NOAO Extra-Wide Field Infrared Imager (NEWFIRM)

Functional Performance Requirements Document (FPRD)

Prepared by the

National Optical Astronomy Observatories

Engineering and Technical Services Group

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Document Acceptance and Concurrence

This document represents the current understanding of the capabilities and performance of the NEWFIRM instrument system to be designed, fabricated, tested, delivered and commissioned by the National Optical Astronomy Observatories for use on the 4-meter telescopes at Kitt Peak National Observatory (KPNO) and at Cerro Tololo Inter-American Observatory (CTIO).

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1. Purpose of this Document

The purpose of the Functional and Performance Requirements Document (FPRD) for the NOAO Extremely Wide-Field Infrared Imager (NEWFIRM) is to provide engineers with the fundamental NEWFIRM requirements which are used to design, fabricate and test the instrument. Subsequent system specification, design, fabrication and test documents, interface control documents, operating manuals and maintenance manuals shall be derived from and traceable to this document.

The NEWFIRM design derived from this document will serve completely the requirements of this document. This means that every feature of NEWFIRM will be traceable to a requirement in this document, and there shall be no feature of NEWFIRM that is not required by and traceable to this document. The NEWFIRM instrument will be designed, fabricated and tested in stages with a design review at the completion of each stage. Comments from the review committee will be incorporated into the instrument design, and into the instrument requirements as necessary. This FPRD, therefore, will be upgraded as necessary, and the new and/or modified requirements will be flowed down into the instrument specification and design documents until Design Freeze.

NEWFIRM reviews will include a Conceptual Design Review (CoDR), a Preliminary Design Review (PDR), a Critical Design Review (CDR) and an Operational Readiness Review (ORR). Design Freeze will be imposed after the comments from the PDR have been incorporated into the various system requirements and design documents.

2. Applicable Documents

"Draft Concepts for the NOAO Extremely Wide-Field Infrared Imager (NEWFIRM)" from the NEWFIRM page on the NOAO website (www.noao.edu)

NOAO Extremely Wide-Field Infrared Imager (NEWFIRM) functional Operational Concepts Definition Document (OCDD), NOAO Document No. XXXX, July XX, 2001

3. Terminology and Acronyms

Acronyms

2MASS	2-Micron All Sky Survey
A/D, ADC	Analog to Digital Conversion
AR	Anti-Reflection
AURA	Association of Universities for Research in Astronomy

CCD	Charge-Coupled Device
CD-ROM	Compact Disk – Read Only Memory
CDS	Correlated Double Sampling
CIRIM	CTIO Infrared Imager
CTIO	Cerro Tololo Inter-American Observatory
DAT	
DMA	Direct Memory Access
DPG	NOAO Data Products Group
FLAMINGOS	University of Florida 2K x 2K infrared imager/spectrograph
FOV	Field of View
FTP	File Transfer Protocol
FWHM	Full Width at Half Maximum
GUI	Graphical User Interface
ICE	IRAF Control Environment
IPAC	Instrument Projects Allocation Committee
IR	Infrared
IRAF	Image Reduction and Analysis Facility
ISPI	Infrared Side Port Imager
KPNO	Kitt Peak National Observatory
MOSAIC	8k x 8k Prime Focus CCD Imager (KPNO and CTIO)
NB	Narrowband (filter)
ND	Neutral Density (filter)
NEWFIRM	NOAO Extremely Wide-Field Infrared Imager

NOAO	National Optical Astronomy Observatories
OCDD	Operational Concepts Definition Document
RMS	Root Mean Squared
WB	Wideband (filter)
α, δ	Right ascension, declination

4. NEWFIRM Top Level Performance and Requirements

A companion document, the NEWFIRM Operational Concepts Definition Document (OCDD), describes the science applications and operational modes of the NEWFIRM instrument. These applications and operational modes lead to the following instrument system requirements.

In summary, NEWFIRM will be a facility-level infrared imager suitable for a broad range of science programs. It will provide infrared image data (no spectroscopy) at moderate spatial resolution over a large field of view on the NOAO 4-m telescopes at KPNO and CTIO. The instrument system includes pipeline data processing capabilities suited to its high bit rate data stream.

4.1 Image Quality

The instrument optical design, plus tolerances for fabrication and for operational variables such as flexure, must not degrade the telescope's delivered image quality by more than **[TBD]**%. This shall be taken as image FWHM of 0.67 arcsec in the K band, 0.80 arcsec in the H band and 0.85 arcsec in the J band.

4.2 Field of View and Sampling

The total, unvignetted NEWFIRM field of view shall be 30 x 30 arcmin ($\pm$ 10%), or discrete sub-areas summing to the same total area. The sampling shall be 0.44 arcsec per pixel ($\pm$ 10%). These values are subject to scientific and engineering performance trades, and shall be fixed by Preliminary Design Review.

4.3 Wavelength Coverage and Spectral Resolution

The instrument shall operate over the infrared wavelength range of 1.0-2.4 μm, with spectral resolutions of ≈5 to ≈100 defined by fixed infrared bandpass filters.

Resolution of ≈5 corresponds to the common broad bandpass filter values J, H, Ks and K. Wavelength ranges for these bands are shown in Table I below. Narrowband filter resolutions of ≈100 are desirable for isolating spectral lines. The maximum resolution to be supported by

NEWFIRM involves trades between scientific performance (increasing line-to-continuum ratio), optical design (maximum acceptable angle of incidence of light on the filter) and subsequent impacts on dewar design, and filter manufacturability. These trades shall be fully explored by Preliminary Design Review.

Table I: Central Wavelengths and FWHMs for the J, H, K and Ks Bands

Band	Central λ (μm)	FWHM (μm)
J	1.25	0.3
H	1.65	0.35
K	2.20	0.40
Ks	2.15	0.30

4.4 Sensitivity

Sensitivity shall be best effort, with high weight in design trades. The optical design shall use the minimum number of optics necessary to achieve required imaging performance. Optics shall use broadband antireflection coatings. Filters shall be the highest feasible transmission. Detectors shall have the highest photon-to-electron conversion efficiency consistent with procurement within project schedule and budget. The throughput goal is 30%, from photons at the telescope focal plane to electrons at the detector.

