of D/360, with a goal of D/240.

Discussion: D/240 corresponds to one-quarter of a subaperture. This is a direct flow down of requirement [REQ-1-OAD-2750].

[REQ-2-NFIRAOS-3430] The pupil shift budget for shifts caused by NFIRAOS itself in RMS, assuming a Gaussian distribution with RMS = 1 sigma shall be 0.074% of pupil diameter.

Discussion: The system pupil shift is defined as the lateral shift of the first primary mirror (entrance pupil) image onto DM0. Further possible pupil shifts introduced by the misalignment of the science instrument are not considered here. The observatory pupil budget is *based on [RD24] TMT.SEN.CCD.07.001.DRF01. This is a direct flow down of requirement [REQ-1-OAD-0715].*

[REQ-2-NFIRAOS-3440] NFIRAOS shall meet its requirements without pupil derotation.

Discussion: This is a direct flow down of requirement [REQ-1-OAD-2755]. Pupil derotation reduces optical throughput and/or increases opto-mechanical complexity.

[REQ-2-NFIRAOS-3450] NFIRAOS shall allow the execution of a new observation acquisition sequence in less than 5 minutes if an instrument change is not needed.

Discussion: This requirement flows down from [REQ-1-ORD-1805]

REQ-2-NFIRAOS-3460] NFIRAOS shall allow the execution of a new observation acquisition sequence in less than 10 minutes if an instrument change or a major instrument reconfiguration is needed.

Discussion: This requirement flows down from [REQ-1-ORD-1810] & [REQ-1-ORD-1815]

[REQ-2-NFIRAOS-3470] NFIRAOS functions on the critical path (after the telescope has pointed to the desired field) to acquire guidestars and close and settle all control loops shall be as defined in Table 11.

Discussion: This requirement is only the NFIRAOS portion of the acquisition time requirement [REQ-1-ORD-1805]. The remaining portion involves the TCS, AOESW, LGSF, and OIWFSs. This requirement is broken down into NFIRAOS subsystem requirements in Table 11.

Table 11 NFIRAOS time allocation on acquisition critical path

Requirement No.	Subsystem	Time Allocation
[REQ-2-NFIRAOS-3480]	Configure NFIRAOS HW & SW	TBD
[REQ-2-NFIRAOS-3490]	Acquisition Camera Exposure	10 seconds
[REQ-2-NFIRAOS-3500]	Acquisition Camera Readout	0
[REQ-2-NFIRAOS-3510]	Offset Gimbal mirrors for NGS/TWFSs	TBD
[REQ-2-NFIRAOS-3512]	Detect if spots on NGS WFS	TBD
[REQ-2-NFIRAOS-3514]	Calibrate NGS/TWFS on sky	TBD
[REQ-2-NFIRAOS-3516]	Instrument Selection Fold Mirror	10 seconds
[REQ-2-NFIRAOS-3518]	Close AO Loops	TBD
[REQ-2-NFIRAOS-3520]	Detect if spots on OIWFS	TBD
[REQ-2-NFIRAOS-3522]	Real Time Controller settling	20 seconds
[REQ-2-NFIRAOS-3524]	Contingency	TBD

Discussion: Note that these times are durations that a subsystem may be on the critical path. If for example the Acquisition Camera readout can be accomplished in parallel with *the ISFM repositioning, and complete sooner, then its allocation is zero. Linearly summing the items in this table gives the total contribution of NFIRAOS to the time budget for target switching.*

An allocation for sky background measurement done by offsetting the gimbals away from the guide star is in [REQ-2-NFIRAOS-3510].

[REQ-2-NFIRAOS-3530] NFIRAOS must support adaptive optics mode guiding, where the image motion contribution of guiding anywhere in the field of view of a given instrument shall be less than 0.002 arcsec RMS after AO correction.

Discussion: This requirement includes only the residual windshake and atmospheric turbulence and is traceable to [REQ-1-ORD-2730] whose purpose is to qualify the sky coverage requirement [REQ-1-ORD-3525].

[REQ-2-NFIRAOS-3540] During adaptive optics mode guiding, image smearing, anywhere in the field of view of a given NFIRAOS client instrument shall be less than 0.0005 arcsec RMS after AO correction.

Discussion: This requirement is quoted directly from [REQ-1-ORD-2732], but may not be consistent with astrometry requirements

Discussion: This requirement is included in the DRD as a receiver link from the ORD. It then will flow down to the interfaces to the client instruments when a budget is allocated. The image smearing budget is added in quadrature to the guiding error budget in [REQ-1-ORD-2730], and consists of residual NFIRAOS optical distortion, rotator errors, ADC motion and optical errors, OIWFS probe motion errors, differential flexure between probes and science detectors, atmospheric refraction and dispersion modeling errors. It was set during discussions with the IRIS science team on 2008-08-08. [RD26] evaluates the effects of NFIRAOS optical distortion vs. exposure time.

3.6.6 Offsetting, dithering and nodding

[REQ-2-NFIRAOS-3550] None of the NFIRAOS subsystems shall be on the critical path during offsetting and dithering.

Discussion: This requirement is quantified by the following requirements in this section, which apply to the visible natural WFSs gimbal mirrors, barrel rotators, ADCs and to the RTC.

[REQ-2-NFIRAOS-3560] During an AO guider offset, the NFIRAOS must be able to offset with a positional error of at most 0.002 arcsec RMS on the sky.

Discussion: This requirement is quoted directly from [REQ-1-ORD-2761]. It flows down most directly to the OIWFSs, and also implies that the tip tilt mirror shall be able to follow the resulting commands accurately.

[REQ-2-NFIRAOS-3570] NFIRAOS shall be able to repetitively offset and settle between two or more given positions not farther apart than 1 arcsec, i.e. nod or dither, with a full nodding period of 10 seconds or dithering period of [number of end points] x [5 seconds].

Discussion: This requirement is derived from [REQ-1-ORD-2765]. Together with the duty cycle [REQ-1-ORD-2775] it implies that NFIRAOS can move and settle 1 asec in 1 second time.

[REQ-2-NFIRAOS-3580] NFIRAOS shall be able to repetitively offset and settle between two or more given positions not farther apart than 10 arcsec, i.e. nod or dither, with a full nodding period of 20 second (nodding) or dithering period of [number of end points] x [10 second].

Discussion: This requirement is derived from [REQ-1-ORD-2770]. Together with the duty cycle [REQ-1-ORD-2775] it implies that NFIRAOS can move and settle 10 asec in 2 seconds time.

[REQ-2-NFIRAOS-3590] NFIRAOS shall spend at least 80% of the period at the end points of nodding and dithering.

Discussion: This requirement is derived from [REQ-1-ORD-2775]

[REQ-1-NFIRAOS-3592] Visible Natural WFS gimbals, ADCs and pupil rotators shall follow data streams from the telescope control system (TCS) to control WFS positioning in coordination with the mount to perform non-sidereal tracking, dithering, and differential refraction compensation.

Discussion: Traceable to [REQ-1-OAD-8050] and to [REQ-1-ORD-2710]. The system is required to track solar system targets, using “fixed” natural guide stars as the guiding reference. This is a maximum of 16.5 arcsec/s on the sky. This results in a maximum speed in azimuth of 895 arcseconds/second and a maximum elevation speed of 15.5 arcseconds/second.

[REQ-1-NFIRAOS-3594] During dithering, the trajectories of the VNW star selection mirrors shall be within 0.25 (TBC) arcseconds of that specified by the follow stream of time-stamped waypoints from the TCS.

Discussion: An allocation of half the tolerance in [REQ-1-OAD-8055]. During dithering, the coordinated trajectories of the NFIRAOS gimbals and the telescope shall be within 0.5 (TBC) arcseconds. *The intent is to stay within the capture range of WFSs and to limit transients induced onto tip-tilt mirrors during AO guiding.*

3.7 SYSTEM ATTRIBUTES

3.7.1 Reliability

[REQ-2-NFIRAOS-3610] The overall allowable downtime for NFIRAOS is 0.4%

Discussion: The governing specification is [REQ-1-OAD-0348] that allocates downtime among observatory subsystems. The NFIRAOS portion is internally subdivided in [REQ-2-NFIRAOS-3900] and Table 12.

[REQ-2-NFIRAOS-3620] As strong goal, optomechanical subsystems to be used in the optics enclosure shall be tested at -35 C to ensure operating margin.

3.7.2 Material Limitations

[REQ-2-NFIRAOS-3630] NFIRAOS must not employ ozone-susceptible elastomers.

Discussion: Materials like Neoprene are vulnerable to ozone on Mauna Kea.

3.7.3 Availability

[REQ-2-NFIRAOS-3640] NFIRAOS-specific calibration shall consume <0.7% (TBC) of scheduled science nights.

Discussion: This specification is traceable to [REQ-0-SRD-0710] “Overall efficiency of AO modes -- Night-time calibration should need no more than 1% of the observing time.” The LGSF is allocated the remainder of the 1%. Other science instrument-specific calibrations such as instrument non-common path aberrations, wavelength and flat fields are not included in this allocation.

[REQ-2-NFIRAOS-3660] Implementation and commissioning of NFIRAOS or its upgrade shall not result in the loss of more than 10 (TBC) nights per instrument of productive science observing time.

Discussion: This requirement is traceable to [REQ-1-ORD-4205]. Note that the upgrade will be mostly accomplished using scheduled engineering time. But only 10 nights (TBC) of scheduled science time may be lost. This requirement limits the amount of rework and commissioning required to implement new capabilities on the observatory, and places a requirement on the early light NFIRAOS to be implemented in a fashion that supports seamless upgrades to its capabilities. The actual rework to NFIRAOS will disable it for more that 10 nights, but will not preclude scientific use of other instruments.

3.7.4 Safety and Security

3.7.4.1 General Safety

[REQ-2-NFIRAOS-3670] NFIRAOS shall comply with all applicable local and national safety regulations and standards listed in the TMT Environment, safety and health plan.

Discussion: This requirement is traceable to [REQ-1-ORD-7000]. Relevant standards are identified by systems engineering in reference document [RD23].

[REQ-2-NFIRAOS-3680] The safety priorities of NFIRAOS shall be: (i) protection of persons, (ii) guarding the technical integrity of the observatory and other equipment potentially affected by the operation of the observatory, and (iii) protection of scientific data, in this order.

Discussion: Quoted from [REQ-1-ORD-7003] Specific safety measures are expanded in section 3.7.4.2

[REQ-2-NFIRAOS-3690] NFIRAOS hazard analysis and safety practices will be governed by an order of precedence as follows:

1. Design for Minimum Risk: The primary means for mitigation of risk shall be to eliminate the hazard through design.

2. Incorporate Safety Devices: Fixed, automatic or other protective devices shall be used in conjunction with the design features to attain an acceptable level of risk. Provisions shall be made for periodic functional checks as applicable.

3. Provide Warning Devices: When neither design nor safety items can effectively eliminate or reduce hazards, devices shall be used to detect the condition, and to produce an adequate warning to alert personnel of a hazard. Devices may include audible or visual alarms, permanent signs or movable placards.

4. Procedures and Training: Where it is impractical to substantially eliminate or reduce the hazard or where the condition of the hazard indicates additional emphasis, special operating procedures and training shall be used.

Discussion: This requirement flows down from [REQ-1-ORD-7005] and is expanded in section 3.7.4.2.

3.7.4.2 NFIRAOS Safety

[REQ-2-NFIRAOS-3720] Interlocks on doors and port plugs shall prevent opening them unless the optics temperature is > 3 K above the frost pointof the air outside the NFIRAOS optics enclosure. When the optics are warmer than 0 C, the interlocks shall prevent opening unless the optics are at least 3 K above the dew point

Discussion: Frost point is warmer than dew point and is applicable below the freezing point of water. A good approximation to frost point is dew point in degrees C – 10%. I.e. a dew point of -30 C is a frost point of ~ -27 C. At 0 C, both are equal.

[REQ-2-NFIRAOS-3725] Interlocks on electrical enclosure doors shall prevent opening them if the internal temperature is below (dew point + 3 K) of the air outside the NFIRAOS electronics enclosure.

Discussion: The nominal operating temperature of the electronics enclosure is 10 C.[REQ-2-NFIRAOS-3730] Interlocks shall shut down the DM high voltage if the DM temperature is below the frost point in the optics enclosure near to the DM.

