NOAO Extremely Wide Field Infrared Imager (NEWFIRM)

Operational Concepts Definition Document (OCDD)

Prepared by the

National Optical Astronomy Observatories

Engineering and Technical Services Group

July 30, 2001

Rev. Oct 10, 2001

Document Acceptance and Concurrence

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

Roy Gene Autry, NEWFIRM Project Manager

Ronald G. Probst, NEWFIRM Project Scientist

Larry Daggert, Manager, NOAO Engineering and Technical Services

Tod Boroson, Manager, NOAO Data Products Group

Taft Armandroff, IPAC

(NAME), KPNO

(NAME), CTIO

Table of Contents

7. NEWFIRM Observing Scenarios

7.1 Scenario 1

7.2 Scenario 2

7.3 Scenario 3

List of Tables

List of Figures

1. Purposes of this Document

The purpose of the Operational Concepts Definition Document (OCDD) for the NOAO Extra-Wide Field Infrared Imager (NEWFIRM) is to provide the scientific user community with a description of the astronomical observations and research to be accomplished with NEWFIRM, the instrument system requirements which are driven by these science programs, and how the instrument system will be used in practice. This science user perspective provides the underpinnings for the engineering requirements detailed in the Functional and Performance Requirements Document.

This document begins with observational programs, outlined at various levels of detail, which define NEWFIRM's scientific parameter space, and the distinct modes in which these programs may be conducted. From these are derived the top level science driven instrument system requirements. A resulting instrument system design is described and related back to these requirements. Finally, we describe how the instrument system will be used to conduct typical observing programs.

More detailed discussions of some system components, in terms of requirements, practical constraints, and realizations in hardware/software, shall be available as System Design Notes now, and as the design effort progresses.

The NEWFIRM instrument system shall enable every type or kind of program described here. All of its functional requirements, and hardware/software realization, shall be traceable back to these science drivers. No type or kind of program (in terms of observational requirements) for which NEWFIRM is intended shall be omitted in this document.

2. Applicable Documents

"Supporting Capabilities for Large Telescopes", a workshop held in Tucson AZ, 26 – 28 September 1997 (www.noao.edu/scope/supcap_workshop/)

"Science Case for NEWFIRM", summary of NOAO scientific staff discussion on 5 February 1999 (www.noao.edu/ets/newfirm/sci99.html) .

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

NOAO Extremely Wide Field Infrared Imager (NEWFIRM) functional Performance Requirements Document (FPRD), NOAO Document No. XXXX, July XX, 2001

3. Terminology and Acronyms

2MASS	2-Micron All Sky Survey
CIRIM	CTIO Infrared Imager

CTIO	Cerro Tololo Inter-American Observatory
FLAMINGOS	University of Florida 2k x 2k Imager/Spectrograph
FOV	Field of View
FPRD	Functional Performance Requirements Document
FTP	File Transfer Protocol
H	H band, standard IR filter covering 1.5-1.8 microns
ISPI	Infrared Side Port Imager
J	J band, standard IR filter covering 1.1-1.4 microns
K	K band, standard IR filter covering 2.0-2.4 microns
K_S or K-short	Standard IR filter covering 2.0-2.3 microns
KPNO	Kitt Peak National Observatory
MOSAIC	8k x 8k Prime Focus CCD Imager (KPNO and CTIO)
NB	Narrow Band (optical filters)
NEWFIRM	NOAO Extremely Wide-Field Infrared Imager
NOAO	National Optical Astronomy Observatories
OCDD	Operational Concepts Definition Document
UKIRT	United Kingdom Infrared Telescope
USA	United States of America
WB	Wide Band (optical filters)
WFCAM	Wide-Field Camera for UKIRT (proposed)
YSO	Young Stellar Object

4. Scientific Basis and Operating Modes for NEWFIRM

4.1 General Background and Scientific Drivers

4.1.1. Support capabilities for 6.5-10 meter telescopes workshop

The 1997 "Supporting Capabilities for Large Telescopes" workshop at NOAO/Tucson brought together 46 scientists from 26 institutions to identify and quantify the support capability needs for major science programs to be conducted with 6.5-10 meter telescopes. All of the panels within this workshop identified large-scale sky surveys as essential to defining meaningful observing programs for the very large aperture telescopes then extant or planned. The survey parameters discussed by the panels and by the workshop as a whole indicated that telescopes in the 2.5 to 4-meter class would be required. These findings are discussed in the working group report (ww.noao.edu/scope/supcap_workshop/). The infrared survey support needs are summarized here. Some of these programs also have optical components; see the report for details.