4.5 Focal plane location

NEWFIRM shall operate at the Ritchey-Chretien ("Cass") focus of the NOAO 4-m telescopes. NEWFIRM shall fit within the existing Cass cage envelope. Installation shall be accomplished through the Cass cage installation portal. The NEWFIRM instrument construction shall allow it to be installed intact or piecewise through the portal using an instrument stand or an installation stand built for or modified for the NEWFIRM instrument.

NEWFIRM shall incorporate a dedicated guider. Instrument rotation is not required. The existing 4-m rotator-guider units may be left in place, or removed, as instrument design and operational convenience dictate.

4.6 Operations

NEWFIRM will be installed on the telescope by NOAO technical and scientific staff. Once installed, the instrument will be used in a hands-on, interactive way both by experienced scientific users and by novices. It may be used in a highly automated fashion by technically competent but scientifically inexpert observatory staff. Modes of use are further discussed in the Operational Concepts Definition Document. The instrument shall present a user-friendly interface to a non-expert user, and the instrument/telescope assembly shall operate efficiently with internal safeguards to protect the instrument and telescope from harm. Present NOAO instruments (e.g. MOSAIC) provide examples of acceptable standards.

NEWFIRM shall be designed for a useful life of 10 years It shall be robustly built to withstand handling, temperature cycling, filter motions, transportation between sites, etc. for this period. Routine maintenance, including replacement of components with shorter lifetimes, shall be permitted as a design option.

4.7 Data Processing

The NEWFIRM instrument system shall include appropriate hardware and software for highly automated ("pipeline") image data processing. This shall include production of intermediate data products suitable for performance evaluation, and final data products suitable for delivery to a data archive. Development of this portion of the instrument system shall be the responsibility of the NOAO Data Products Group, with appropriate charges to and oversight by the NEWFIRM Project.

5. Optical Design and Performance

The NEWFIRM instrument shall be a refractive collimator-camera design with a single optical channel. Flat mirrors may be used for beam path folding to fit within the space envelope. The final focal surface shall be flat.

NOAO staff members shall develop an optical design and prescription. Performance, manufacturability and cost of optics shall be considered, as well as tolerances in construction and use. The design shall be suitable for use with the Mayall telescope at KPNO and with the Blanco telescope at CTIO. The project team shall perform an optical tolerance analysis of the instrument design and shall develop a tolerance budget, including fabrication, flexure, and thermal effects. Ghosting and stray light analyses shall also be carried out.

5.1 Wavelength Coverage

The instrument shall operate over 1.0 to 2.4 microns wavelength.

5.2 Spectral Resolution and Filters

Spectral resolution shall be: $5 < \lambda/\Delta\lambda < 100$, as per Section 4.3 above.

The instrument shall use only fixed bandpass filters and no dispersive elements. Filter design and construction shall be consistent with cryogenic use.

Optical image points far off axis correspond to collimated beams incident on the filter (near the pupil) at relatively steep angles. This may cause a shift of filter effective wavelength (or equivalently, a transmission loss at the wavelength of interest) for these points. Filter characteristics shall be specified so as to maximize field coverage for narrowband filters.

The filter complement for NEWFIRM shall include four wideband (WB) filters, J, H, K, and Ks (see Table I). A suite of narrowband (NB) filters appropriate for initial science programs shall be identified and provided. This may include, for example, 1.64 μm [Fe II], 2.12 μm H_2, and 2.17 μm Brackett γ plus appropriate continuum filters. A blocked (opaque) filter position shall be provided for calibration. If the filter mechanism permits insertion of two filters in series (a goal), then one or more neutral density (ND) filters may be provided to extend the instrument's dynamic range to brighter objects for calibration purposes. The total filter count supportable as a science configuration shall be 15 filter positions including the blocked position.

5.3 FOV and Sampling

The instrument shall image a field of 30 x 30 arcmin, or subfields arranged symmetrically about the optical axis which sum to the same equivalent area. Tolerance on this requirement is ± 10% of linear field size. The sampling shall be 0.44 arcsec per pixel, ± 10%, consistent with the field size, to match an anticipated 4096 x 4096 or equivalent detector array geometry.

5.4 Image Quality

Optical performance shall deliver 80% ensquared energy within a 2 x 2 pixel area across the entire FOV in any of the JHK bands. This performance shall include telescope diffraction effects and misalignments within the tolerance budget, but it shall not include effects external to the optical system (atmospheric aberrations, mistracking, wind shake, etc.). Telescope refocusing between bands is permissible to achieve best performance.

The tolerance budget shall include the effects of geometric design, diffraction, alignment, flexure, and thermal variations. The thermal budget shall allow for image defocus due to lateral or longitudinal shifts of optical elements, or of the detector array induced by temperature gradients or temperature variations in the optical support assembly. It shall not include allowances for steady-state effects such as contraction of the opto-mechanical system upon cooldown. These effects shall be accommodated in the instrument detailed design. Table II gives an example of an image quality budget for an infrared astronomical imaging instrument. A similar table shall be defined for the NEWFIRM instrument.

Table II: Example Tolerance Budget for Image Quality*

Band	Final FWHM	Geometric Optical Design	Telescope Diffraction Budget	Alignment Budget	Flexure Budget	Thermal Budget
J	30 μm	24 μm	7 μm	10 μm	10 μm	7 μm
H	30 μm	24 μm	7 μm	10 μm	10 μm	7 μm
K	30 μm	24 μm	7 μm	10 μm	10 μm	7 μm

* Assumes 18 micron pixels and tolerances added in quadrature

5.5 Distortion

Geometric distortion across the FOV shall not exceed 2%, with 1.5% as a goal. Distortion shall be analytically expressible in (ρ, θ) coordinates and symmetric about the optical axis, which is assumed coincident with the detector array center.

5.6 Pupil Stop

The instrument optical path shall include a single fixed cryogenic pupil stop. Lateral aberration of the pupil image shall not exceed 3% of the pupil image diameter over the J, H or K bands, referenced to a pupil plane optimally placed for the K band. Longitudinal motion of the pupil stop to achieve this performance is not allowed.

The pupil plane shall be mechanically accessible for purposes of introducing a fixed stop. There shall be adequate mechanical room near the pupil for the insertion of filters.

5.7 Throughput

System throughput shall be best effort. All lenses and windows shall be broadband AR coated for 1.0-2.4 microns. Filters shall be specified for highest transmission consistent with adequate out-of-band rejection. Mirror coatings shall be chosen for highest reflectivity consistent with long service life in a vacuum cryogenic environment. Detector shall be the highest quantum efficiency devices available within constraints of project schedule and budget.