[REQ-2-NFIRAOS-3740]When the optics enclosure doors are open,Interlocks shall shut down the DM high voltage if the DM temperature is below the ambient dew point + 3 K.

Discussion: This requirement is to guard against the scenario where NFIRAOS is under test with doors open and the humidity rises in the outside air. The intent is to shut down prior to moist air entering NFIRAOS.

[REQ-2-NFIRAOS-3750] There shall be an oxygen monitor inside the NFIRAOS optics enclosure.

Discussion: Refrigerant leaks may reduce oxygen inside this enclosure posing a safety risk.

[REQ-2-NFIRAOS-3760] There shall not be possibility of injury to any personnel or damage to any components of NFIRAOS in the event of software faults.

[REQ-2-NFIRAOS-3770] There shall not be possibility of injury to any personnel or damage to any components of NFIRAOS in the event of unexpected loss of any or all normal services. Services include, but are not limited to:

- Motor/mechanism power
- Computer power
- Coolant
- Dry air supply
- Computer network
- Safety interlock signals

[REQ-2-NFIRAOS-3780] NFIRAOS shall have Emergency Stop buttons located at the Optics enclosure, and at the electronics enclosure.

[REQ-2-NFIRAOS-3790] The Emergency Stop buttons shall stop all motors and shut down the high voltage (>250 V) supplies.

[REQ-2-NFIRAOS-3792] Remote control of mechanisms while the optics enclosure is open shall only be possible if a local override is enabled.

Discussion: Moving mechanisms from a remote computer, with the enclosure open, will be disabled by default unless e.g., a dead-man switch is activated.

3.7.4.3 Standards

[REQ-2-NFIRAOS-3800] NFIRAOS shall comply with all local and national standards and regulations relevant to the construction and operation of NFIRAOS. In justified cases, when (i) meeting the requirements of these standards would incur significant additional expenses, and (ii) deviation from the standard does jeopardize neither personal safety, nor the technical integrity of the system, the TMT Project Manager may grant an exception to meeting a standard.

Discussion: Flowed down from [REQ-1-ORD-1005] Relevant standards are identified by systems engineering in reference document [RD23], and include compliance with the National Electrical Code.

[REQ-2-NFIRAOS-3802] NFIRAOS shall comply with software standards in the Software Management Plan [RD21].

3.7.5 Maintainability

[REQ-2-NFIRAOS-3810] NFIRAOS shall be designed to be efficiently maintained.

Discussion: This requirement flows down from [REQ-1-ORD-6410]. Maintenance will be a major component of the observatory operations costs. Designs should be assessed for reliability and maintainability.

[REQ-2-NFIRAOS-3812] NFIRAOS shall be designed so that all maintenance and servicing shall be done on the Nasmyth platform.

Discussion: TMT will not have laboratory facilities at the summit. This requirement flows down from [REQ-1-ORD-3020.

[REQ-2-NFIRAOS-3820] To meet the unscheduled technical downtime requirement NFIRAOS shall take measures during the design and implementation phase to minimize the number of such failures as well as minimize the cost and time necessary to recover from such failures.

Discussion: such measures shall include:

- *Identify all potential single-point failures. Whenever technically and fiscally possible, build in redundancy to minimize the number of potential single-point failures.*
- *Enable sub-system condition monitoring through implementation of mechanical and/or electronic wear and performance indicators. As much as possible, such condition information shall be captured and stored electronically for monitoring and analysis purposes.*
- *Identify all parts likely to become obsolete during the first TBD years of operation and procure enough spare parts (consistent with their expected Mean Time Between Failures) to cover all expected failures in that period.*
- Use common mechanical and electronic parts and solutions for common tasks and requirements.
- *Design assemblies so that components can be replaced quickly in the event of a failure*

Discussion: This requirement flows down directly from [REQ-1-OCD-3095]

[REQ-2-NFIRAOS-3850] NFIRAOS shall be designed for maintainability, including use of standard components where possible, standardization on metric hardware, etc.

Discussion: This requirement flows down directly from [REQ-1-OCD-3000]

[REQ-2-NFIRAOS-3860] In cases where sub-system components are custom fabricated, operational spares should be produced when the original components are fabricated, if appropriate.

Discussion: This requirement flows down directly from [REQ-1-OCD-3010]

[REQ-2-NFIRAOS-3880] Built in diagnostics shall be provided to detect and report hardware and software faults.

[REQ-2-NFIRAOS-3890] All standard maintenance shall be performed by the TMT operations staff.

[REQ-2-NFIRAOS-3900] Downtime shall be allocated among NFIRAOS subsystems as shown in Table 12:

Table 12 Downtime Allocation

Requirement No.	Subsystem	Downtime Allocation
[REQ-2-NFIRAOS-3910]	Real Time Computer	0.1%
[REQ-2-NFIRAOS-3920]	WFS detectors and controllers	0.02%
[REQ-2-NFIRAOS-3930]	Opto-mechanics	0.2%
[REQ-2-NFIRAOS-3940]	Conventional Electronics	0.04%
[REQ-2-NFIRAOS-3950]	Cooling systems	0.04%

Discussion: Table 12 subdivides the allocation of 0.4% of scheduled nights in [REQ-1-OAD-0348] for NFIRAOS downtime. Separate allocations are also in the OAD for the LGSF and the AOESW.

[REQ-2-NFIRAOS-3960] NFIRAOS shall be designed for a lifetime of 20 years, with preventive maintenance, while meeting all operational specifications.

Discussion: There may be an upgrade after the first 3 years (TBR). Preventive maintenance means servicing, repairing, and replacing components and subsystems based on their expected lifetime, as opposed to their failure. This requirement based on historical obsolescence of AO systems, and is a special case of [REQ-1-ORD-1000] (The observatory shall be able to operate and meet all the requirements for 50 years with preventive maintenance.)

[REQ-2-NFIRAOS-3970] NFIRAOS shall be designed to provide access to all required NFIRAOS and client instrument locations for regular servicing and maintenance via walkways, elevators, lifts and stairs. Sufficient space shall be provided for personnel and the required equipment to access the service locations.

Discussion: This is a direct flow down of requirement [REQ-1-OAD-1485]

[REQ-2-NFIRAOS-3980] NFIRAOS shall be designed to be consistent with the servicing and replacement intervals and scenarios shown in the table below

Discussion: These entries are initial estimates, and are subject to change.

Discussion: This requirement is flowed down directly from [REQ-1-OAD-2845]

NFIRAOS Servicing Requirements

TBD

3.8 ACCESS AND HANDLING

3.8.1 Shipment

[REQ-2-NFIRAOS-3990] NFIRAOS shall be transportable in sections for integration, testing, and mounting on the telescope.

[REQ-2-NFIRAOS-4000] Each section of NFIRAOS must fit within a standard 8 x 8 x 20 feet shipping container, except for NFIRAOS.TABL which may be shipped intact.

[REQ-2-NFIRAOS-4010] NFIRAOS shipping containers and sub-containers must withstand drops up to 200 mm, and withstand overturning accidents, without damaging NFIRAOS or its components.

3.8.2 Servicing

3.8.3 Instrument Changing

[REQ-2-NFIRAOS-4020] NFIRAOS shall permit changing instruments without warming it above the ambient dew point prior to removing or installing client instruments.

Discussion: The plan is to close a remotely activated, but uninsulated gate valve, manually remove an insulated port plug, and then install an instrument.

[REQ-2-NFIRAOS-4030] It shall be possible to change instruments without disassembling NFIRAOS other than removing and installing port plugs.

3.9 GENERAL REQUIREMENTS

3.9.1 Stray Light Sources

[REQ-2-NFIRAOS-4090] No components of NFIRAOS shall unintentionally emit light at visible or near-infrared wavelengths during scientific observations, i.e., no LEDs, lasers or other light sources are allowed unless sealed inside light-tight enclosures, or remotely controlled.

Discussion: This specification is intended to prevent light pollution both within the dome and within NFIRAOS' optics enclosure, while permitting calibration sources.

3.9.2 Mechanisms

[REQ-2-NFIRAOS-4100] All mechanisms shall hold their position with the power off.

[REQ-2-NFIRAOS-4110] Maintaining position of mechanisms in the optics enclosure shall be done with zero power dissipation

Discussion: These two requirements do not apply to DM0, DM11, or the Tip/Tilt stage.

[REQ-2-NFIRAOS-4120] Any continuously moved mechanisms, as a goal, should be balanced in order to minimize power dissipation.

3.9.3 Temperature Monitoring and Control

[REQ-2-NFIRAOS-4130] Temperature monitoring, logging and alarms shall be present at:

- mechanisms (e.g. motors, actuators, DMs)
- Multiple places on any optical benches
- outside window and inside above window
- detectors (e.g. WFSs).

- coolant inlet, coolant outlet and free-standing within each enclosure (opto-mechanical and all electrical)

[REQ-2-NFIRAOS-4140] Hardware shutoffs with manual resets shall exist where damage to equipment may result in the event of temperature extremes.

Discussion: Temperature extremes could be either too high or too low. Manual reset refers to requiring human intervention to reset. This may be, for example, a remotely controlled power switch.

3.9.4 Component Technology, Future Upgrades and Software

[REQ-2-NFIRAOS-4150] NFIRAOS shall utilize existing and near-term component technology whenever possible to reduce cost and schedule risk.

Discussion: This is a direct flowdown of requirement [REQ-1-OAD-2740]

[REQ-2-NFIRAOS-4160] NFIRAOS shall be upgradeable to meet the wavefront error requirement presented in [REQ-2-NFIRAOS-3360]

Discussion: This is a direct flowdown of requirement [REQ-1-OAD-2745] and [REQ-1-ORD-4225]

[REQ-2-NFIRAOS-4170] NFIRAOS shall be designed to be upgradeable to a higher order AO system that interfaces to wider-field near infra-red science instruments as envisioned in the SAC first decade instrument suite.

Discussion: This is a direct flowdown of requirement [REQ-1-OAD-2825] The early light implementation of NFIRAOS provides acceptable image quality for the early light adaptive optics instrument suite, IRIS and IRMS. However, an upgrade of NFIRAOS will be required to meet the full SRD performance requirements for these two instruments and additional first decade instrumentation including NIRES-b and WIRC.

NFIRAOS OPERATIONS CONCEPT DOCUMENT

TMT.AOS.CDD.05.001.REL06

June 24, 2010

TABLE OF CONTENTS

TABLE OF FIGURES

LIST OF TABLES

1. INTRODUCTION

The NFIRAOS Operations Concept Document (OCD) describes the operation and maintenance of NFIRAOS. Along with the NFIRAOS Design Requirements Document (DRD; **AD1)**, these two documents flow down the requirements from the level 1 requirement documents: the Operations Concept Document (OCD; **AD2**), the Observatory Requirements Document (ORD; **AD3**) and the Observatory Architecture Document (OAD; **AD4**). NFIRAOS, as described here, is consistent with the design presented in the NFIRAOS Preliminary Design Report (PDR; **AD5**) and the Observation Workflow (**AD6**).

In addition, we have strived to make the NFIRAOS OCD consistent with the Observation Workflow for the TMT. The NFIRAOS-enabled science summarized in this document is taken from the TMT Detailed Science Case (DSC; **AD7**) with additional information from the Science Flowdown Document (**AD8**).

This NFIRAOS OCD replaces the previous NFIRAOS OCDD that was in place for the Conceptual Design Review, and which pre-dated the TMT ORD, OCD and Observation Workflow.

1.1 PURPOSE

The present document discusses observational and operational concepts for NFIRAOS. This document and the TMT Observation Workflow document together consider the entire observing process from the preparations for observing through to the processing of recorded data, as well as the calibration and maintenance procedures that support these observations. This document will serve as an engineering description of NFIRAOS operations. The NFIRAOS OCD will also be useful for astronomers and engineers working with the NFIRAOS client instruments, so they will understand how NFIRAOS is used with their science instruments.

1.2 SCOPE

The NFIRAOS OCD gives an overview of the instrument and describes some of the key science cases that will be addressed. Most of the rest of the document describes how NFIRAOS will be used; first the NFIRAOS operating procedures when feeding the client science instruments will be described, then basic operations associated with cooling the instruments, physically switching client instruments, and maintenance will be discussed. Finally, we discuss the safety features associated with NFIRAOS.

1.3 APPLICABLE DOCUMENTS

Applicable documents are those containing information that shall be applied in the current document. Examples are higher level requirements documents, standards, rules and regulations. Documents should be hyperlinked as shown below.