Table 1. Infrared survey programs in support of 6.5-10 meter telescope science

Program	Title	Location	Sq Deg	Filters	Limits	Other requirements
2a	Three ages of the Mass-Luminosity Relation	Pleiades	10	J, K	J=16.5 K=15.5	
2c	Variations in the Substellar Mass Function	Hyades	50	Z * H short H long	Z = 20 H = 19	20% photometry at H
"	" "	5 young clusters	5 x 10	Z *	Z = 21	5% photometry
4a	The Nature of Protostars	Star forming Regions < 1 kpc	120	J H K L	J = 18.5 H = 18 K = 17 L = 14.5	10% photometry
4b	IMF in Nearby Star Forming Regions	10 molecular clouds	120	J H K L	J = 18.5 H = 18 K = 17 L = 14.5	10% photometry, variability survey to I = 20, FOV large enough to tie in with Hipparchos
7a	Formation and Growth of Galaxies	5 fields across sky	5	J H K	J = 26 H = 24 K = 23	20% photometry
8a	Large Scale Structure At High Redshifts	4 fields across sky	10	J H K	K = 21.5	5% photometry
"	" "	Deep field	0.5	J H K	K = 23	5% photometry

* The Z band observations could be carried out with either an optical CCD or an infrared camera.

In general, the bulk of this IR survey science requires capability for imaging in J H K (1-2.4 microns) over many square degrees with low to moderate photometric precision. Most of the followup large telescope science is spectroscopy, so there is an implied requirement for astrometric accuracy sufficient to position narrow (0.1 arcsec) slits on selected sources.

4.1.2. NOAO staff discussion and instrument definition

The above mentioned survey workshop identified widefield infrared imaging capability as a crucial support need for large telescope science. Subsequent programmatic discussion within the KPNO division of NOAO identified this as a highly desirable core instrument for the Mayall 4-m telescope, well matched to its role and capabilities (www.noao.edu/ets/newfirm/case.html).

To further define the science case and resulting instrument requirements, a number of NOAO scientific staff participated in a science oriented discussion in February 1999. Several scientific programs were put forward and a set of template questions regarding instrument requirements addressed (e.g. field of view, pixel scale, sensitivity, spectral resolution). A report may be found at www.noao.edu/ets/newfirm/sci99.html . The science cases discussed are similar to those identified in the Support Capabilities Workshop, while the instrument requirements are more fully fleshed out. We give a summary here.

Table 2. NOAO definition of the science case and instrument requirements for NEWFIRM.

Program → Requirement ↓	**Characteristics of the Galactic Brown Dwarf Population**	**YSOs and the IMF Across Space and Time in Nearby Molecular Clouds**	**Evolution of Galaxies And Galaxy Clusters at High Redshift[1]**
Field of view per pointing	Large as possible for detection efficiency	Large enough for definition of background reference frame for proper motions	~0.5 deg for survey efficiency
Pixel scale	As required for good point source photometry	As required for photometric and astrometric accuracy	0.3-0.5 arcsec/pixel for star-galaxy separation
Positional accuracy[2]	0.05 arcsec for followup spectroscopy on large telescopes	5 milli arcsec, for proper motions on 5-10 year baseline	0.05 arcsec for followup spectroscopy on large telescopes
Sensitivity	H=19 or K=19 minimum	J, H $\leq$ 20, K $\leq$ 19	K ~ 22, J ~ 24
Photometric accuracy	(10% ?)	0.03 mag in each filter	(10% ?)
Wavelength coverage	H, K required; J, L desirable	J H K	J H K
Spectral resolution	R = 20 (5% filters for methane band detection)	R = 5 (standard broadband filters)	R=5 and R> 100
Special features of program	Custom intermediate bandwidth filters	IR proper motions for candidate selection[3]	Includes narrowband survey for primeval galaxies

(1) Three science programs are summarized under this general heading.
(2) This requirement was not explicitly addressed by the template questions.
(3) Proper motion selection has been superceded by photometric variability selection, see 4.x.x below.

The major results for science driven instrument requirements are: coverage of the J H K windows; pixel scale providing photometry to 3% precision and positional accuracy to 0.05 arcsec on image centroids; largest field of view consistent with pixel scale requirements; ability to use narrowband filters up to R ~ 100.