A throughput of 0.3 (input photons to output electrons) is a goal. This includes telescope mirrors, internal optics, filter, and detector conversion efficiency.

5.8 Stray Light Control

5.8.1 Scattered Light

The total amount of unstructured, diffuse scattered light illuminating the detector array with a given filter shall be <10% of the total amount of light in the pass band which enters the instrument within the science beam. Internal blackening, threading and baffling shall be used in the opto-mechanical design to minimize scattered light onto the detector array.

5.8.2 Ghost Images

Ghost images generated in the instrument optics shall have a maximum surface brightness (brightest pixel) $< 10^{-3}$ the maximum surface brightness of the parent source.

The science impact of ghosts depends on their size, location and intensity with respect to the source. Large faint ghosts may be preferable to compact bright ones. The optical designer shall confer with the project scientist regarding ghosting properties of the design and potential trades.

5.9 Calibration

There shall be one cold blanked (opaque) position in the filter complement. The instrument shall not incorporate any other on-instrument calibration.

5.10 Tolerancing

The optical design shall accommodate normal manufacturing tolerances of optical elements to meet performance requirements. Re-optimization of element spacings using as-received element prescriptions shall be done to achieve best performance.

The optical design shall not require excessively tight tolerances of the mechanical design, e.g. for alignment and flexure. The optical designer shall communicate closely with the mechanical design team to quantify and meet this requirement.

See also Sections 5.4 and 6.6.

6. Mechanical Design and Performance

6.1 Dewar

The optical elements shall be incorporated into a cold assembly supported within a single cryostat volume. This assembly also shall provide the interface to the detector package. It shall be designed to permit a one-time longitudinal respacing of the optical elements to permit optimizing the optical design performance with as-delivered optical elements. This may be done as a design change prior to fabrication, or permitted as an adjustment of the fabricated assembly. Active and passive radiation shielding and/or multilayer insulation shall be incorporated into the mechanical design for temperature control. Surface blackening, baffles, etc. shall be used to meet stray light and ghosting performance specifications.

Interface to warm electronics shall be via appropriate cables and vacuum-penetration connectors. The Dewar and/or its support structure may be used as a platform to provide mechanical support for warm electronics, consistent with results of mechanical and thermal analyses.

6.2 Telescope Interface

NEWFIRM shall attach to the telescope at the R-C focus via direct attachment of the instrument truss structure to the telescope mirror cell. The instrument shall interface to the telescope in a manner which permits angular boresight adjustment while maintaining rigidity between telescope and detector focal planes. The instrument shall be mountable on the telescope without requiring optical realignment, exclusive of boresighting as a unit to the telescope axis. The Dewar and any external components supported by it shall fit within the available volumes of the present Mayall and Blanco telescope Cass cages below the mirror cells. NEWFIRM shall be mounted by removal of the Cass cage bottom, as with other instruments.

An instrument handling cart and/or other fixtures shall be used to support and install the instrument in a controllable and safe fashion.

The fixed internal pupil stop shall be aligned with respect to the telescope to within 0.007 of the projected size of the secondary mirror. This alignment shall be repeatable, and lockable once achieved.

6.3 Flexure

The range of normal operating geometry shall be a zenith angle of up to 60 degrees at any azimuth. Extreme geometry shall be zenith angles between 60 and 75 degrees. Flexures refer to gravity-induced motions within the instrument, or between the instrument and the telescope interface. They do not refer to flexure of the telescope itself, such as sag of the telescope truss.

6.3.1 Pupil Flexure

The pupil image formed by the optics at the internal cold stop shall not wander with respect to the mechanical stop by more than 0.007 of the pupil image diameter over the normal operating geometry.

6.3.2 Pointing Flexure

The telescope focal surface, as reimaged onto the detector, shall not shift by more than 5 pixels between any two pointings anywhere within the range of normal operating geometry.

6.3.3 Tracking Flexure

The telescope focal surface, as reimaged onto the detector, shall not wander by more than 0.1 pixel over a 15 minute interval of continuous tracking, for telescope initial pointing anywhere within normal operating geometry.

6.3.4 Defocus Flexure

Flexure-induced defocus (longitudinal displacement of the optical elements due both to gravitational and to thermal contributions) shall not degrade the image at the detector array by more than 10% of the starting value of image FWHM during two hours of continuous tracking within the normal operating geometry.

Defocus within a bandpass shall be less than 10% of image FWHM for any two telescope pointings within thirty degrees of total angular separation.

Any position-dependent hysteresis of flexure-induced defocus shall be less than 0.1 pixel at the detector array.

6.4 Focusing

There shall be no provision for active cold internal focusing.

Telescope, pupil and detector image planes shall reach their design spacings upon cooldown of the Dewar to stable operating temperature. Provision shall be made for shimming of the detector mount and slight longitudinal adjustment of the cold pupil stop as iterated adjustments during the instrument test phase to achieve this requirement.

Approximate instrument focus with respect to the telescope shall be achieved by locating the Dewar longitudinally, via the telescope interface, with the telescope set to its nominal focus. Accuracy of this setting shall be **+/- TBD**.

The final working focus of the instrument Cass configuration shall be achieved by motion of the telescope secondary.

6.5 Collimation

There shall be no provision for active collimation of internal cold optics with respect to each other or to the telescope.

Collimation shall be achieved wherever possible by machining precision rather than by mechanisms or adjustments. Where an element adjustment is deemed necessary, its implementation shall allow the element to be pinned to a reference surface once final collimation is achieved and demonstrated. Transverse collimation (element displacements normal to the optical axis) shall be achievable and demonstrable at room temperature. Longitudinal collimation may be achieved by a warm/cold iterative process. If cold imaging performance is to be used as a collimation tool, it is required that cold observables, such as image shapes, displacements and fluxes, be related to element collimation in a way that is not degenerate and that does not require unachievable precision in practice.

6.6 Tolerancing

Mechanical stability requirements are dependent on the optical tolerance analysis. The total optical alignment tolerance accounting for small variable or unpredictable effects shall be budgeted among fabrication, initial alignment, flexure and thermal effects.