AD1 – NFIRAOS Design Requirements Document (DRD), (TMT.AOS.DRD.07.002)

AD2 -- Operations Concept Document (OCD), (TMT.OPS.MGT.07.002)

AD3 – Observatory Requirements Document, (TMT.SEN.DRD.05.001)

AD4 – Observatory Architecture Document, (TMT.SEN.DRD.05.002)

AD5 – NFIRAOS PDR Book, (TMT.AOS.PDD.08.020)

AD6 – Observation Workflow for TMT, (TMT.AOS.TEC.07.013)

AD7 – Detailed Science Case (DSC), (TMT.PSC.07.006)

AD8 – TMT Science Flowdown Document (TMT.PSC.DRD.09.001)

1.4 Reference Documents

RD1 –

1.5 Change Record

Revision	Date	Section	Modifications
REL04	15, February, 2006	All	NFIRAOS CoDR Version - Davidge, Veran, Hickson, Herriot
REL05	18, April 2010	All	Included latest information from TMT OCD, ORD, Observation Workflow, Detailed Science Case, and NFIRAOS DRD – Andersen; Added Ellerbroek's comments on rough draft
REL06	24, June 2010	All	Updated all sections for 4 OAP design– Andersen; Incorporated comments from Boyer and Herriot.

1.6 Abbreviations

DM – Deformable Mirror

DRD – Design Requirements Document

DSC – Detailed Science Case

FOV – Field of View

HOL – High Order Low bandwidth (TWFS)

HRWFS – High Resolution Wavefront Sensor

IRIS – InfraRed Imaging Spectrograph

IRMS – InfraRed Multi-object Spectrograph

ISFM – Instrument Selection Fold Mirror

LGS – Laser Guide Star

MCAO – Multi-Conjugate Adaptive Optics

MOR – Medium Order Radial (TWFS)

NFIRAOS – Narrow-Field InfraRed Adaptive Optics System

NGS – Natural Guide Star

NIRES – Near InfraRed Echelle Spectrograph

OAD – Observatory Architecture Document

OAP – Off-Axis Parabola

OCD – Observation Concept Document

ORD – Observatory Requirement Document

OIWFS – On-Instrument WaveFront Sensor

PDR – Preliminary Design Review

PSF – Point Spread Function

RTC – Real-Time Computer

T/T – Tip and Tilt

TMT – Thirty Meter Telescope

TWFS – Truth Wavefront Sensor

WFS – WaveFront Sensor

WIRC – Wide field InfraRed Camera

2. NFIRAOS OVERVIEW

One of the most compelling scientific motivations for developing 30-metre-class telescopes is the unprecedented angular resolution that can be achieved when these facilities are used at their diffraction limit. This capability will impact a broad range of science programs that span topics as diverse as the search for extrasolar planets to studies of the first objects to illuminate the Universe. Also, for many programs, there is an accompanying gain in sensitivity over smaller ground-based facilities that scales as the fourth power of the entrance aperture size – the so-called D^4 advantage.

NFIRAOS is a MCAO facility for TMT designed to provide high-quality diffraction-limited image quality to three primary science instruments: the first light InfraRed Imaging Spectrometer (IRIS), the Near-InfraRed Echelle Spectrometer (NIRES) and the Wide-field Infrared Camera (WIRC). In addition to IRIS, another first light instrument that will eventually be replaced by NIRES is the InfraRed Mutil-object Spectrograph (IRMS).

In this section, we review the NFIRAOS subsystems, the NFIRAOS client instruments, and the science case for those instruments.

2.1 NFIRAOS SUBSYSTEMS

NFIRAOS can be broken down into a number of different subsystems (Figure 1). In the sections below, we describe the basic functions of these subsystems.

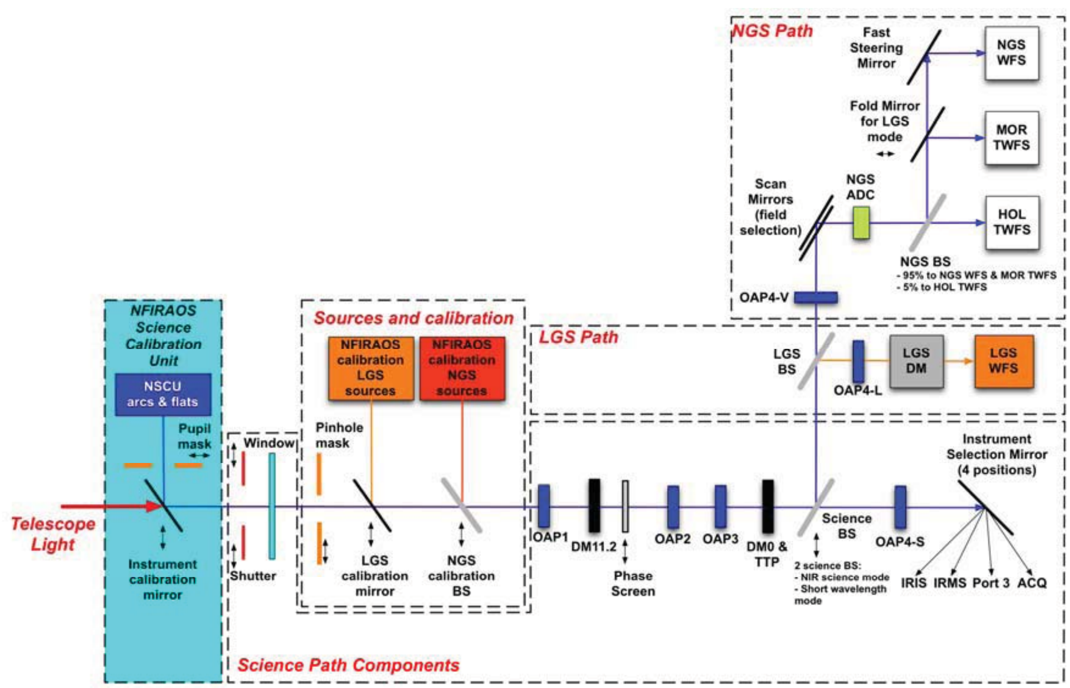

Figure 1: NFIRAOS layout

2.1.1 NSCU

The NFIRAOS Science Calibration Unit (NSCU) is not formally a part of NFIRAOS, but it will be permanently mounted in front of the NFIRAOS entrance window. The NSCU will provide flat fields and arc lamps for NFIRAOS client instruments. It will also provide a pupil position and shape reference to be used by NFIRAOS.

2.1.2 Internal source simulators

NFIRAOS is required to furnish internal calibration sources for its wavefront sensors. The NFIRAOS Calibration Unit (distinct from the NSCU described above) contains two sub-assemblies for this purpose: the NGS and LGS source simulators.

Two separate optical sub-systems are necessary to simulate natural and laser guide stars. This is because the NGS asterisms are optically conjugate to infinity, but the laser sources are optically conjugate in a range of 85 km to 200 km (with a goal of 235 km) and therefore must be relayed by a system of optics that simulate the finite and variable range distance to the sodium layer. The internal source simulators will be used to calibrate the NFIRAOS LGS WFS and TWFS.

The NGS Source Simulator consists of two rings of ~9 stationary sources and a single on-axis source that patrols over the central part of the field. Light from these sources are directed into the NFIRAOS optical path with a deployable fold mirror.

The LGS Source will reproduce the asterism of 6 LGS expected from the LGSF. The fiber sources will be mounted on a simple support frame that will move directly into the NFIRAOS optical path. The difference in aberrations between these sources and from the LGSF can be accounted for using a different set of maps for the LGS DMs (section 2.1.5).

2.1.3 Main OAP Relay

The science path is characterised by two matched pairs of off-axis paraboloids (OAPs) that relay the telescope focus and provide a pupil between the focal surfaces (there are actually 3 identical final OAP elements – one for the science path, one for the LGS WFS path, and one for the VWFS path). These mirrors determine the minimum possible length of NFIRAOS. One deformable mirror is located between each OAP pair, the first being conjugate to 11.2 km altitude (“DM11.2”) and the second being ground conjugate, i.e. located at the telescope pupil (“DM0”). DM0 incorporates a two-axis gimbal mount to provide additional tip-tilt correction (referred to as the Tip Tilt Mount).

Following the deformable mirrors, the light encounters the science beamsplitter, which reflects visible light and transmits infrared. The reflected light is sent to the wavefront sensor optics, and is described below. Two beamsplitters having different wavelength cutoffs, can be accommodated on a beamsplitter selector mechanism.

2.1.4 Science Path

After the science beamsplitter the final OAP reflects the science light onto the instrument selection fold mirror (ISFM), a large, steerable flat mirror that selects between one of three science instrument foci or the acquisition camera. This ISFM is the final optic that light encounters in NFIRAOS during a science observation. It is a large element with a mass of 60 kg. The available slew time of the ISFM is derived from an observatory workflow requirement; it must change between any two positions in <10 s (REQ-2-NFIRAOS-0650).

2.1.5 LGS WFS Path

The visible light reflected off of the science beamsplitter is split again by the LGS beamsplitter. 589nm light from the Sodium guidestars reflects off the beamsplitter and enters the LGS WFS assembly. A portion of the LGS optics is common to all six laser guidestars in the asterism. This portion consists of OAP4-L, a single trombone which brings images from all sodium layer distances to a fixed plane (and a set of field stops). This trombone keeps the laser beacons focused on the WFS as TMT changes its zenith pointing. The trombone can accommodate beacons with a range distance between 85 and 235 km (zenith angles between 0° and 65°). Six separate, open-loop DMs correct field-dependent non-common path wavefront errors from the telescope and NFIRAOS optics. Final adjustments to the DM shapes is done using phase diversity measurements from the science images.

The LGS zoom optics are arranged as six separate channels in a pentagon formation with one centre channel. The central channel of the LGS zoom defines an axis about which the peripheral five channels are disposed, equally spaced.

2.1.6 Visible WFS Bench

The visible natural path is fed by the light reflected by the science beamsplitter and transmitted by the LGS beamsplitter. Light with wavelengths between 600 nm and 800 nm (or 1 μm depending on the science beamsplitter) is reflected by another copy of OAP4 ("V") toward a scanning gimbal mirror which directs the light to the visible wavefront sensor optics.

The visible natural wavefront sensor bench is positioned approximately 1.4 m above the assemblage of science benches. It is populated with the three visible wavefront sensors, ADC, field stop, beamsplitters, and gimbal mirrors that feed this system. Adjacent to the bench are the LGS beamsplitter and a large packaging fold mirror. A support frame connects these components and has legs which attach it to the science benches below.

Discussion: This section needs to be updated. The position of the VWFS bench has changed in the new 4 OAP design.

The Visible WFS bench is populated by two Truth WFS (TWFS) and a NGS WFS. The NGS WFS is an order 60x60 subaperture WFS that can be used with stars as faint as R<19 (with a correspondingly low amount of correction). The (High Order Low-bandwidth) HOL TWFS is order 120x120 and will monitor flexures, thermal distortions, and the shape of the rotating TMT pupil at rates less than 0.1 Hz. The Moderate Order Radial (MOR) TWFS is order 12x12 and will sense radial wavefront distortions arising from variations in the structure of the Sodium profile at ~10 Hz. In LGS mode, 95% of the light will go to the MOR TWFS and the remainder will illuminate the HOL TWFS. In NGS mode, a fold mirror will instead direct 95% of the light to the NGS WFS with the remaining 5% again illuminating the HOL TWFS.

2.1.7 Acquisition Camera

Guide star acquisition will be assisted by an infrared wavelength acquisition camera which receives light from the fourth station served by the ISFM. The camera fore optics consist of two groups of lenses which rescale the image to fit a commercial NIR camera detector. The camera assembly will be supported by a framework that attaches to the optical bench. The 1024x1024 NIR detector will image the entire 2 arcminute FOV of NFIRAOS (0.125" per pixel). This camera is sensitive to near-IR light (between 1-1.6 μm) in order to reduce acquisition integration times from tens of minutes for a visible detector (worst case) to seconds.

2.1.8 Electronics Enclosures

The majority of the NFIRAOS electronics, to the greatest extent practical, will be located in a cooled (with glycol) and insulated cabinet located on the Nasmyth platform 7 m below the optical axis. The enclosure is not mounted directly on NFIRAOS in order to reduce vibration from fans and heat exchangers, and to reduce wind blockage of the telescope primary mirror. The NFIRAOS electronics enclosure(s) will house the Component Controller, the TWFS/ACQ Detector Controller, the motion and monitoring electronics, the Real Time Controller, the DM electronics, power supplies, network equipment, and a node of the LGSF safety system.