4.1.3. Workshop on the groundbased optical/infrared system

The decadal report of the Astonomy and Astrophysics Survey Committee laid out a new paradigm for groundbased optical/infrared (O/IR) astronomy, stating that "all facilities, whether nationally or independently operated, should be viewed as a single integrated system". To explore the consequences in terms of existing and needed capabilities, NOAO sponsored a workshop in Scottsdale, AZ on October 27-28, 2000. There were 81 attendees from 47 U.S. and 1 foreign institutions. Attendees formed six breakout groups in major science areas. These groups developed observational projects and defined the capabilities needed to undertake them. A report may be downloaded from www.noao.edu/gateway/oir_workshop/ .

We summarize here instrument capability needs identified in this process and relevant to IR imaging.

- *Cosmic history of star formation and chemical evolution*. This topical area extended from resolved stellar populations in nearby galaxies to characterization of the primordial galaxy population at z > 6. Four out of five programs in this area identified a need for IR imagers on 4-m or larger telescopes with field of view 0.25-1 square degree, 0.5 arcsec image quality, and 1-2.4 microns wavelength coverage with broadband filters.

- *Searching for origins in protostars and planets*. Topics included the connections between physical processes and the stellar initial mass function, formation of protostars, and the formation of circumstellar disks and planetary systems. IR imaging needs are for photometric surveys: 4-6 m telescope, 0.5-1 degree field of view, 1-2.4 microns wavelength coverage, and both broadband and narrowband (R~100) filters. Software needs for database formation and access ("data mining") were also identified.

Final overall workshop recommendations for instrumental capabilities repeated the need for widefield near-IR imagers on 4m and larger telescopes, with fields of tens of arcminutes and good sampling of the point spread function. Necessary enabling technology is the development of new larger format IR arrays.

4.1.4. The WFCAM and VISTA science cases

WFCAM is an IR camera analogous to NEWFIRM, being built at Royal Observatory Edinburgh for use on the 3.8-m UKIRT telescope on Mauna Kea (see http://www.roe.ac.uk/atc/projects/wfcam/index.html). VISTA is a widefield imaging survey facility incorporating a dedicated 4m telescope and optical and IR imagers. It is being built by a British consortium and will be sited on Cerro Pachon, Chile with shared usage by ESO (see http://www.vista.ac.uk). We have examined the science cases and resulting instrument parameters as defined by these foreign communities, and summarize them here. They are very similar to results from the various U.S. forums noted above. This suggests both that we are getting the science right, and that NEWFIRM will be internationally competitive.

(a) WFCAM

WFCAM science:

- Surveys and catalogs of local galaxies at $z < 0.1$
- Characterizing the galaxy population at $z > 2$
- Statistics of high redshift galaxy clusters as cosmological tests
- Cosmology with NIR color selected quasar samples
- Galactic plane surveys for detection of brown dwarfs, characterization of the IMF in star forming regions, and definition of Galactic structure from the stellar component

WFCAM instrument parameters:

- 3.8 m telescope
- 0.4 arcsec/pixel resolution, equal to median image FWHM
- Use of microstepping to recover angular resolution from undersampled images
- 27 x 27 arcmin total field of view in single pointing
- Broadband filters for 0.85-2.4 microns ($ZJHK_SK$) plus narrowband filters

WFCAM science emphasizes large scale surveys, and the instrument is accordingly optimized for survey speed rather than photometric or astrometric precision in its pixel size choice. WFCAM pixels are coarse in terms of the telescope image quality. The field of view is divided among four arrays openly spaced, like a checkerboard. The effective FOV for surveys, allowing for overlaps, is 26 x 26 arcmin per pointing. Although no need for narrowband filters is identified in the science case, provision for them is made explicitly in the instrument requirements (M. Casali et al., WFCAM Conceptual Design Review documents, August 1999).

(b) VISTA

VISTA science:

- Cluster and field brown dwarf surveys
- The initial mass function in star forming regions
- Multicolor atlas of local galaxies
- Search for low surface brightness galaxies
- Large scale structure to $z = 0.8$
- Evolution of structure at $1 < z < 2$
- Abundance of rich clusters at $z < 2$
- Quasar population to $z = 3$

VISTA instrument parameters:

- 4 m dedicated telescope
- 0.3 arcsec/pixel resolution for critical sampling of 0.7 arcsec image FWHM
- 31 x 31 arcmin total field of view in single pointing
- Broadband filters for 0.85-2.4 microns ($ZJHK_SK$) plus narrowband filters

VISTA and WFCAM science have a great deal of commonality (no doubt due to their common community of origin) and the facilities may operate jointly to complete some surveys. Although VISTA will be dedicated exclusively to surveys, it has opted for finer sampling of the image PSF than WFCAM. Both the resolution and the focal plane geometry are subject to change (J. Emerson, private communication). As with WFCAM, provision is made for narrowband filters although no science case calls for them explicitly.