Repeatable, non-varying effects, such as parts shrinkage upon cooldown, shall be accommodated by design and by one-time adjustments during integration and test. These mechanical tolerance budgets are equivalent to the image quality error budgets in Sec. 5.4.

The thermal budget shall accommodate lateral or longitudinal shifts of optical elements or of the detector array induced by temperature gradients, temperature variations or uncertainty in coefficients of thermal contraction in the optical support assembly.

A format for the tolerancing budget is given in Table III.

Table III: Tolerance Budget Format Example

Optical System Element	Total Tolerance	Fabrication Budget	Alignment Budget	Flexure Budget	Thermal Budget
Collimator 1 tilt decenter despace					

6.7 Filters and Filter Handler

Provision shall be made for an assortment of wideband and narrowband filters that can be inserted and removed mechanically under cryogenic conditions.

6.7.1 Filter Position

Filters shall be located in a handling mechanism such that they can be placed very near the cold pupil stop. A goal is provision for two filters to be placed in series in the optical path. These need not be any two arbitrary filters from the total complement.

6.7.2 Filter Geometry

Filter diameter shall be dictated by the diameter of the caustic at the filter location, plus clearance within the cell, plus a mechanical edge allowance for mounting. Filter thickness shall be specified for mechanical safety and avoidance of any undesired optical effects. Filter geometry may be square or round, depending on fabrication choices. Filters may be implemented as monolithic units, or as mosaics of smaller pieces consistent with tolerances derived from the optical design.

6.7.3 Number of Filters

There shall be at least 16 filter positions allocated in the filter handling mechanism. This number allows for J, H, K and Ks WB filters, a cold blank (opaque beam block), one or more opens (no filter in the optical path), a neutral density filter, and the more commonly used NB filters.

6.7.4 Positioning Speed and Repeatability

Filter positioning speed shall be such that a change while observing, from one filter to any other arbitrary filter installed in the mechanism, shall be accomplished in 20 seconds or less.

Filter positioning shall be repeatable and stable with respect to the optical axis to 0.01 of the filter diameter. Clearance in the cell shall allow for this variation in positioning. Positional repeatability is more important than absolute centration so long as vignetting does not occur. Detent type mechanisms are preferred to continuous-positioning mechanisms.

6.7.5 Servicing

Provision shall be made for changing filters with minimum disturbance to the instrument. Filters shall be changeable without the need to realign any optical elements or the detector array to the instrument optical axis. Alignment of filters with respect to the pupil must be automatically recovered by reassembly after changing the filters. Servicing procedures must avoid the possibility of small parts such as screws being dropped inside the Dewar.

7. Cryogenics Design and Performance

7.1 Detector Array Operating Temperature and Temperature Stability

The steady state operating temperature of the detector array shall be between 77 deg K and 80 deg K, OR between 30 deg K and 40 deg K depending on whether the detector array is HgCdTe or InSb, respectively. The detector array material choice shall be made sufficiently early in the design phase that the cryogenic design for array cooling can be fixed to one of these temperature ranges.

The cryogenic design and detector array mount design must maintain the detector array temperature constant to $\pm$ **TBD** K per hour.

7.2 Cryostat Operating Temperature and Temperature Stability

The cryostat temperature requirement assumes that the detector array is sensitive to incident radiation to a longwave limit of 2.6 µm. A detector array with wavelength sensitivity above 2.6 µm shall be blocked with a cold, short pass filter just above its surface to restrict the wavelength band of radiation incident upon it. The transmission of any such blocker shall be included in detector QE and system throughput calculations or comparisons.

The instrument's cryogenic design must account for thermal gradients within the instrument and for thermal variations in the instrument's operating environment. The range of ambient temperature shall be assumed to be +20 deg C to –5 deg C.

The cryostat shall maintain an internal temperature such that the internal thermal radiation photon background incident on the detector array is less than the 1 sigma Poisson noise of the external background from source, sky and telescope within any filter. The background sky photon flux (photons per second per 0.44 x 0.44 arcsec pixel) for WB filters is given in Table IV.

Table IV: Background Photon Flux

Infrared Band	Photons sec^{-1} pix^{-1}
J	3.6.x.10^3
H	1.9 x 10^4
K	3.1 x 10^4
Ks	1.7 x 10^4

Temperature stability must be such that internal temperature variations produce DC signal differences between two succeeding frames less than 0.1 of the externally caused Poisson noise of the frame difference, for any filter.

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7.3 Cryogenic Infrastructure

Instrument cooling may be done using closed cycle helium gas refrigeration, or liquid nitrogen, or both. A goal is a single mode of cooling for both initial cooldown and steady state operation.

7.3.1 Closed Cycle Cooling

Implementation of closed cycle coolers shall be compatible with existing infrastructure on the Mayall and Blanco 4-m telescopes. If closed cycle cooling is chosen, then during the instrument design phase the engineering design team shall evaluate and mitigate the impact of cold head vibration on image quality, instrument mechanical functioning and other aspects of the instrument plus telescope.

7.3.2 Liquid Cryogens

If liquid cryogens are used for primary cooling in the NEWFIRM instrument, cold reservoir volumes and geometries shall permit retention of cryogen amounts adequate for 14 hours of instrument operation in the normal range of orientations of the Dewar (up to 60 degrees from zenith in any azimuth direction) once steady state operating temperature has been achieved. Operation includes meeting the temperature and temperature stability criteria in Sections 7.1 and 7.2. The cryostat shall use one or more cryogen tanks with fill and vent lines. These shall be capable of being filled with the instrument on the telescope (at zenith) and with the instrument in its handling cart. Cryogen boil-off shall be directed away from the instrument and from other equipment in the vicinity.

Instrument cooldown with liquid cryogens shall not require refills during the night subsequent to initial daytime cooldown.

7.4 Cooldown and Warmup Time

Cooldown to initial instrument operating temperature **(NEED VALUE)** shall take place within 24 hours as a goal, either on or off the telescope.

Warmup to ambient temperature shall take place within 24 hours of cryogen exhaustion or cold head turnoff, either on or off the telescope. Circulation of dry nitrogen gas and/or use of active resistance heating may be used to exhaust cryogens and speed the warmup to meet this requirement.

Warmup and cooldown shall be thermally managed so that outgassed or "getted" material is not deposited on the instrument's optical elements or the detector array.