2.2 NFIRAOS CLIENT INSTRUMENTS

The overarching operational consideration for NFIRAOS is that, when coupled with TMT instruments, it provides scientifically useful capabilities. As a unique observational platform, the TMT will tackle a rich range of science programs, and the scope of these programs places operational constraints on the NFIRAOS system. Hence, the scientific motivation for NFIRAOS and the instruments with which it will be used are briefly discussed here.

2.2.1 IRIS

IRIS is a first generation instrument that will provide moderate spectral resolution (R ~ 4000) spatially resolved spectroscopy and imaging over a small field of view in the wavelength region from 0.8 µm to 2.5 µm (extensions of this range to 0.6 µm and 5 µm are desirable). It will be capable of working spatially at the diffraction limit of the 30 m telescope at all wavelengths longer than 1 µm. Spectra will be obtained with an integral-field unit (IFU) that will have a field of view of up to 2 arcsec. IRIS will also have a diffraction-limited, larger-field direct imaging mode over a 17 x 17 arcsec field. Simultaneous imaging and spectroscopic capabilities are enabled, as this is advantageous for some projects, and may provide knowledge of the point-spread function that would prove to be useful for analyzing the IFU data. This is the highest priority instrument for TMT because (1) it takes full advantage of the capabilities unique to a 30m telescope with images corrected to the diffraction limit, and (2) it offers a range of capabilities that will be used for a broad range of science areas. IRIS will be a first generation TMT instrument, and will be the first to be used with NFIRAOS.

2.2.2 IRMS

IRMS will be an early first decade science instrument, and it will be an adaptation of the MOSFIRE instrument being built for Keck. It will be capable of taking multi-slit spectroscopy of up to 46 objects over an entire atmospheric window (J, H, or K-band). Slits can be positioned anywhere within a ~1x2 arcminute FOV. IRMS will be able to function using either the NFIRAOS seeing-limited mode or LGS mode. It is expected that IRMS will occupy the top client instrument port of NFIRAOS.

Discussion: Introduce seeing-limited mode here and why NGS mode is not desirable with IRMS.

Although MOSFIRE is a mature design, its adaptation into IRMS has only been considered at a feasibility level. It will occupy part of the 2.0 m diameter by 4.0 m long generic space envelope and its mass will be 2.5 tonnes. It is expected that IRMS will use the same wavefront sensor module as IRIS, therefore the snout, seals, and thermal control design will be similar.

2.2.3 NIRES

NIRES is a first decade instrument that offers high-resolution (20,000 < R < 100,000) spectroscopic capabilities through a diffraction-limited slit or IFU. A slit length of up to 2 arcsec is specified, so the instrument requires only a modest corrected AO field of view. Wide wavelength coverage in a single exposure in the range between 1µm – 2.4 µm is also specified. An acquisition camera that can act as a small (10 arcsec-diameter field) well-sampled imager may also be part of NIRES.

2.2.4 WIRC

WIRC, a possible first decade instrument, is a direct imaging camera. It will provide diffraction-limited images through a variety of filters, providing excellent photometric accuracy and high-quality astrometric information. Wavelength coverage is 0.8 μm – 2.5 μm. The imaged field is 30 arcsec, and astrometric precision is a prime consideration for this instrument.

2.3 NFIRAOS-DRIVEN SCIENCE PROGRAMS

The TMT Detailed Science Case (DSC) for the TMT highlights 8 high-priority science drivers for NFIRAOS and its client instruments. For each pillar of the DSC, we outline some of the specific observing programs that will be undertaken with NFIRAOS. What is written below is traceable from the Science Flowdown document.

Table 1: Summary of NFIRAOS-enabled science Cases

Topic	**Science Case**	**NFIRAOS Client Instrument**
Fundamental Physics and Cosmology	Dark matter	IRIS, WIRC
	Milky Way central black hole	IRIS, WIRC
	Dark energy	IRIS, WIRC
	Extreme objects	NIRES
Early Universe	First stars	IRIS
	z ~ 7 Intergalactic medium	NIRES
Galaxy Formation and IGM	Star formation, extinction & metallicity	IRMS, IRIS IFU
Extagalactic SMBH	SMBH masses in local volume	IRIS
	SMBH mass-halo relation evolution	IRIS
	AGN studies	IRIS
Exploration of Nearby Galaxies	Local group chemical enrichment	NIRES
	Star formation histories	IRIS, WIRC
Formation of Stars and Planets	Stellar initial mass function	IRIS
Exoplanets	Doppler shift detections	NIRES
	Self luminous Jovian planets	IRIS
Our Solar System	Kuiper Belt Object composition	IRIS
	Chemistry of comets	NIRES
	Mapping surface of Jovian satellites	IRIS

2.3.1 Fundamental Physics and Cosmology

To understand dark matter, it is worthwhile exploring the kinematics of dwarf galaxies, which are the most dark-matter dominated objects we know. Astrometry from IRIS and later from WIRC can be used to work out the proper motions of stars in dwarf galaxies which in turn will be used to determine the radial mass profile.

The black hole at the centre of our galaxy offers a number of tests of relativity and is also a laboratory for studying dark matter. Imaging and spectroscopy with IRIS and WIRC will undoubtedly lead to numerous scientific breakthroughs.

Dark energy is even more mysterious than dark matter. Theories of dark energy are constrained through a combination of data from supernovae, Baryonic Acoustic Oscillations and the cosmic microwave background. IRIS and later WIRC on TMT will be able to detect even higher redshift supernovae which will provide significantly tighter constraints on theory.

NFIRAOS and its instruments will also be able shed light on some extreme objects in our universe. High resolution NIRES spectroscopy of the NIR afterglow from Gamma-Ray Bursts, thought to be associated with the collapse of massive stars, will shed light on these most energetic explosions in the Universe. The D^4 advantage of NFIRAOS on TMT will also allow us to obtain IRIS spectroscopy of Supernovae Type IIb. The supernovae, associated with the collapse of stars with masses more than 80 times that of the sun, are very rare and allow us to better understand the extreme high end of the stellar luminosity function.

2.3.2 The Early Universe

The earliest stars formed from primordial, metal-free, gas and formed at redshifts between 7 and 20. IRIS would be able to spectroscopically identify these so-called population III stars out to a redshift of ~14.

These first stars and galaxies had a profound effect on the primordial inter-galactic medium. Analyzing the detailed structure of the Ly-alpha line from these first light objects with IRIS will help us understand how the Universe was re-ionized.

Even at redshifts above 7, we can use high resolution spectroscopy of the dark gaps in the Ly-alpha forest from NIRES to determine the structure and neutral fraction of the intergalactic medium at this epoch.

2.3.3 Galaxy Formation and the Intergalactic Medium

IRMS will allow for the multiplexed spectroscopy of multiple high redshift galaxies. We will be able to follow the usual visible wavelength lines into the near-infrared and obtain measures of star formation, internal extinction and even metallicity ratios. Some of these galaxies can be also observed with the IRIS IFU, which will allow us to dissect individual galaxies that are undergoing formation. The velocity fields of these galaxies, will give us clues about their mass and merger history. We will also be able to understand the resolved star formation history of these objects.

2.3.4 Extragalactic Supermassive Black Holes

The apparent link between the mass of supermassive black holes and the dark matter halo in which they reside is intriguing, but is based on a relatively small sample. IRIS on TMT is in position to significantly increase the number of black hole mass measurements in nearby galaxies over a much wider mass range of dark halos.

Understanding if there is any evolution in this relation will require IRIS on TMT. IRIS should be able to measure the central velocity dispersion in galaxies at redshifts up to 1.5.

The history of supermassive black hole formation can be followed to even higher redshift through detailed studies of Active Galactic Nuclei (AGN). AGN occur only over a short time relative to the age of supermassive black holes, but they peak during an important era of galaxy formation. IRIS will be able to establish links between AGN and their environment.

2.3.5 Exploration of Nearby Galaxies

Local galaxies provide us with a fossil record of their chemical evolution. High resolution spectroscopy from NIRES will allow us to perform this archeology of chemical enrichment in galaxies not only in our Local Group, but also out to the nearest clusters.

In a similar way, we can study the star formation histories of the nearest galaxies in great detail using imaging and spectroscopy from IRIS and later WIRC.

2.3.6 The Formation of Stars and Planets

Most TMT science focusing on star and planet formation is enabled by mid-infrared observations, but young clusters are observable in the NIR with IRIS and will provide us with improved measurements of the stellar Initial Mass Function. The exact form of the initial mass function plays a central role in galaxy formation models.

2.3.7 Exoplanets

NIRES will be the instrument on TMT capable of detecting terrestrial planets around low mass stars through the Doppler motion of the stellar lines. IRIS will also be used to try and detect self-luminous (relatively low contrast) Jovian planets before the Planet Finding Imager (PFI)[1] becomes available.

2.3.8 Our Solar System

The composition of Kuiper Belt Objects will be best determined with IRIS spectra obtained with TMT. Understanding the composition of these objects help us to understand the composition of the material that formed the planets. We can perform even more detailed chemical composition studies of comets using NIRES when it becomes available.

The resolving power of TMT will allow us to map the surface of the Jovian satellites at a resolution of ~25 km. We will be able to study the weather, vulcanism and tectonic activities on these moons with IRIS.

3. OPERATIONAL GUIDELINES

3.1 General Considerations

Based on current scientific interest and technology limitations, the telescope is expected to be initially used roughly 50% of the time for seeing-limited observations and 50% of the time with diffraction-limited observations (using NFIRAOS). As the instrument suite of TMT changes, this percentage may change.

NFIRAOS is designed to support classical observing, as per the level 1 requirements, but NFIRAOS and all other systems shall be upgradable to support queue mode observations

All NFIRAOS functions will be configured, controlled and coordinated by the AO executive software for all scheduled science observations, calibrations, and engineering modes.

3.2 Reliability and Calibration Efficiency

NFIRAOS will be the workhorse AO system for at least the first few years of TMT operations, and it is certain that NFIRAOS will be used extensively from the time of first light to well into the era of

[1] The Planet Finding Imager is a first decade TMT instrument which will be able to achieve high contrast images of planets near bright stars in the NIR.

routine operations. Minimizing the downtime of NFIRAOS is therefore a critical factor in maximizing the number of available night time science integration hours. The overall allowable downtime for NFIRAOS is 0.4%. However, there are obvious operational issues for keeping NFIRAOS working at its peak scientific capability.

In addition to regular maintenance, there will likely be a regular program of basic calibrations, such as checking the alignment of the telescope pupil with the NFIRAOS optics. To minimize the time spent performing night-time calibrations, there is a requirement that all operational instruments with independent light paths be capable of obtaining simultaneous daytime calibrations without interfering with each other. For the NFIRAOS client instruments which all share the services of the NSCU it will not be possible to obtain internal calibrations (e.g. detector bias frames) simultaneously for all instruments. Therefore, NFIRAOS night time calibrations are required to take no more than 1% of the observing time.

3.3 SYSTEM PERFORMANCE

As the number of science integration hours decreases, so does the potential for transformational observations. To maximize the quality of those available science integration hours, NFIRAOS needs to maximize the possible image quality (as set by the NFIRAOS wavefront error budget) and total system throughput while minimizing the system background. NFIRAOS has therefore been designed with the minimal number of optical elements needed to provide good image quality and is cooled to -30° C to keep the background from NFIRAOS less than 15% of the sky plus telescope background at all operating wavelengths.

NFIRAOS is also required to provide at least 50% sky coverage at the galactic poles. This requirement has been placed on NFIRAOS to ensure that most scientific targets of interest can be observed with NFIRAOS client instruments.

3.4 COMPATIBILITY

NFIRAOS will be operated as a facility AO system. Consequently, the operations of NFIRAOS must be compatible with those of all other TMT systems, and it must be capable of feeding a number of TMT instruments and be fed by systems, such as a facility calibration capability that is required for flat-fielding. In fact, the operations of NFIRAOS and the instruments that it feeds will be intertwined, as the tip-tilt OIWFS and the field de-rotator are within the instruments. Finally, the look and feel of the NFIRAOS control interface should be compatible with that of other TMT instruments and systems as defined by TMT.