4.2 Example Science Programs

From the above discussion, NEWFIRM may already be characterized as a widefield imager (~0.5 x 0.5 deg) with ~0.5 arcsec/pixel sampling on the NOAO 4 m telescopes, covering ~1-2.4 microns in wavelength. The Observatories of the Carnegie Institute of Washington (OCIW) is building a large-format IR camera, "6Pack", for the Magellan II telescope. The throughput will be similar to NEWFIRM and there is commonality in the science goals. In the course of developing proposals for funding, the two institutions defined some key programs which might be carried out jointly. We present these here as science examples at the next level of detail. In addition to NOAO staff, contributors were Pat McCarthy (OCIW) and John Bally (U. Colorado).

4.2.1 Galaxies and Structure at High Redshift

NOAO and OCIW have identified two coordinated surveys that address outstanding issues in understanding the formation of galaxies and structure at high redshifts. Both surveys involve significant resources of instrumentation and observing time on large public and private telescopes. This responds to the Decadal Survey call for a system of integrated facilities.

We are entering an era of precision cosmology and multi-wavelength empirical studies of galaxy formation. In the coming years a number of investigations of the cosmic microwave background (CMB) and of distant supernovae will lead to precision determinations of the fundamental cosmological parameters. There is a reasonable expectation that we will soon know the shape and normalization of the power spectrum on large scales from redshift surveys (2DF, SDSS) and from space and balloon-borne CMB experiments. Great progress has been made in understanding the basic phenomenology of star-forming galaxies at large redshifts and their 3D spatial distribution on modest scales. The epoch of re-ionization is now well constrained and may be observed directly in a short time. Key areas in which our understanding remains weak are the evolution of the massive early-type galaxy population, star formation in heavily obscured galaxies, and the formation of the first stars. Advances in these areas require near-IR surveys with an unprecedented combination of depth and area.

4.2.1.1 Evolved Galaxies and Clustering at 2 < z < 3

The evolution of the clustering of field galaxies and the abundance of rich galaxy clusters provide a strong discriminant between different models of galaxy and structure formation. Clustering studies not only provide independent checks of the cosmology and the power spectrum, they probe the growth of structure in nonlinear regimes. Rich clusters provide efficient laboratories for studies of galaxy evolution in dense environments where a number of dynamical and gas-phase processes come into play. The clustering of field galaxies and the space density of massive evolved galaxies provide additional tests of formation models. Surveys now in progress are designed to measure the abundance of clusters at z~1 (e.g., Gladders 2000, Elston et al. 2001) and to penetrate to z~1 for early-type field galaxies (Daddi et al. 2000, 2001; McCarthy et al. 2000, 2001; Chen et al. 2001; Firth et al. 2001). The field galaxy survey results illustrate the power of adequate field size and appropriate filters. They reveal little change in the space density of luminous red galaxies and the characteristic scale of their 3D spatial clustering—in stark contrast to earlier reports of strong evolution in the early-type population from studies based on small fields and optical color selections.

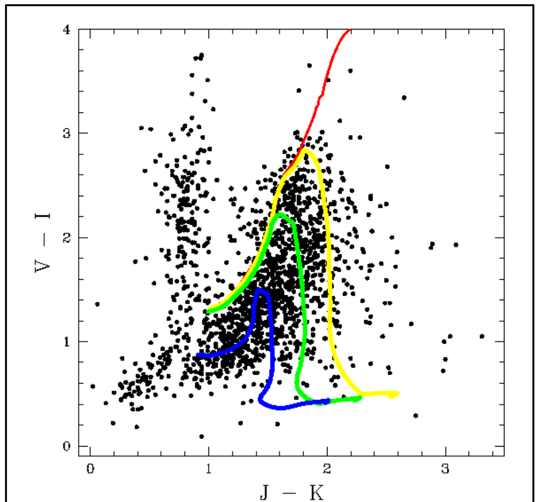

***Figure 1**. The V-I vs. J-K color-color diagram for a 150 square arcminute region of the LCIR survey. The nearly vertical track at J-K = 0.7 contains galactic fore-ground stars. The model tracks are for a non-evolving early-type galaxy (red) and exponentially decaying star formation with e-folding times of 1 and 2 Gyr (yellow and green) and a constant star formation model (blue). The objects with J-K > 2 are candidate ellipticals at z > 1.5.*