7.4.1 Maximum Rate of Temperature Change

The rate of temperature change at the detector array during cooldown and warmup shall not exceed 0.25 deg K per minute.

The rate of temperature change of the optical elements during cooldown and warmup shall not exceed 0.5 deg K per minute.

Temperature sensors closely coupled to these elements and active heating circuits may be used to limit the cooldown and warmup rates to meet this requirement. Any active temperature control during cooldown or warmup shall be implemented by a self contained controller unit with battery backup.

8. Vacuum Design and Performance

8.1 Required Operating Vacuum

The NEWFIRM instrument's operating vacuum shall be 10^{-5} Torr or lower in any instrument orientation.

8.2 Vacuum Hold Time

After thermal and vacuum cycling during the NEWFIRM system integration and test phase, prior to delivery, the instrument shall maintain the vacuum specified in Section 8.1 for 30 days without warm or cold pump out, or other intervention.

8.3 Vacuum Infrastructure

Instrument vacuum shall be attained and maintained using an external, oil-free turbomolecular pump and a single pump-out port on the Dewar. This port shall be accessible with the instrument on the telescope or in its handling cart. The pump may be permanently mounted on the Dewar for operational convenience.

An adequate volume of a suitable getter material may be used to maintain the cold vacuum as per the requirement of Section 8.2.

The instrument design shall include provision for changing getter material by a minor incursion into the cryostat (warmed and pressurized) while mounted on the telescope or in its installation cart.

9. Electronics Design and Performance

9.1 Functional partitions

For purposes of this section, "electronics" shall refer to the following functions and related system components:

- Conversion of photons to electrons: the detector array(s)
- Electronic operation of the array(s), including voltages, clock signals, etc. necessary to integrate and retrieve signal charge and to convert it to digital form: the array controller
- Monitoring and control of instrument functions (e.g. filter motions) and status (e.g. internal temperatures): the instrument controller
- Two way communications with the observatory (telescope, dome, guider) and the astronomer user: the system manager

The "components" are identified here and discussed separately below for conceptual purposes only. No requirements are implied for the hardware realization of array control, instrument control, and system management.

9.1.1 Power Requirements

For all electronics, dual capability permitting operation with either 120 VAC, 60 Hz, single phase or 120 VAC, 50 Hz, single phase input power is required.

9.2 Detectors

NEWFIRM shall use a 4096 x 4096 element infrared array, possibly consisting of four 2048 x 2048 arrays. These may be packaged separately or as a set of mechanically closely spaced arrays forming a mosaic. The optical design and the detector array packaging choice are closely interrelated.

9.2.1 Performance Requirements

Table V gives the minimum detector array performance requirements that will satisfy the science goals of the instrument. The per pixel requirements are met by the largest arrays currently in use for astronomy, ALADIN (InSb, 1K x 1K) and HAWAII-1, HAWAII-2 (HgCdTe, 1K x 1K and 2K x 2K).

9.2.2 Mechanical Interface

The 4096 x 4096 package shall be removable and replaceable from the dewar without loss of optical alignment, including translation, rotation, and defocus. Mosaic elements (assumed to be 2K x 2K format) shall be removable and replaceable from the package without loss of optical alignment, including translation, rotation, and defocus.

9.2.3 Thermal Interface

The detector array shall be held at operating temperature by a combination of passive (liquid cryogens) or active (closed cycle cooler) cooling and an active heater circuit.

The thermal connection and mount design must maintain temperature stability of the detector array to within **TBD** K/hour. This stability requirement insures that temperature-induced video output drift will remain well below read noise for ~ 5-minute integrations.

Table V: Detector Array Requirements to Meet NEWFIRM Science Goals

Parameter	Requirements	Comments
Format	4096 x 4096 pixels	Satisfies FOV and sampling requirements
Quantum Efficiency	> 60%	Satisfies throughput requirement
Charge Capacity	≈ 100,000 e^-/pixel	For adequate dynamic range; function of QE and realizable readout rate
Linearity	$\geq$ 5% at ½ full well	Provides photometric accuracy of ~ 1% with modest nonlinearity correction over adequate dynamic range above sky flux
Read Time per Pixel	< 3 µsec (goal)	Permits full array readout in seconds without excessive controller complexity.
Read Noise	< 23 e^- with ten-read Fowler sampling	Insures background-limited operation (read noise < 5% of total noise) for 5 min exposure with NB filter in J window
Dark Current	1.8 e^-/pixel/sec	Insures background-limited operation (dark current noise < 5% of total noise) for 5 min exposure with NB filter in J window
Electrical Stability	Bias variations < read noise over 300 sec, gain variations < 0.5% over 3600 sec	Insures background-limited operation at low flux levels, and photometric calibration over typical periods between standard star calibrations.
Temperature Stability	Video output variation with temperature < **[TBD]** e^-/deg K	Holds thermal drift variation to ~ 1/2 total RMS noise over 300 sec with realizable active temperature control of the array
Usable Pixels	> 95% pixels within 25% of mean values for QE, dark current, read noise	Insures efficient imaging use without excessive integration time or image dithering to compensate for bad pixels
Cosmetic Characteristics	No contiguous areas of unusable pixels > 20 pixels extent both in X and in Y	Insures image dithers < 6 arcsec in any direction for bad pixel removal, maximizing useful sky field in final data set

9.2.4 Optical Interface

The detector array shall be positioned at the cold focus of the camera optics with a longitudinal tolerance of **[TBD]** mm.

The detector array shall be centered with respect to the optical axis within **[TBD]** mm in X and Y.

The array mounts shall be normal to the optical axis to within **TBD** arc minute of tilt.

The array position requirement shall ensure that final focus can be attained by slight refocusing of the telescope secondary without materially degrading the image quality at the detector array. The centration requirement shall ensure radially symmetric imaging performance with respect to the mechanical center of the array. The tilt requirement shall ensure that tilt-induced defocus does not degrade imaging performance by more than 10% of the geometrical RMS diameter at any point in the field of view.

9.2.5 Wiring Harness

Wiring from the detector array to the controller shall use preassembled wire bundles, ribbon cable and/or flex circuitry for robustness and for ease of installation.

The number of connector interfaces shall be minimized. Connectors shall be located for ease of electrical and mechanical assembly in the vicinity of the array mount.

Wire types, dimensions and run lengths shall seek to minimize capacitance, consistent with thermal isolation and a clean layout within the mechanical design.