3.5 STABILITY

NFIRAOS will be used for key science programs that require homogeneous observations recorded over moderately long time baselines; for example, the identification of exosolar planets and the characterization of their orbits will require data recorded over timescales of months to years, and system stability is essential to reduce potential systematic effects. From an operational perspective, this means that the performance of key elements, such as the DMs and the WFS, must remain stable over these timescales. The operational performance of NFIRAOS must also be maintained at or near its peak potential. One implication is that the alignment and cleanliness of optical components must be stable over timescales of months to years. This translates into a regular maintenance schedule coupled with a design that highlights stability over the range of environmental conditions at the TMT site.

3.6 EASE OF USE

Because NFIRAOS likely will be operated by non-AO experts in the TMT night crew, it is essential that NFIRAOS have an operating interface that will permit non-expert users to gain quickly basic competency in operating the system. AO systems have been in use on 4 – 10 metre telescopes for well over a decade, and the lessons learned from using these systems should be applied to NFIRAOS.

Specifically, TMT, NFIRAOS and its client instruments need to make tools available for observing run preparation, make easy-to-use and complete user interfaces, provide high-quality user documentation, provide well, self-documented science data, provide well-designed data processing software with good user documentation (both at cookbook and details level), and finally support an efficient user helpdesk.

3.7 RAPID DEPLOYMENT AND CONFIGURATION

Observing time on the TMT will be an expensive commodity, and all telescope systems must strive to maximize observing efficiency. NFIRAOS will feed a total of 3 output ports, with selection being performed by the ISFM. It is likely that there will be nights when multiple instruments may be used, and so it is important that the time to deploy or re-configure NFIRAOS be kept to a minimum. NFIRAOS is required to be ready for observations with a 10-minute notice with any of its client instruments when a change of instruments is necessary and a 5-minute notice when no change of instruments is required. In addition, the operational aspects of this deployment should be made as straight-forward as possible to increase efficiency and decrease overheads. NFIRAOS should also be set up to allow for rapid changes in configuration, both during and between observations. In particular, time losses due to dither pattern offsets should be under 1 second for up to a 5 arcsec offset, and 5 sec for up to a 30 arcsec offset. TMT, NFIRAOS and its client instruments are also required to move from any point in the sky to any other and be ready to begin observing in less than 5 minutes when no instrument change is required and in less than 10 minutes when an instrument change is required. This time includes time needed to slew the telescope, rotate the instrument, rotate the dome, acquire several guide stars, and set up the ADC and NFIRAOS. The overhead for setting up NFIRAOS is TBD.

3.8 CLIENT-INSTRUMENT INTERFACES

The full technical field will be provided to instruments fed by NFIRAOS. NFIRAOS will pass light between 0.8-2.5 μm (or 0.6-2.5 μm depending on the science beamsplitter) to the client instruments. During LGS science exposures, all NGS tip/tilt and focus sensing, and atmospheric dispersion compensation will be performed internally within the instruments. NFIRAOS will supply mounting faces for a rotator bearing for two vertically-oriented instrument ports. Instruments fed by the one horizontal side port are responsible for their own field rotation, either by a rotisserie or by K-mirrors.

4. OPERATING MODES

4.1 LGS MODE

The TMT Laser Guide Star Facility (LGSF) will generate the asterism of 6 Sodium LGS for NFIRAOS: one central laser beacon and 5 on a 35 arcsecond radius regular pentagon. Tip-tilt and focus corrections will be obtained from low-order NIR OIWFS internal to the client science instruments. IRIS will deploy two tip-tilt OIWFS and one tip-tilt-focus OIWFS. IRMS will use a single tip-tilt-focus OIWFS. These WFSs must have access to as much of the delivered field as possible to permit the highest possible sky coverage. By operating in the NIR, the OIWFS will have two advantages over optical OIWFS. First, the stars will be significantly sharpened, allowing for diffraction-limited plate scales to be used on the detectors which thereby improve the low order mode measurements. Secondly, it will be possible to work in areas of higher extinction than might otherwise be the case.

There will also be two visible TWFS within NFIRAOS that will receive light from the brightest star in the field (this can also be a OIWFS star). The MOR TWFS will sense radial modes that arise from asymmetries in the Sodium layer. The HOL TWFS will sense slowly varying changes to the TMT pupil as the elevation of the telescope changes during the course of an observation.

It is anticipated that LGS mode will be the most heavily requested operational mode once the LGSF is commissioned, as the sky coverage will be much higher than can be achieved in NGS mode.

4.2 NGS MODE

The NGS mode makes use of a single, bright star to feed a single high order visible NGS WFS. The NGS mode will also make use of the HOL TWFS to sense changes in the TMT pupil. This mode will be capable to delivering Strehl ratios of 50% in K-band for 16th magnitude stars. The bandpass of the NGS WFS is set by the light passed by both the science and LGS beamsplitters. This mode will be used throughout the lifetime of the instrument, as the NGS mode will be capable of delivering somewhat higher Strehl ratios for bright NGS, albeit with an extremely limited sky coverage and a smaller corrected field-of-view.

4.3 CALIBRATION MODE

NFIRAOS shall include or make allowance for all necessary components and processes for self-calibration and calibration of the instruments that NFIRAOS feeds. It will feed internal natural star simulated sources to client instruments, especially to calibrate non-common path errors and pointing models for OIWFSs. Additional internal point sources will simulate both natural stars and laser guide stars at varying range distance in order to perform closed loop AO operations. In both of these closed loop modes, NFIRAOS shall be able to feed the output beam to the High Resolution WFS (HRWFS) test instrument on the top port, without tip/tilt/focus feedback, but in neither case will NFIRAOS require the HRWFS to be mounted.

By employing a turbulator, NFIRAOS shall be able to operate in closed loop in the presence of artificial turbulence. This ability will allow for diagnostic checks on system performance.

NFIRAOS shall pass flat field and wavelength standard light from an external calibrator in front of NFIRAOS through to client instruments.

4.4 SEEING LIMITED MODE

NFIRAOS shall include a Seeing Limited Mode, in which fast guiding is performed via the NFIRAOS tip/tilt stage using measurements from a science instrument OIWFS, together with sending slow speed MOR TWFS measurements of telescope aberrations to the telescope control system.

4.5 STANDBY MODE

In this mode, NFIRAOS is ready, on a 10 minute notice, to be used on sky. Mechanisms are all parked and unpowered (or perhaps in the case of the DMs, being supplied with a set of flat commands). The shutter is closed. The optical enclosure, however, is cooled and held at the operating temperature.

4.6 Off Mode

All devices are parked and powered off. The shutter is closed. The enclosure has been warmed to the ambient temperature. Panels on NFIRAOS can be opened for internal maintenance and repair.

5. PREPARATIONS FOR OBSERVING

Various tasks will have to be performed prior to observing. These should be considered to be part of the NFIRAOS system, as they are essential for the successful execution of observing programs. These tasks include:

5.1 The selection of tip-tilt stars for laser guide star mode

Depending on the client instrument, between 1 – 3 OIWFS tip-tilt stars are required within an arcminute of the field center to operate in LGS mode. A source for the truth WFS also needs to be identified. The stars should be selected so that they fall within the field passed to NFIRAOS during the entire dither sequence. If not (e.g. the dither motions are large and/or the reference star is near the edge of the NFIRAOS field) then it will be necessary to select additional T/T and TWFS stars for use during the dither sequence. This will impact observing efficiency and the repeatability of the dither sequence.

In the basic observing model, it is assumed that the user can find these NGS for their particular science target. To achieve high sky coverage, some of the tip-tilt and truth WFS sources will, by necessity, be faint. Reference stars or the MOR TWFS and OIWFSs can be obtained from catalogs, pre-imaging obtained by the astronomer, a virtual observatory, or a next-generation survey telescope. There may be difficulty finding suitable guide stars for a number of reasons, however:

- While NFIRAOS can operate with NGS brighter than J<22, there are no all-sky NIR surveys planned with magnitude limits that faint.
- There will be a level of galaxy/star confusion present in the catalogs. Even extended objects that are less than 0.1 arcseconds across will not be suitable as the plate scale on the OIWFS is chosen to sample the 30 m diffraction-limited PSF (about 0.004 arcseconds per pixel).
- Most all-sky catalogs are optically selected. Good multi-band photometry can help to separate stars and galaxies and even be used to estimate the J-band magnitudes, but at the faint end of these catalogs, photometric errors will again lead to confusion.
- Proper motion errors in stellar catalogs could also lead to difficulties in acquiring the NGS.

If LSST is on-line and is providing multi-band optical data deep enough for our NGS needs, that may solve this problem of finding suitable NGS, but then the TMT would need to have access to the LSST data products.

Furthermore, it is important that these sources be properly characterized. In particular, the tip-tilt stars should have positions known to between 10 mas and 1 arcsec (depending on the science case) along with photometric information (brightness and color) that is reliable to within +/- 0.1

magnitudes. Ideally, 3 T/T stars should be found that are located across the science field, as this will produce more uniform corrections than if the T/T stars are clustered to one side of the science target.[2]

5.2 The definition of reference asterisms

In the case of problems on-sky identifying tip-tilt guide stars (see next section) the performance of the NFIRAOS tip-tilt WFS system could be checked by acquiring a reference constellation of moderately bright guide stars. Such asterisms should be identified prior to the commissioning of NFIRAOS, and a grid of these reference constellations should be defined at various points in the sky so that at least one can be acquired at any time of night.

5.3 Modelling of observations

Astronomers will need a simple tool to help understand what they can expect in terms of NFIRAOS performance. The Strehl ratio (and ensquared energy within a given spaxel) delivered by NFIRAOS will depend most critically on the seeing at the time of observations. However, other factors may also have a significant impact on the system performance. These factors include the fraction of light returning from the Sodium layer, the degree of generalized anisoplanatism, the location and brightness of the NGS, the airmass of the observations, sky transparency, and moon phase (ambient sky background). There may also be trade-offs to be made; for example, is the system better with a mildly extended tip-tilt source close-in to the target or using a known star that is located at the outermost limits of the tip-tilt guide field? To properly identify the observing conditions that are required for successful NFIRAOS observing (i.e. those that allow the science goals to be realized), and make informed decisions regarding guide stars, the user will need access to NFIRAOS-specific tools that will allow the science field to be modeled with a variety of input parameters. Hopefully, look up tables of delivered NFIRAOS wavefront error can be compiled for three or four values of each parameter, using common astronomical language (e.g. airmass=1, 1.25, 1.5; quartiles in seeing). Then if the results for these look up tables could be coupled to an analytic simulation of the low order errors associated with the location of the NGS, astronomers would have an easy way to assess trade-offs for a specific science case. This NFIRAOS tool may be just a component in more complete client instrument observation tools. (Ideally, the tool should be quantitative enough to be used as part of an instrument exposure time calculator. This should be possible.)

Discussion from Boyer: I think I agree that this AO guide star selection tool should be available as part of the high level set of tools used by an astronomer to prepare his observations. I think we

---

[2] One possible but undesirable mode for identifying tip-tilt stars is to do this at the telescope, using the acquisition camera that covers the 2 arcmin patrol field and is available whenever NFIRAOS is fed by the telescope. With a 30 m aperture, exposures amounting to only a few tens of seconds would be needed to reach a depth of J ~ 22. Automated software would have to be available to analyze each such image to identify stars (and distinguish them from galaxies). The benefits of this approach are that stars could be identified at the same epoch as the science observations. However, for those sources that do not have tip-tilt stars then precious set-up time will be lost. Furthermore, for observations that require large dither or offset motions (e.g. to monitor the sky background when the object being studied is larger than the science field or is located in a diffuse, high-background area, such as the inner regions of a galaxy) then one or more of the T/T stars may be offset outside of the NFIRAOS field of view. In this case new T/T stars must be used when observing the offset fields, and these objects can only be identified at the outset if a field that is larger than that passed by NFIRAOS is mosaiced. Due to these complications and the observing overhead involved, it is thought that method of acquiring guide stars will be forbidden by TMT.

need to add this tool in AOESW just to make sure it is included somewhere for cost estimates. At the moment I am not sure which software tools will be delivered by the instruments. I have already included a tool in OSW to access catalogs, surveys… for guide star selection but the tool does not provide all the functionalities that you are describing.