Various flavors of CDM make distinctly different predictions regarding the number of galaxy clusters at redshifts beyond 1 (e.g., Holder et al. 2000; VIRGO consortium) and the evolution of the clustering length in the field (Kaufmann et al. 1999). The field galaxy surveys find strong angular clustering among the reddest galaxies at faint levels. The next observational step is to perform similar investigations at redshifts beyond 1.5, where the expected evolutionary and cosmological effects are large. Near-IR imaging is required to delineate the 4000Å break and steep rest-frame visible continuum at high redshift. A survey to K=22 will comfortably reach z = 3 and will sample more luminous galaxies at larger redshifts. The J-K color varies sharply with redshift for early type galaxy progenitors. Figure 2 shows a V-I vs. J-K color-color diagram for a subregion of the LCIR survey to a depth of K=20.5. Superposed on the data are the tracks of three evolving models. Even at this depth we are beginning to see the population of bright evolved galaxies at z > 1.5. The wide spread in V-I colors reveals a range in levels of ongoing star formation and further emphasizes why optical surveys alone are not able to pick up the evolved galaxy population at z > 1.

The detection of massive clusters and intermediate mass groups at z > 1.5 will require significant areas of sky. N-body simulations by the VIRGO consortium (e.g., Evrard et al. 2001) indicate that an adequate sample of clusters and groups requires a survey of several square degrees to faint levels. Accurate determinations of galaxy luminosity functions by type or color require large samples. The expected surface density of z~2 early-type candidates to K=22 is expected to be ~1000 per square degree, so large-area surveys are needed.

To characterize large-scale structure, the survey linear dimension (and so angular scale) must be at least comparable to the turnover length of the power spectrum. Survey area should be contiguous and approximately square to avoid severe aliasing effects and unfavorable window functions from coarse periodic sampling (Postman 2001 and references therein). This has implications for detector development and focal plane geometry as well as for survey observing protocols.

Large, deep IR imaging surveys will also detect rare objects found with SIRTF, e.g., high luminosity obscured starburst systems, and characterize their redshifts and luminosities. Our wide-field survey will be targeted to one or more of the SIRTF Legacy fields. This should lead to the identification of many thousands of SIRTF sources and hundreds of ultra-luminous IR galaxies at intermediate and large redshifts. Large ground-based campaigns are currently planned to support the SIRFT legacy programs, but they are typically 2-3 magnitudes shallower than the program outlined here, or cover only tiny areas of sky.

4.2.1.2 Young Galaxies and Quasars at z > 5

In recent years a number of techniques have led to the discovery of large populations of star-forming galaxies at redshifts from 2 to 4, once thought to be the realm of primeval galaxies. The observed population of z=3 galaxies, however, does not appear to have the properties of primordial systems and they require an earlier generation of star formation. A handful of objects with z > 5 have been discovered either from their strong Lyman-alpha emission lines or from photometric redshifts. The properties of these galaxies are poorly known. They may represent the tail end of the first episode of primordial star formation. Current estimates of the epoch of re-ionization range from z=7 to 11 and the detection of objects forming just after re-ionization is no longer beyond contemplation.

Star-forming galaxies at very large redshifts have distinctive photometric signatures arising from Lyman continuum absorption. The “drop-out” technique is an extremely powerful tool for identifying star forming galaxies with z > 2. At very large redshifts (z > 6), near-IR colors are required to sample the rest frame UV-optical continuum. The most luminous members of the 5 > z > 10 population are within the reach of large ground-based telescopes, provided sufficiently large areas of sky can be surveyed to great depth.

We have estimated the surface density of galaxies with z > 5 from the models of Haiman and Loeb (1998, 1999). Our proposed 900 square arcminute ultra-deep survey should detect on the order of 4,000 z > 5 star forming systems and roughly 40 systems with z > 10. Even if these predictions are optimistic, there is no doubt that we will detect a significant sample of objects with z > 5, as small area surveys have turned up a handful, and there are reasonable expectations that we can sample the bright end of the z ~ 10 population. The 400 nJy depth of our ultra-deep survey corresponds to star formation rates of a few tens of solar masses per year at z~5. Our survey with its wide field and great depth will either produce large numbers of such objects or severely constrain models of the first galactic units.