All wiring to the detector array shall be cold stationed with a high thermal conductivity path to a surface meeting the internal temperature requirement of Section 7.2.

9.3 Array Controller

The detector array controller may be NOAO produced, procured from a commercial vendor or procured from another IR instrument group. Commonality with other instruments built and supported by NOAO is a goal.

Preamplifiers are considered to be part of the array controller, although they may be physically separate cold electronics located inside the Dewar.

9.3.1 Performance Requirements

The detector array controller shall provide the necessary number of bias, clock, signal and power supply lines to operate the array and to capture its output. The controller shall provide programmable waveforms and timings for array clocking to optimize performance. There shall be an engineering interface for modification of voltages, waveforms, and timings.

The array controller shall provide hardware protection for the array against electrically hazardous conditions, including software-specified operating parameters.

The array controller shall provide analog signal processing and 16-bit A/D conversion. Image data shall be output to the data handling system in a standard format such as FITS (this is not a requirement for image descrambling in the controller). The controller shall generate image header information appropriate to its functions and pass this to the data handling system.

The array controller shall be capable of operating the arrays synchronously in an idle-and-run mode. It shall be capable of performing correlated double sampling (CDS) and multiple nondestructive reads in support of Fowler sampling or sample-up-the-ramp operating modes.

The array controller shall be capable of reading out the entire 4k x 4k pixel set in < 3 seconds and of transferring the digital data to the data handling system at this rate, continuously. Depending on capabilities provided by the detector, it shall also be capable of reading and transferring image subarrays at a faster rate, and/or data characterization information (e.g. bias drift).

The array controller shall provide an engineering interface to the detector. This shall allow operation of the array, including readout to the data handling system, independent of higher level instrument control and system management. This interface shall be capable of querying and reporting array related status information, and of permitting low level coding of array operations for engineering purposes.

To permit operation of the array independent of other system components, the array controller shall monitor array and detector mount temperatures, and shall control any active heating applied to the detector mount for temperature stabilization.

Array controller electronics noise shall be low enough that total noise shall be no more than 1.1 times the Poisson photon noise of the external signal in a low background, moderate integration time case. This is taken to be 50 e^- rms (1% bandpass, J band, one minute integration). This budget shall include all non-photon-induced noise sources in the path from the detector array to the digitized signal output by the array controller. A sample noise budget is given in Table VI.

Table VI: Electronics Noise Budget

Noise Source	Budget
System	< 23 e^- RMS*
Detector Array	<10 e^- RMS**
Array Controller	< 20 e^- RMS

* Ensures that total noise shall be no more than 1.1 times the natural Poisson photon noise.
** Array read noise for the HAWAII 2 arrays as specified by the manufacturer.

9.3.2 Mechanical Interface

Controller electronics which must be in close proximity to the dewar, and/or which require special electrostatic precautions for coupling/decoupling to the dewar, shall be mounted in such a manner as to be an integral part of the NEWFIRM assembly that attaches to the telescope. The controller power supply shall be mounted within the Cass cage on the Dewar, on the telescope or in a cage-mounted rack.

9.3.3 Thermal Interface

Array controller electronics, power supplies, etc. which are located in the Cass cage shall not dissipate more than 50 W of heat directly into the cage. These may be air-cooled by circulation of ambient air ducted to a remote location, or liquid-cooled with a remote heat exchanger.

A goal is that all instrument heat sources in the Cass cage remain at local ambient temperature by conduction of heat to a remote location.

9.4 Instrument controller

Instrument control is a functional, but not necessarily hardware, partition. This is largely a software function. It may be implemented by reusing or adapting existing code and programming environments (MOSAIC, SOAR ArcVIEW) or be a new effort. There may be functional "leakage" into array control and system management functions depending on the configuration adopted for the total system.

9.4.1 Functional requirements

The instrument controller shall accept all commands and execute all functions which configure NEWFIRM for taking data. It shall pass array specific commands to the array controller. It shall drive the filter changing mechanism and monitor its status. It shall similarly operate any other mechanisms that may be identified as the design progresses. It shall monitor instrument temperatures and any other non-array related status information as shall be desired. It shall receive array related status information from the array controller. The instrument controller shall relay all status information to the system manager.

The instrument controller shall provide an engineering interface to the instrument. This shall allow communication and control of the instrument (filter motions, array operation, engineering status information) independent of connection to the telescope and observatory via the system manager. This interface shall permit coding of software for instrument control and status functions.

9.4.2 Temperature Sensors

Temperature sensors shall be installed at selected locations inside the Dewar, including the detector array mount, cryogen reservoirs, optical mounts and the filter handling assembly. These shall be monitored by the instrument controller, with temperatures included in the instrument status information.

9.5 System manager

System management is a functional, but not necessarily hardware, partition. There may be functional "leakage" into the instrument control function depending on the configuration adopted for the total system. Fundamental to its operation are command queueing, command sequencing, and priority for observing resources.

9.5.1 Functional requirements

The system manager shall handle all communications between the instrument and external systems: the telescope, the observatory, and the observer.

It shall provide a command set and user interface for astronomer control of observing actions and definition of observing sequences involving the telescope, the instrument, and the detector. It shall accept astronomer commands, relay them with reporting back to the astronomer as required, and report instrument and system status (e.g. telescope pointing, focus, filter position, integration time). It shall queue and sequence astronomer commands for logical and efficient execution. It shall generate lower level command sequences as necessary from the astronomer command set.

The system manager shall pass commands to, and accept acknowledgement and status information from,

- The telescope: position and focus
- The guider: guide probe positioning, and guider interaction with telescope position
- The dome: positioning
- The instrument controller: filter position, other mechanisms, instrument status
- The array controller (via the instrument controller): integration time, integration sequences

This list is illustrative but may not be inclusive.

The system manager shall use the commands and status information which pass through it to generate instrument and system specific image header information, and pass this to the data handling system.