6. THE USER INTERFACE

It is desirable that all user observing tools, including the NFIRAOS user interface, have the same or similar user interfaces to maximize user efficiency. The NFIRAOS user interface will be the means of interacting with the AO Sequencer which controls the components of NFIRAOS and its interaction with the RTC. The user interface should provide measures of data quality assurance, including providing regular reports to future users for planning purposes and previous users for analysis purposes, detecting sudden changes in performance to enable timely corrective actions, and detecting gradual changes in performance to enable timely corrective actions (ref. REQ-1-OCD-2300). This system performance information will also be available to the TMT community through some on-line service. The user interface determines the look and feel of NFIRAOS. Two interfaces will be provided:

The engineering interface will display the detailed diagnostic information that is essential for detailed systems engineering and fault analysis. The interface will enable the movement of all components. The engineering interface will only be used by technically expert users, who will likely be TMT staff or from institutions involved with the development of TMT AO systems.

The science interface will provide very simple control of NFIRAOS and basic information that is required to assess the quality of correction provided by NFIRAOS. Whereas the engineering interface will be geared to low level functions (e.g. move such and such a component so-and-so microns), the science interface will focus on high-level procedures involving a number of low-level functions (e.g. 'clear the optical path', 'start AO guiding' etc). Sequences of steps that would be executed individually in the engineering interface will be combined as single functions in the science interface. The science interface will be used by visiting observers and/or TMT staff conducting day and night-time observations.

Discussion from Boyer: The AO Sequencer will be controlled by the TMT master sequencer, and a dedicated user interface will be available for the telescope operator. The plan is two have a UI for the telescope operator and another one for the staff astronomer or visiting astronomer. AO will be controlled by the telescope operator. At the moment we have an engineering UI per AO sub-systems (RTC, CC, …) but not a NFIRAOS global engineering user interface. There is a AO sequencer user interface which allows the execution of all procedures that you are describing (e.g. "clear optical path", etc.). I will add a global engineering user interface for NFIRAOS in the AO Sequencer scope because there 4 different sub-systems involved and it may be a good idea to have only one global engineering interface.

6.1 THE ENGINEERING INTERFACE

The engineering interface will be used during initial commissioning and acceptance tests, and throughout the lifetime of the instrument. It will allow any mechanical components to be moved or adjusted, with safety settings in place to prevent damaging the instrument. It is anticipated that the interface will consist of a number of pull down menus dedicated to various components. The interface will only be used by individuals who have a high level of technical competency with NFIRAOS. The engineering interface will have a look and feel that is common to all other related control systems on the TMT. Finally, it must be organized so that it can be controlled by a single individual.

6.2 THE SCIENCE INTERFACE

The NFIRAOS science interface is of great importance to operations. To prevent overwhelming the TMT night crew responsible for observing with NFIRAOS who may be pre-occupied with other observing tasks and who may have only limited experience with AO systems, the science interface must be a compromise between providing information that is essential for quickly identifying and de-bugging potential problems while at the same time providing a relatively simple look and feel. The look and feel of the science interface will be similar to that of the interfaces for all other TMT instruments.

The control menu will contain a bare minimum number of features, including configuring the light path for observations and a NFIRAOS guiding on/off toggle (i.e. activation/de-activation of tip-tilt motions and DMs). For most applications, the gain will be set automatically by software.[3] A possible model is the interface used by the Gemini MCAO system or the Pueo system on CFHT, where the user is presented with only a modest number of menus and diagnostic information. The user interace needs to be sufficiently simple that competency can be built up quickly, even among users with minimal knowledge of AO systems.

The science interface will display the following:

A graphical interface showing a simple schematic of the NFIRAOS light path. Controllable components, such as DMs, tip-tilt mirrors and filters, will be colour coded to show their status; for example, when the DMs are guiding on a source they may be colored green, but yellow when de-activated or flattened, and red when working close to their maximum stroke.

A graphical output showing the PSF and encircled energy as a function of angular offset from the center of the PSF delivered by NFIRAOS at a given central wavelength or in a certain filter bandpass. The PSF and encircled energy curves will be constructed from information supplied by the WFSs, and will be updated on a regular basis. A measure of anisoplanicity should also be provided, preferably as the PSF and encircled energy at some distance off axis from the target. This information will be of prime importance for some observing modes, such as IRIS with IFU, as there may not be bright stars in the small science field, which makes it difficult to judge delivered image quality purely from the data recorded on the science detector. The interface would have the ability to warn the user if the delivered image quality does not meet a specified level (e.g. if the Strehl ratio is lower than the value needed to obtain scientifically useful data). This will be especially useful on nights with variable seeing conditions.

Disscussion: The telemetry needed for PSF reconstruction will be saved for determining the PSF in post-processing (not real time). However, it would be useful if there were some real time indication of the expected image quality.

An image showing the actuator motions on the DMs would be useful. This will allow the user to assess quickly if there are problems with the optical alignment, which will cause non-uniform illumination of the DMs, poor seeing conditions, or problems with the telescope optics. Also, a tool for monitoring the WFSs would be useful. A vector diagram representing the slopes of the WFSs could highlight any persistent non-null slopes being measured. Co-added stacks of WFS images could be useful for visually identifying if there is a non-uniform illumination on any of the WFSs.

7. NFIRAOS OBSERVATION SEQUENCES

[3] An engineering control menu may also allow for the gain of the correction system to be set manually by individuals who have a high level of technical competency with NFIRAOS.

The OCD requirements on observing efficiencies dictate that the entire observatory adopt a common workflow for science acquisition as set out in the Observation Workflow for the TMT document. NFIRAOS will comply with this workflow. Because NFIRAOS is only one subsystem, there are redundancies in the Observation Workflow as it relates to NFIRAOS (e.g., whether or not the NGS is the science target will not affect the workflow of NFIRAOS). In this document, we describe the unique workflows of NFIRAOS as laid out in the TMT Observation Workflow Document.

7.1 Initialization

Before beginning nightly astronomical observations, NFIRAOS will be initialized. Sensors, DMs, motors, software systems and interfaces need to be initialized before observations can begin.

7.2 NGS Acquisition

- The AO Sequencer initializes NFIRAOS
  - The ISFM is moved into the Acquisition Camera position
  - The NGS starts follow mode which moves the Visible WFS bench gimbal mirrors to the position of the NGS (position provided by the TCS)
  - The NGS WFS ADC starts following (rate set by airmass information from TCS)
  - Set the Visible WFS bench selection mechanism to feed 95% of light to NGS WFS and 5% of light to HOL TWFS.
  - Configure RPG module for NGS operation and start computing AO RTC reconstructor
- Did NGS WFS acquire NGS?
  - Read NGS WFS frame at minimum frame rate (10 Hz)
  - Compute the number of illuminated subapertures (by comparing subaperture intensity to threshold)
  - If all subapertures are illuminated, the NGS WFS has acquired the NGS
  - The subaperture intensities would be compared to the expected magnitude of the NGS. If there is a discrepancy, the user is warned of this difference. Regardless of whether a warning is issued, the exposure time will be set automatically.
- If NGS WFS did not acquire NGS, use acquisition camera
  - Take acquisition camera frame using appropriate exposure time as defined by user.
  - If using an automatic mode, a dedicated algorithm will identify the NGS. If using a manual mode, the user will identify the NGS (probably by dragging a box around the object).
  - The OCS asks the TCS to perform a blind offset based on the expected coordinates of the NGS and its position in the acquisition camera frame.
  - Return to step above, to determine if NGS WFS has acquired the NGS
- AO Sequencer configures NFIRAOS for client instrument observations
  - The ISFM is moved into position to feed the appropriate client instrument

    - The NGS and HOL TWFS integration times are adjusted based on the apparent brightness of the NGS
- Observation begins
    - The AO sequencer closes the NGS AO loops.
    - Background tasks and optimization loops begin. Commands are offloaded to the TCS as needed.
    - NFIRAOS NGS Acquisition is complete

7.3 LGS Acquisition

- The AO Sequencer initializes NFIRAOS
    - The ISFM is moved into the Acquisition Camera position
    - The TWFS starts follow mode which moves the Visible WFS bench gimbal mirrors to the position of the TWFS NGS (position provided by the TCS)
    - The TWFS WFS ADC starts following (rate set by airmass information from TCS)
    - Set the Visible WFS bench selection mechanism to feed 95% of light to MOR TWFS and 5% of light to HOL TWFS.
    - Configure RPG module for LGS operation and start computing AO RTC reconstructor
    - Start the acquisition camera in continuous readout mode
- After the LGS asterism is propagated, the LGS centroid gain optimization loop and zoom offset computation are also started.
- Identify the OIWFS NGS and TWFS NGS (if different from OIWFS star)
    - The ISFM is moved into position to feed the appropriate client instrument
- After blind offset command sent to TCS, the AO sequencer closes the high order DM loops using the LGS WFS (to sharpen the images on the OIWFS).
    - The tomography and fitting step parameters will be updated as conditions change
    - Turbulence and AO parameters are computed
    - Telescope modes are computed and off-loaded
- Did MOR TWFS acquire NGS?
    - The MOR and HOL TWFS integration times are adjusted based on the apparent brightness of the NGS
    - If still not illuminated, TBD trouble shooting procedures will be employed
    - Offset NFIRAOS visible WFS bench gimbal mirrors
    - Measure MOR and HOL TWFS sky values
    - Offset gimbal mirrors back to NGS
    - Start TWFS LGS reference vector computation
- Observation begins
    - All remaining background and optimization loops are closed.

- NFIRAOS LGS Acquisition is complete

7.4 Seeing-Limited Acquisition

- The AO Sequencer initializes NFIRAOS
  - The ISFM is moved into the Acquisition Camera position
  - The TWFS starts follow mode which moves the Visible WFS bench gimbal mirrors to the position of the TWFS NGS (position provided by the TCS)
  - The TWFS WFS ADC starts following (rate set by airmass information from TCS)
  - Set the Visible WFS bench selection mechanism to feed 95% of light to MOR TWFS and 5% of light to HOL TWFS.
  - Configure RTC for Seeing-limited mode (includes flattening DMs)
  - Start acquisition camera in continuous readout mode
- Identify the OIWFS NGS and TWFS NGS (if different from OIWFS star)
  - The ISFM is moved into position to feed the appropriate client instrument
- Did MOR TWFS acquire NGS?
  - The MOR and HOL TWFS integration times are adjusted based on the apparent brightness of the NGS
  - If still not illuminated, TBD trouble shooting procedures will be employed
  - Offset NFIRAOS visible WFS bench gimbal mirrors
  - Measure MOR and HOL TWFS sky values
  - Offset gimbal mirrors back to NGS
  - Start TWFS LGS reference vector computation
- Observation begins
  - Seeing-limited acquisition is complete

7.5 Tracking

The AO sequencer will receive data streams from the TCS and will in turn keep the Visible Natural WFS gimbals, ADCs and pupil rotators following the sky and TWFS (and NGS WFS) guide star. The AO sequencer and all components can accommodate the motions associated with either sidereal or non-sidereal tracking.

7.6 Offsetting, dithering and nodding

NFIRAOS is required to:

- [REQ-2-NFIRAOS-3560] During an AO guider offset, the NFIRAOS must be able to offset with a positional error of at most 0.002 arcsec RMS on the sky.
- [REQ-2-NFIRAOS-3570] NFIRAOS shall be able to repetitively offset and settle between two or more given positions not farther apart than 1 arcsec, i.e. nod or dither, with a full nodding period of 10 seconds or dithering period of [number of end points] x [5 seconds].

- [REQ-2-NFIRAOS-3580] NFIRAOS shall be able to repetitively offset and settle between two or more given positions not farther apart than 10 arcsec, i.e. nod or dither, with a full nodding period of 20 second (nodding) or dithering period of [number of end points] x [10 second].
- [REQ-2-NFIRAOS-3590] NFIRAOS shall spend at least 80% of the period at the end points of nodding and dithering.
- [REQ-1-NFIRAOS-3594] During dithering, the trajectories of the gimbals shall be within 0.25 (TBC) arcseconds of that specified by the follow stream of time-stamped waypoints from the TCS. During dithering, the coordinated trajectories of the NFIRAOS gimbals and the telescope shall be within 0.5 (TBC) arcseconds. *The intent is to stay within the capture range of WFSs and to limit transients induced onto tip-tilt mirrors during AO guiding.*

7.7 Control Optimization

While observing, NFIRAOS will be performing a number of background tasks in order to optimize the control. During an exposure the seeing and transparency may change. NFIRAOS will update the control bandwidth, the exposure times, and centroid gain accordingly. It is required: [REQ-2-NFIRAOS-1290] The optical, wavefront sensing, and control subsystems of NFIRAOS shall be adjustable and/or adaptive to optimize performance as seeing, the sodium layer profile, and other atmospheric parameters vary during an observation.