The survey will be targeted at deep SIRTF fields (e.g., the Chandra Deep Field South) and it will be well suited to follow-up with ALMA. In addition to providing a groundbreaking look at the very highest redshifts, the ultra-deep survey will sample the intrinsically faint galaxy population of faint galaxies at intermediate redshifts and complement the wide-field survey.

4.2.1.3 The Extragalactic Surveys

We parameterize here two IR surveys which jointly address the science goals outlined above. The first program is a wide-area medium depth survey to detect galaxy clusters at $z > 1.5$ and to measure the clustering of field galaxies at $z > 2$. The infrared data would be supplemented with optical data from the NOAO 4-m CCD mosaics and the Magellan IMACS imaging spectrograph. The survey volume at $1 < z < 4$ is over 10^8 Mpc3 and so we will sample even the rarest objects. This survey also includes 4 x 10^7 Mpc3 in the $5 < z < 6$ range and so will provide a very sensitive sampling of the bright end of the galaxy luminosity function and faint end of the quasar LF at this critical epoch.

Table 3. The Extragalactic Infrared Surveys

Parameter	Wide Field Survey	Ultra-Deep Survey
Area	5 sq. degrees	900 sq. arc-minutes
Filters	JK (+ BVRIz′)	JHK (+ BVRIz′)
Depth	K=22; J=24	K=23; J=25
Sky Locations	NOAO Deep Wide Survey fields	Deepest SIRTF/ALMA fields
Facilities	NEWFIRM + 6Pack	NEWFIRM + 6Pack
Science Goals	z = 2 clusters, field clustering, luminosity functions	z > 5 space density, faint end of LF at z > 2, merger rates
Number of Nights	50 NOAO, 20 Magellan	30 Magellan, 20 NOAO

The second program is an ultra-deep survey of one-quarter square degree. Companion deep optical images would be obtained with the IMACS imaging spectrograph and the NOAO 4-m CCD mosaic cameras. We will target a suitable field that maximizes data at other wavelengths while ensuring easy access with ALMA. This survey will sample the sub-L* population of red galaxies at $z \sim 2$ and will provide the most sensitive search for $z > 5$ objects. The deep survey will sample 8 x 10^6 Mpc3 in the $5 < z < 10$ range and should provide a fair sampling of objects at very early epochs.

These surveys will enable a wide range of follow-up programs. We will need spectroscopic redshifts and stellar population diagnostics that are only practical with the multi-object capabilities offered by the IMACS and GMOS spectrographs. A key issue is the degree to which the faint red galaxy population is a mix of early types and heavily reddened star burst systems. High resolution imaging of the reddest galaxies with the Gemini AO systems will address this issue.

4.2.2 The Life Cycle of Baryonic Matter in the Galaxy

The formation and evolution of stars and planetary systems, within the ecosystems of molecular clouds, are key processes determining the fate of baryonic matter in our own and other galaxies. The 1-2.4 micron region is an essential band for the study of star formation, energy exchange, and chemical recycling in molecular clouds. Its astrophysical advantages include much reduced extinction, increased sensitivity to cool and low-mass objects, access to reprocessed radiation from the inner regions of protostellar disks, and an abundance of shock and nebular diagnostic lines. We will apply wide-field IR imaging of continuum and emission line radiation to a fundamental problem in star formation, the origin of the stellar initial mass function (IMF). Linking the emergent pre-main sequence (PMS) IMFs in nearby molecular cloud complexes (MCCs) to local physical and chemical conditions is a critical step in understanding the evolution of the stellar and gaseous components of galaxies over the lifetime of the Universe.

4.2.2.1 Defining the Stellar Initial Mass Function in Molecular Clouds

Current generation IR instruments are being used for targeted surveys probing IMFs down to the hydrogen-burning limit in selected regions of nearby MCCs (Lada et al. 2001). For determination of star formation rates as a function of mass, age, and environment, we need complete PMS samples across entire MCCs, sampling substantial time intervals and penetrating well into the substellar regime for the current star-forming generation.