It shall recognize certain critical status information as representing "out of bounds" conditions, interrupt operations and report to the astronomer. This includes, for example,

- Filter wheel not in desired position
- Filter wheel not in any defined position
- Guide probe not in, or incapable of reaching, defined position
- Telescope not in, or incapable of reaching, defined position

- Detector temperature out of operating range

9.6 External Cabling

External cabling shall, wherever possible, conform to existing telescope interfaces and shall use existing long cable runs (e.g. to the operational control room and computer room). Connections shall be unambiguously labeled, and robust connectors shall be used. No connections or cables shall be shared with other instruments. Any connection which requires electrostatic protection for connect/disconnect, or otherwise potentially endangers the detector, shall be mechanically protected against inadvertent connect/disconnect and shall not require connection or disconnection in normal service including telescope mount/dismount.

10. Guiding

Guider function requirements are limited to providing a telescope guiding signal from a source outside of the science field. No calibration lamps, internal flatfield sources, on-axis acquisition capability, or other such additional features are required. The telescope guider shall be able to acquire suitable guide stars over the entire sky, including at the galactic poles and in dark clouds, under full Moon sky brightness. This leads to requirements on sensitivity, field of view, etc. Information and calculations in support of these requirements will be found in a NEWFIRM System Design Note "Implementation of Guiding".

10.1 Functional and Performance Requirements

The guider shall maintain telescope positioning accuracy of 0.05 arcsec with a closed loop bandwidth of 10 Hz and limiting magnitude of $V \geq 18$ in a dark sky.

The total accessible guide field shall be at least 25 arcmin^2. This shall be allocated to two fields, each with its own sensor , located around the perimeter of the science field. These may be on two adjacent sides or two opposite sides. Each sensor shall be independently positionable within its field.

Use of guider sensor types also used in other KPNO/CTIO applications is a goal.

The guider sensor assemblies shall not vignette the science field.

Guide sensor positioning, between any two arbitrary points within the guide field, shall require a maximum of **TBD** minutes.

Guide star acquisition and guider lock shall require a maximum of **TBD** seconds after the sensor is positioned and the telescope is initially pointed at the field.

Subsequently, reacquisition and lock for offsets < 30 arcseconds (α, δ vector sum) shall require a maximum of **TBD** seconds.

The guider assembly shall attach rigidly to the NEWFIRM dewar. It shall be referenced to the telescope via the NEWFIRM mounting interface.

The guider shall incorporate a manual dark slide, operable with the guider and NEWFIRM installed. This shall seal the total entrance aperture (both guide fields and the science field) against dust.

The guider assembly shall incorporate means for removal of heat generated by motors, power supplies, etc. such that heated air does not enter the science beam.

Guider software for sensor positioning, centroiding, telescope control, etc. shall be as nearly identical as feasible to the existing “Linux guider” control software. This may impact sensor choice.

Guide star selection software shall be provided. This shall refer to existing astrometric catalogs for suitable stars. Users shall be provided with appropriate tools for identifying guide stars in advance of observing, and for creating program source catalogs which match science target positions and guide star positions for rapid acquisition.

11. Operations

11.1 Operational Lifetime Requirements

It is expected that the instrument will be heavily used for five years from first light, and moderately used for five years more. Components and assemblies which are not usually and explicitly intended to have shorter term maintenance or replacement intervals shall be designed for a minimum ten-year service life.

Components which have shorter maintenance intervals, such as closed cycle cooler heads, internal gearboxes, and cryogenic getter material, shall be readily removable and replaceable. A minimum one-year service interval is a requirement, with a longer interval as a goal.

11.1.1 Telescope Mounting Cycles

Telescope mounting and dismounting involves handling the entire instrument and connecting/disconnecting mechanical, electrical and cryogenic connections. These connections shall be designed to withstand six connection/disconnection cycles per year for ten years.

11.1.2 Cooldown Cycles

The mechanical-cryogenic design shall be sufficiently robust to withstand 300 thermal cycles over a ten-year service life.

Based on previous experience, 20 warm-cold-warm cycles are estimated for the Dewar in the course of system integration and test over a six-month period. Thereafter, one cycle per month for five years and one cycle per two months for five years are estimated, plus 3 cycles annually for internal servicing. This totals 140 thermal cycles over the instrument service life, and the instrument shall be designed to withstand these with 100 % margin.

11.1.3 Filter Handler Cycles

Anticipated maximum filter handler motions are 20 filter changes/hour (intermittently, as when observing standard stars); 10,000 cycles per year; and 100,000 cycles over the ten-year instrument lifetime. Annual inspection and maintenance of the filter handler assembly is permitted. However, this inspection should not require major disassembly of the cryostat, nor should it perturb the instrument's optical alignment. Maintenance procedures may be incorporated into the filter replacement procedure (Section 6.7.5). Any custom parts likely to be required for maintenance shall be identified for spare parts fabrication.

11.1.4 Shipping Between Sites

The instrument may be shipped between the KPNO and CTIO 4-m telescopes. The design shipping cycle shall be one round trip between KPNO and CTIO per year for ten years. It shall be of sufficiently rugged construction to allow shipment by air freight in suitable shipping containers. Warm electronics shall be disconnected and separately packaged. Shipping containers with shock isolation rated for 3 G accelerations in all directions shall be provided as part of the instrument design and fabrication effort. The instrument may be shipped in its transport/installation cart if this provides best protection.

11.2 Operating Rules

The instrument shall be installed, brought into service and kept operable on the telescope (e.g. cryogen fills) by NOAO personnel trained on the instrument. Cabling shall remain fixed on the instrument so far as is practical and consistent with the operation of other instruments. It shall be possible to perform cabling tasks, initial cooldown/cryogen fills and software initialization during the day while the instrument is in service.

The instrument system shall support safe and efficient operation by a telescope operator or visiting astronomer after a review of user documentation and a brief hands-on introductory session with an expert astronomer. Hardware and software designs shall anticipate and prevent harm to the instrument from injudicious commands or command combinations, or incorrectly specified detector array operating parameters. Present instrument systems, e.g. MOSAIC, Phoenix, shall serve as examples of good practice in these respects.

11.3 Instrument Status and Performance Checks

Instrument vacuum status shall be verifiable with an appropriate gauge at the Dewar independent of all other operational status of the instrument. Instrument temperature readouts, electronics and detector status readings (e.g. critical voltages), and cryogen status shall be monitored continuously during instrument operation via the instrument electronics (see Sec. 9).

A set of startup performance checks shall be defined in the Operation and Maintenance Manuals, accompanied as necessary by tables, graphs, standard image patterns and/or other information, to permit NOAO site technical staff to verify nominal instrument operation. The performance checklist shall include electronics, software and array health as indicated by dark current, noise and signal measurements.