8. NFIRAOS CALIBRATION

The OCD requires that the amount of night time needed for acquiring calibration data shall be minimized during steady-state science operations. In terms of the overall budget of how time should be spent, it has been set that NFIRAOS-specific calibration shall consume <0.7% of scheduled science nights[4]. Therefore, NFIRAOS has been designed to maximize the fraction of calibrations that can be performed during the day, independent of the telescope.

Discussion: At present this discussion mainly focuses on the calibration equipment with only a brief reference to the steps required to calibrate NFIRAOS. This section will evolve in conjunction with the development of the NFIRAOS calibration plan.

8.1 Flat Field and wavelength calibration

NFIRAOS shall pass flat field light and wavelength calibration standards from the NSCU to client instruments. The flat field lamp will also play an important role in NFIRAOS calibration, as it shall illuminate the deployable focal plane mask.

8.2 Deployable Focal Plane Mask

The NFIRAOS deployable focal plane mask will be back-illuminated by the NSCU with both arc lamps and broadband light (flat field lamps). Its purpose is to create reference asterisms for calibrating pointing models for the natural visible WFS gimbals, the instrument selection fold mirror, and for the client instrument OIWFSs and rotators. It also provides a reference for

[4] There are 3000 hours dedicated to science per year. Half of this time will be scheduled for AO observations, so 0.7% corresponds to 10.5 hours per year.

calibrating image distortion. Also, in conjunction with the pupil mask in the NSCU, the focal plane mask simulates pupil illumination onto the DMs and the WFSs. The focal plane mask will be fixed in position when it is deployed, but the tip-tilt stage will allow for short range movements of the images for, e.g., mapping the distortion on the OIWFS detectors. The focal plane mask will be curved to represent the telescope focal plane.

The focal plane mask will have one hole that has a diameter of the median seeing. This seeing-limited spot will illuminate the TWFS. It will be located just outside the IRIS IFU FOV. All other holes will be diffraction-limited. One diffraction-limited hole will be right on axis and will used as a reference for aligning NFIRAOS. All of NFIRAOS will be surveyed into place relative to this position. The mask shall have local dense grids of diffraction-limited holes covering IFU fields of view and imager fields. It will also have an array of diffraction-limited holes throughout a 2.6 arcminute field of view.

8.3 Pupil Pointing Calibration

NFIRAOS is required to have a means for internally determining a reference pupil image on the TWFS. This process will make use of the pupil mask in the NSCU, which has a rotating pupil mask and optics that can simulate the telescope illumination of DM0, and the deployable focal plane mask. Once the NSCU illuminates the pupil mask and the focal plane mask is deployed, the NGS gimbals. Then the registration of the DM and WFS is verified by applying waffle patterns to DM0. Finally, with flat DMs, the TWFS will measure reference slopes (or subaperture illumination levels) for different pupil rotations.

The NFIRAOS TWFS processing computer shall measure on-sky pupil magnification and differential magnification at 0 and 45 degrees with respect to the reference image. Pupil magnification is estimated on-sky based upon the change in illumination in three sets of opposing edges oriented at 0, 45 and 90 degrees on the TWFS CCD. It is related to plate scale and will be a useful diagnostic. Note however, that offloading of telescope plate scale modes will be accomplished by projecting the DM figure onto these modes, for the purpose of maximizing DM stroke available for atmospheric correction. While the frequency of this calibration procedure is still TBD, it is likely that it will occur infrequently (i.e., less than once a month).

8.4 Source Simulators

NFIRAOS includes simulated NGS and LGS sources. These can be deployed at the NFIRAOS focal plane. Most of the sources from these simulators will be at fixed locations in the FOV (there will be a single on-axis NGS source with a small patrollable range). The LGS source simulator will produce 6 simulated LGS at range distances between 85 and 235 km. The intensities of these LGS sources will be adjustable with intensities which cause between 250 to 2000 photo-detections per subaperture pre frame on the LGS WFS. There will be a modest number of NGS sources including one on-axis and probably two additional rings of sources. The NGS sources will be broadband and have adjustable brightnesses to mimic stars between $16<m_J<22$ (and $12<m_R<20$ for the TWFSs).

The sources (NGS & LGS) will be used to characterize and calibrate system performance, system alignment, deformable mirror (DM) to wavefront sensor (WFS) influence functions, WFS detectors, and non-common path aberrations between the wavefront sensing and science optical paths. These sources can be used with the turbulence simulator to allow for a full simulation of NFIRAOS behavior in closed loop.

Discussion: How best are WFS detectors calibrated when lenslets are present? Is flat-fielding possible and useful?

8.5 LGS DEFORMABLE MIRRORS

The DMs in the LGS WFS assembly remove telescope and NFIRAOS optics aberrations from sources at 85 – 135 km. These DM shapes are learned in a boot-strapping method. We have initial DM maps obtained from ray traces of the telescope plus NFIRAOS. With these initial shapes applied (for NFIRAOS plus its LGS sources at first), NFIRAOS generates a flat wavefront measured with the HRWFS. The DM shapes are then adjusted to center the LGS spots in the subapertures. Applying these offsets to the baseline ray-tracing generated DM shapes for TMT plus NFIRAOS, the procedure is now repeated on-sky now using phase diversity measurements from IRIS.

Discussion: Will local LGS WFS figure sensors be needed for these DMs?

8.6 TURBULENCE SIMULATOR

NFIRAOS will include a phase screen that in conjunction with the two DMs is capable of reproducing the typical turbuence above Mauna Kea (reproducing r_0, θ_0 and θ_2). The phase screen will be deployable in the main OAP relay.

8.7 HIGH RESOLUTION WAVEFRONT SENSOR

NFIRAOS will have a 120x120 high resolution wavefront sensor (HRWFS) mountable on an available port. This HRWFS will be a diagnostic alignment and calibration tool for NFIRAOS. It will be able to patrol the NFIRAOS FOV in XYZ. The final NCPA, however, will be measured from images taken with each client instrument.

Discussion: HRWFS was originally envisioned for the top port of NFIRAOS. If IRMS is slated for this port, HRWFS should be usable at the side port as well. The difference in gravity vector will need to be accounted for in the design.

8.8 NON-COMMON PATH CALIBRATION

The NFIRAOS field dependent NCPA calibration procedure will also be achieved using boot-strapping. First, using the NSCU sources and the internal LGS source simulator, NFIRAOS will generate a flat wavefront on the HRWFS. The MOR and HOL TWFS will then record slope offsets with respect to this flat wavefront. On sky, these offsets should be close to the final truth, in that all new aberrations are common path. However, there will be slightly different field dependent aberrations that arise when the optics are illuminated by real starlight (and laser beacons) versus light from the NSCU and LGS source simulators. Updates to the TWFS slope offsets can be learned from phase diversity measurements from IRIS.

9. PROCESSING DATA OBTAINED WITH NFIRAOS

9.1 DATA MANAGEMENT

It is required that “All TMT science instruments shall produce data with the meta-data necessary for later organization (‘find all science data associated with this science observation’), classification (‘identify the type of science data, e.g. environmental conditions, instrument, instrument mode, etc.’), and association (‘identify calibration data and processing algorithm needed to process these science data’)” [REQ-1-OCD-2350]. NFIRAOS will be required to produce TBD status and diagnostic telemetry for the purposes of performance monitoring and failure analysis. A TBD subset of these data shall be captured and stored locally for at least one (1) year. This subset shall include both low-level (e.g.NFIRAOS enclosure temperature) and high-level (e.g. delivered image quality) information. Two copies shall be maintained with enough physical separation that one copy will survive in the event of a local catastrophe (e.g. fire). Survival requirements related to major earthquake survival are still TBD. The merits and costs of a permanent off-site copy shall be analyzed during the data management design phase.

For NFIRAOS, the most important data to be saved relates to the PSF. The PSF, reconstructed from WFS telemetry, will be generated from a post-processing of the RTC real time data and it will then be saved with the science data. The low rate telemetry will be stored in the TMT engineering data base. High speed real time storage of telemetry is available for debugging purposes as well as for PSF post-processing.

9.2 Data processing

The operational considerations for NFIRAOS extend past the mechanics of data acquisition and management. As with all facility instruments, NFIRAOS must log information while it is operating that will be used by the astronomer during data reduction and by engineers for performance analyses. A NFIRAOS user will require the following information:

- Basic information about the configuration of NFIRAOS while the data were recorded. For example, a list of any neutral density or color filters that were in the light path, and/or the gain of the control loop. It is anticipated that information of this nature will be saved in the header of all data recorded using NFIRAOS.
- PSF information. Some of the basic operational modes of instruments that will be used with NFIRAOS (e.g. the IFU in IRIS and NIRES) will have a small field of view, and there is only a slight chance that reference stars that are bright enough to be used to empirically measure the PSF will be sampled. Hence, it is crucial that NFIRAOS provide PSF information (available in post-processing, not real time), which can be obtained from the RTC real time data. This information will not be restricted to the on-axis case, but will also give guidance as to how the PSF varies across the field.[5]
- WFS signals. The signals from the WFS should be logged. While this information may not be of interest to the typical astronomer, it will be useful for long term statistical studies of atmospheric characteristics and monitoring the optical throughput of NFIRAOS, which in turn will be of use for developing future AO systems and improving or cleaning NFIRAOS.

  Discussion from Boyer: The RTC telemetry storage is 90TB so it is limited to a few nights of operations. There is no tool planned to analyze the data in a systematic manner at the moment. I suppose such functionality could be added to the PSF Reconstructor.
- Environmental Information. To make full use of the scientific capabilities of the TMT, it is anticipated that atmospheric properties will be monitored during the night. Any information of this nature, such as the C_N^2 profile, should be made available to NFIRAOS users.

[5] While separate reference fields may be observed to monitor the PSF, this is not a foolproof technique for assessing the PSF, as image quality can vary with time and location on the sky. In any event, it is anticipated that for the very faint objects that are the intended targets of the TMT, it will be necessary to spend a considerable period of time integrating on source. It may also prove useful to not only provide a single, time-averaged PSF for an observation, but also the range in PSF properties, to assess the range in variation in the seeing.

10. COOLING NFIRAOS

The ORD states that "NFIRAOS shall not increase the (inter-OH) background by more than 15% over natural sky + the telescope with an assumed emissivity of 5% at 273 K" [REQ-1-ORD-3660]. To meet this requirement, the NFIRAOS optical enclosure must be cooled to -30 C and held at this temperature. The NFIRAOS Conceptual Design Report estimated a cool down time of about nine hours, based on the thermal properties of the elements within the optical enclosure. This cool down time will be achieved with the combined use of refrigeration air handling units blowing cold air over the optical elements, forced thermal convection, and thermal conduction through the cooling of a metal shell embedded within the enclosure wall. There are four functional phases of the optical cooling system: the Cool-down Phase, the Standby Phase, the Optical Observation Phase and the Warm-up Phase.

Discussion: Details in this section will change based on the new design, but NFIRAOS will still be held at -30 C.

10.1 COOL-DOWN PHASE

During the cool-down phase, NFIRAOS is thermally prepared for science operations. The optical elements within the enclosure are cooled to -30 C. At the beginning of the cool-down phase, all elements of NFIRAOS are powered off and at the telescope enclosure temperature. The enclosure is purged with dry air. The cool-down phase is initiated when:

- The Air-Handling Units (AHUs) within the NFIRAOS optical enclosure are cycled on for full cooling
- The optical enclosure cold wall is cooled
- The interior point source cooling is modulated near full capacity.
- At this stage, the AHUs establish the cooling rate, and the cold wall and internal point source are modulated to prevent over cooling of these elements
- The external electrical equipment and the electrical enclosure on the Nasmyth platform are powered on and in a stand-by mode. The DM high-voltage amplifiers remain powered off.

10.2 STANDBY MODE

During the standby phase, the NFIRAOS optical system is not functioning but is ready to resume operations. The temperature is held at -30° C, and the cold wall of the optical enclosure operates at the same capacity as during the optical observational phase (at slightly lower capacity as during the cooling phase). The interior point source elements receive full cooling as needed while the exterior point source cooling along with electrical enclosure on the Nasmyth platform are in a stand-by mode. Within the optical enclosure, the AHU is cycled off, and no power or refrigerant flows to the unit.

10.3 OBSERVATION MODE

During the optical observation phase, the optical elements within the enclosure are at a uniform temperature of -30° C, operating at full functionality, and the supporting electrical equipment power is on. The cold wall of the optical enclosure operates at a reduced capacity relative to the cool-down phase, and keeps the interior at -30° C. The interior and exterior point source cooling units along with the electrical enclosure on the Nasmyth platform all function at full capacity.

Within the optical enclosure the AHUs are cycled off, and no power or refrigerant flows to these units.

10.4 Warm-up Phase

In order to service the optics, the enclosure will have to be warmed up above the dome dew point before being opened. The air handling units will include electric heaters that will accelerate warm-up, although forced dry air could also be used. It is expected that warm up will take several hours. The cold wall will be allowed to passively warm. All interior and exteror point source cooling units will be turned off.

11. INSTRUMENT SWITCH

NFIRAOS is required to be able to physically switch client instruments on its output without warming it above the ambient dew point. Most of the work associated with physically switching instruments concerns only the client instruments. However, there are issues associated with keeping NFIRAOS at temperature which we address here. Physically switching instruments will be a task performed during the day (and will most likely be a seldom occurrence). To make this switch:

- Remotely activate an uninsulated gate valve located right before the instrument interface. The purpose of the gate valve located on each of the output ports is to provide a temporary barrier to ingress of dust, moisture and heat into the Optical Enclosure. Electrical switches on the gate valve motor will indicate whether it is fully open or fully closed.
- If no instrument is currently mounted on the port, manually remove an insulated port plug. The insulated plug provides a semipermanent barrier to the interior of the NFIRAOS optical enclosure. Otherwise remove current instrument.
- Install the new instrument or manually add an insulated port plug. The plug will be attached to the instrument interface using the same attachment points (TBD) as the instruments.

12. ACCESSIBILITY & MAINTENANCE

12.1 Accessibility

12.1.1 Electronics Enclosure

Access to the electronics enclosure will be straightforward, as it is located on the Nasmyth platform. Two entire sides of the enclosure consist of hinged doors, which open to provide unimpeded access to the front panels of the electronics racks inside. The interior portion of these racks, the connectors and cable runs, will be accessed via a corridor down the middle of the enclosure. This corridor is accessed at one end of the enclosure by a hinged door.

In addition to the main enclosure, there are several small cabinets needed for local placement of electronics, on the outside of the main optics enclosure of NFIRAOS. These will have removable covers and will be accessible using an articulated boom lift.

12.1.2 Optics Enclosure

Access to the optics enclosure is limited because NFIRAOS will be kept at a -30° C operating temperature. The optical enclosure will need to be warmed, and the relative humidity inside and outside deemed safe before access to the optics enclosure will be granted.

Access to the optics enclosure of NFIRAOS is constrained by APS (later, by PFI or other instruments), the telescope structure and by the client instruments. The top enclosure panels of NFIRAOS will be removable but it is expected that this feature will be exploited for exceptional maintenance only, for example removal of large components such as DM0. Many of the internal components of NFIRAOS will be located far inside the enclosure and consequently not reachable by personnel standing in an articulated lift or manbasket beside the enclosure. It will be necessary to design and deploy temporary personnel access fixtures that allow personnel to enter the optics enclosure and get close to internal parts requiring maintenance or repair.

A narrow deck inside the flank of NFIRAOS would provide access to a kneeling platform, which a person could use to position themselves above the optical bench to service a component inside NFIRAOS. The second type of fixture, a horizontal pulpit, would permit someone to lie above a component and work on it from above. Both these fixtures would be attached to NFIRAOS and accessed from an articulated boom reaching up from the Nasmyth platform, or from a temporary scaffold erected beside NFIRAOS.

Some routine servicing activities may be possible without entering the optics enclosure. Entrance window cleaning could be performed by personnel standing on a narrow deck at the front of NFIRAOS, using a CO_2 snow cleaning wand. Since access to the internal optics is impeded by the need to warm up the enclosure and remove panels, snow cleaning of internal optics may be facilitated by a built-in CO_2 manifold with fixed cleaning nozzles aimed at various optics. Entrance window cleaning could be performed by personnel standing on a narrow deck at the front of NFIRAOS, using a CO_2 snow cleaning wand.

Discussion: Will remote cleaning facilities for NFIRAOS optics be designed?

12.2 Maintenance

12.2.1 Preventative Maintenance Monitoring

NFIRAOS will monitor the condition of major components through the use of mechanical and/or electronic wear and performance indicators. This information will hopefully indicate when major components will need to be replaced or fixed and allow for scheduled, rather than emergency maintenance. To further this goal of performing preventative maintenance, NFIRAOS will comply with the TMT maintenance plan which includes:

- Comprehensive problem reporting, tracking, and management system
- Work order driven preventive maintenance support system (usually known as CMMS for Computerized Maintenance Management System).
- Warehouse inventory and property control
- Document control center

12.2.2 A Preventative Maintenance Schedule

This schedule will likely be tied to the running of the diagnostic checks outlined above. The hygiene of optical surfaces will be of critical consideration for planet search programs. The schedule will have operational implications. In particular, because NFIRAOS will be operated at a temperature that is below ambient, maintenance will be like that of a cryogenic instrument. There will be a warm-up period prior to performing maintenance. Also, the components will be tuned to work at a certain operating temperature, and system performance will suffer if the temperature varies by some amount (TBD). Consequently, there will then a cool down period following maintenance when NFIRAOS will not be available for use.

12.2.3 Cleaning the NFIRAOS Entrance Window

NFIRAOS is required to make provisions for frequent cleaning of the optics to preserve their low emissivity and high reflectivity or transmissivity. Actual cleaning frequency will depend on site characteristics, but is likely to exceed 1/month. For NFIRAOS, that means that personnel need good access to the NFIRAOS entrance window. Entrance window cleaning could be performed by personnel standing on a narrow deck at the front of NFIRAOS, using a CO_2 snow cleaning wand.

12.2.4 Cleaning the NFIRAOS Internal Optics

It is unlikely that internal optics will need to be cleaned often. But since access to the internal optics is impeded by the need to warm up the enclosure and remove panels, snow cleaning of internal optics may be facilitated by a built-in CO_2 manifold with fixed cleaning nozzles aimed at various optics.

12.2.5 Removing Instrument Selection Fold Mirror

To remove the ISFM, NFIRAOS would first be warmed to ambient temperature and the side port client instrument would be removed, along with enclosure panels near the side port. After the fasteners securing the ISFM are removed a spreader bar and yoke would be used in conjunction with one of the domemounted cranes. The yoke is required to permit a lifting sling to enter the optics enclosure of NFIRAOS without interference by the upper client instrument. Once the sling is attached to the ISFM, it would be delicately extracted from the enclosure and moved to a suitable location.

Discussion: This section may have to be updated based on the latest AIV story boards.

12.2.6 Removing Tip/Tilt Platform

Another example of component removal is the procedure for the tip-tilt platform with DM0. After warming up of NFIRAOS and removing side and top enclosure panels, personnel using access fixtures will disconnect the electrical connectors from DM0 and unfasten it. In addition, the visible WFS fold mirror would be removed and hoisted away, clearing a path for the tip-tilt platform to be lifted clear of NFIRAOS. This, and other, servicing procedures may be facilitated by the addition of local servicing equipment permanently attached to NFIRAOS.

12.2.7 A Clean Maintenance Environment

It is anticipated that all maintenance will be done *in situ* on the Nasmyth platform. To meet emissivity specifications, the hygiene of the optics is of critical importance, and a clean environment will be necessary. On Keck, a portable clean room has been erected around the AO system on the Nasmyth platform to provide such a clean environment. Space should therefore be available on the Nasymth platform around NFIRAOS to allow such a structure to be erected.

13. ENVIRONMENT, SAFETY AND HEALTH (ES&H)

It is imperative that a comprehensive environment, safety and health (ES&H) program following international standards be implemented during all phases of TMT Construction and Operations. NFIRAOS shall comply with REQ-1-OCD-1000: “The TMT ES&H program has the specific objectives to prevent personnel injury or loss of life during all phases of the TMT project and TMT operations; to prevent environmental contamination during the construction, shakedown, or operation of TMT; to prevent damage to equipment caused by accidents during all phases of the project; to comply with all national, state and local laws, rules and regulations."

Throughout TMT, including NFIRAOS, the safety priorities will be: 1) protecting people, 2) preventing damage to equipment caused by accidents and 3) protecting data.

NFIRAOS hazard analysis and safety practices will be governed by the following order of precedence (ref. REQ-1-OCD-1020):

- Design for Minimum Risk: The primary means for mitigation of risk shall be to eliminate the hazard through design.
- Incorporate Safety Devices: Fixed, automatic or other protective devices shall be used in conjunction with the design features to attain an acceptable level of risk. Provisions shall be made for periodic functional checks as applicable.
- Provide Warning Devices: When neither design nor safety items can effectively eliminate or reduce hazards, devices shall be used to detect the condition, and to produce an adequate warning to alert personnel of a hazard. Devices may include audible or visual alarms, permanent signs or movable placards.
- Procedures and Training: Where it is impractical to substantially eliminate or reduce the hazard or where the condition of the hazard indicates additional emphasis, special operating procedures and training shall be used.

13.1 SAFETY DEVICES

NFIRAOS requires an interlock system to help provide a safe working environment for observatory personnel and to protect some of the subsystems.

- Interlocks on doors and port plugs shall prevent opening them if the optics temperature is below the dew point of the air outside the NFIRAOS optics enclosure.
- Interlocks shall shut down the DM high voltage if the DM temperature is below the dew point in the optics enclosure near to the DM.
- Interlocks shall shut down the DM high voltage if the DM temperature is below the ambient dew point and the doors are open. This requirement is to guard against the scenario where NFIRAOS is under test with doors open and the humidity rises in the outside air. The intent is to shut down prior to moist air entering NFIRAOS and damaging the DMs.

The interlock system will be PLC based and may share the same PLC as the Laser Interlock System (LIS). The LIS shutters the laser if the LGS WFS loses signal. The PLC will be installed in the NFIRAOS electronics cabinet. It will require its own set of humidity, temperature and oxygen sensors installed in the optics and electronics enclosures. O_2 sensors are required in case there is a refrigerant (R507) or glycol leak in either enclosure or in case anything other than dry air (e.g. dry N_2) is used to flush the optics enclosure. The interlock system will "lock" all access panels on the optics enclosure when the high voltage (HV) is on, or if O_2 levels are low, or if the optics temperature is below the dome dew point. Locking could mean physically preventing the panels from being opened. Or, it could mean displaying warning lights next to the panels and triggering an audible alarm if a panel is opened. The system will turn off the HV if a panel is open or if the humidity inside the optics enclosure rises above the dew point. The system will also instruct the motion control computer to stop all motors if a panel is open. Some engineering means (tags and keys) of safely defeating this interlock will be required to allow servicing. The interlock system will shut down high power dissipation subsystems in the electronics enclosure if the temperature rises above a safe level.

NFIRAOS will also have Emergency Stop buttons located at the Optics enclosure, at the laser WFSs, and at the electronics enclosure. These Emergency Stop buttons shall stop all motors and shut down the high voltage (>250 V) supplies.

13.2 WARNING SYSTEM

There shall be an oxygen monitor inside the NFIRAOS optics enclosure. This is a safety measure in case refrigerant leaks reduce oxygen inside the optical enclosure thereby posing a risk.

Temperature monitoring, logging and alarms shall be present at:

- mechanisms (e.g. motors, actuators, DMs)
- Multiple places on any optical benches
- outside window and inside above window
- detectors (e.g. WFSs).
- coolant inlet, coolant outlet and free-standing within each enclosure (opto-mechanical and all electrical)

Hardware shutoffs with manual resets shall exist where damage to equipment may result in the event of temperature extremes. These extreme temperature extremes could be either too high or too low. Manual reset refers to requiring human intervention to reset. This may be, for example, a remotely controlled power switch.

13.3 OVERRIDE SYSTEM

It will be possible to control mechanisms even while the optic covers are open only if a local override is enabled. This override may take the form of a dead-man switch.