Image quality, flatfielding, and filter throughput values and performance checks shall be defined in the Operation and Maintenance Manuals, supported by appropriate information. The non-expert astronomer shall be able to verify nominal performance on the sky and on standard sources.

11.4 Maintenance

11.4.1 On-telescope Routine Maintenance

The instrument may remain mounted on the telescope for many weeks continuously. It may be allowed to warm up between science runs if operationally convenient. No routine maintenance other than vacuum jacket pumping from time to time shall be required while the instrument is mounted on the telescope and warm.

11.4.2 Off-telescope Routine Maintenance

Internal interventions in support of science, such as filter changes, shall be limited to no more than two times per year. These shall be performed off the telescope in a clean room environment by the instrument scientist. Site staff responsibility is limited to providing the instrument in its installation cart to the scientist.

Other routine maintenance requiring opening of the dewar, such as changeout of vacuum getter material, shall be the responsibility of the instrument scientist. He/she may designate appropriately trained technical staff to perform such functions.

11.4.3 Troubleshooting and repairs

Troubleshooting and repairs shall be the frontline responsibility of NOAO site personnel once the instrument is accepted. The instrument design and fabrication team, the array controller/instrument electronics team, the data processing software team, and/or other expert assistance within NOAO shall be available as a backup.

11.4.4 Documentation

The NEWFIRM instrument project shall supply sufficient technical documentation to allow installation, performance checks, routine maintenance, trouble-shooting and repairs by site personnel. To this end, the project shall provide Operation and Maintenance Manuals as part of the instrument delivery documentation.

Online access to technical details such as mechanical drawings and electronic circuit diagrams is a goal, to be implemented insofar as electronic documentation is developed in the normal course of the instrument design and fabrication.

The NEWFIRM Operation Manual shall provide a step-by-step guide for normal instrument operation, error recovery procedures for common problems, and suggested protocols for common sorts of observations.

11.4.5 Spare Parts

Spare parts shall be identified and provided for critical uncommon components or for those with a long lead time for delivery from vendors.

Sparing of all warm electronics is a goal. This may be done in conjunction with other instruments using the same hardware, e.g. array controller boards. Sparing shall be done as far as possible at the plug-in replacement level, e.g. complete boards, motors, cable assemblies, etc.

12. Data Handling

12.1 Functions

Data handling includes all data related tasks subsequent to initial image capture and digitization by the array controller. The data handling system shall perform the following functions:

- Interface to the array controller for receipt of digital image data and header information
- Interface to the system manager for receipt of system related header information
- Unscrambling of controller image output to images with correct (row, column, pixel) geometry
- Assembly of header input information into a single comprehensive header for each image or image string
- Storage of raw images and associated headers on some bulk storage medium in a commonly used format, analogous to the present Save the Bits program
- Several stages of automated data processing, defined further below
- Several stages of data quality assessment, also discussed below

- Provision of quick-look assessment and images to the user via the top level user interface (e.g. a GUI with image display tool)

- Input of fully processed image data in some common format, with associated headers, quality assessment, and other information, to a public data archive

- Provision of raw images and headers, and/or fully processed data, to individuals involved with the originating science program, in a format and on a storage medium in common use (e.g. FITS images on CDROM)

The creation and management of the public IR image data archive is beyond the scope of the NEWFIRM program, although the program deliverables shall be consistent with this end. Further science products extracted from the data, e.g. source catalogs, shall be the responsibility of scientific users.

12.2 Processing stages and timescales

Several processing stages, serving different purposes, are identified below. Further definition and development shall involve close collaboration between the Project Scientist and the NEWFIRM data handling team, which is expected to reside within the NOAO Data Products Group. The experience of other groups in handling large data volumes, such as the NOAO Deep Wide Survey Team, shall be called upon in the definition and refinement of the pipeline processing functions.

12.2.1 Quick-look at the telescope

The data handling system shall provide images and data quality metrics that establish that the instrument is functioning normally and that sky conditions are consistent with getting good quality data. This includes characterization of

- Detector properties: dark current, read noise, pattern noise

- Instrument environment properties: temperatures, voltages, local background levels

- Telescope properties: pointing, focus

- Sky properties: background level, level changes, anomalous illumination

Image data may include dark current frames, flatfield frames, and sky subtracted scientific target frames. Metrics may include statistical characterization of dark frames, read noise, flatfields, and science data frames. These listings are illustrative, not complete.

These images and metrics shall be available to the user at the telescope within minutes of completion of the required data taking sequences.

In addition to defined quick-look products, the data handling system shall provide user access to raw image data from an image processing tool (e.g. IRAF) for user defined manipulations while observing.

12.2.2 Quick-reduce during an observing run

The data handling system shall provide processed images and data quality metrics for protocol verification, i.e. to test whether the observing protocol in use for obtaining raw image data is adequate to the scientific purpose. For example, a sky-subtracted, flatfielded, registered and coadded image for every telescope pointing in a moderate sized raster, and the resulting assembled mosaic.

This shall include whatever alternative approaches to steps such as sky subtraction are supported by the input data. This shall result in alternative data products for protocol evaluation.

These images and metrics shall be available within an hour of completion of the required data taking sequence.

Data verification shall be enabled on a nightly basis, with the same data products and alternates as above produced for an entire night's data on a time scale of several hours. The level of sophistication in processing shall be such as to permit evaluation of data quality on a go/nogo basis through visual inspection and simple quality metrics such as background level across mosaic elements vs. time of observation.

Processing shortcuts such as use of standard flatfields shall be permitted in the interest of speed for quick-reduce.

12.2.3 Final reduction for archiving

Final reduction shall use an automated "pipeline" to

- manage the very high data volumes (~60 Gbytes/night)
- remove all instrumental signatures and background sky level
- remove artifacts such as cosmic rays and satellite trails
- assess data quality and reject discordant data
- conduct full error propagation and produce an associated noise map for each reduced image or mosaic
- produce photometric and astrometric calibrations for images and mosaics
- associate a database of observing conditions information with reduced image data

The data handling system shall use the highest level of sophistication in data reduction that is consistent with automated processing, to provide final images, mosaics, and accompanying quality assessment information to the science end users and the public image archive.

The time scale for fully processed data shall be a few days subsequent to obtaining the necessary raw data in full.