Penetrating the time domain has been problematic. PMS stars older than a few Myr are dispersed beyond the high extinction regions in MCCs. These outliers must be identified against the field star background. Our strategy is to use variability as a selection tool. A test case is NGC2264, for which a deep I band variability survey has recovered 80% of known proper motion members (Strom 2001). We shall define PMS candidate lists using variability in I and/or Ks (depending on extinction) augmented by JHKs photometry reaching the Galactic confusion limit, and deeper photometry in regions of very high extinction. We will extend current work by an order of magnitude in spatial coverage and ~3 mag in depth, well into the substellar mass regime and reaching ~20 Myr back in time. These data, in combination with follow-up near-IR spectra, allow estimation of extinction, luminosity, effective temperature, and detection of circumstellar accretion disks via near-infrared excess emission. This database will provide for the first time a sample of sufficient size spanning a wide enough range of ages to address fundamental ancillary problems: (1) the lifetime of the accretion disk phase; (2) the evolution of stellar angular momenta, by observations of stars with and without disks; (3) the interior structure and circulation within convective and radiative/convective PMS stars diagnosed via surface lithium abundance; and (4) the early evolution of stellar surface activity.

4.2.2.2 Energy and Chemical Exchange in Molecular Clouds

The near IR portion of the spectrum is replete with bright spectral lines that trace both shock-excited and photo-excited nebulae associated with young stars. Such nebulae provide fossil records of the recent evolution of forming young stars and trace the injection of turbulent energy into star-forming clouds. One of the most powerful tools in the identification of accreting proto-stars is their ejection of powerful jets and flows that ram the surrounding medium. Most outflow sources are embedded within visually opaque regions of giant molecular clouds (GMCs). Imaging surveys in bright characteristic IR emission lines can identify essentially all these embedded outflows. These data complete the protostar census and, in conjunction with IR spectroscopy and data at other wavelengths, permit unraveling the physics of individual sources (e.g., Yu et al. 1999, Yu et al. 2000).

Recent work has established significant ties between outflows and global problems of star formation and cloud collapse. Millimeter-wave maps of GMCs show that filamentary structure is common. While gravitational collapse and fragmentation can produce such structure, it has long been known that the resulting star formation rate is grossly inconsistent with observations. An alternative mechanism is magnetohydrodynamic turbulence, which however requires a replenishment mechanism (see discussion and references in Allen and Shu 2000). The combination of infrared and optical imaging and CO maps has demonstrated that giant protostellar outflows, with scales of parsecs, are common in GMCs. These drive strong shocks into the cloud, dissociate molecules, produce large-scale turbulence, and can profoundly affect cloud structure. The jets, winds, and radiation from young stars may be a key mechanism in self-regulated star formation (Bally et al. 1999; Yu et al. 2000).

A narrowband IR imaging survey of several nearby star-forming molecular clouds will provide complete, unbiased samples of outflow populations and define their local and global impact. These data will also provide the source lists for follow-up IR spectroscopy with 8- to 10-m telescopes. Our targets will be the high extinction regions of the IMF program fields, imaged in three spectral lines: (1) 2.12 μm H2 emission traces outflow morphology on large scales (Eisloffel 2000; Stanke et al. 2000). It is excited by collisions or fluorescence, so provides a signpost for follow-up diagnostic spectroscopy. (2) 1.64 μm [Fe II] discriminates between fast shocks and other types of excitation, and is an indicator of regions in which significant dust grain destruction has occurred (Greenhouse et al. 1991). (3) 2.16 Br γ traces photoionized material. These three lines are formed in distinct physical circumstances. Morphology and relative intensities can be used to deconvolve observationally complex regions (Bloomer et al. 1998). Integration times can be estimated from previous work. Table 2 gives some details of our program.

The science goals are to explore individual outflow-interstellar medium interactions, which may have an angular scale of degrees, and to determine the total input of turbulent energy into an MCC by its outflow population. These require contiguous, uniform coverage of large areas. This places requirements on detector format and focal plane geometry.

4.2.2.3 The Galactic Surveys

We present here two observing programs which address the Galactic science goals. For the IMF science, the multiparameter nature of the observational program and the extraordinary value of the database for both the primary science and ancillary investigations require a survey approach with broad community input. In Table 2 we parameterize a strawman survey of a toy model MCC for illustration. Our model MCC has an extended low extinction "halo" and a high extinction "center" with embedded very high extinction "cores." Survey parameters will of course be tuned to actual target regions. Potential targets include the MCCs in Taurus-Auriga, Sco-Cen-Ophiuchus, Corona Austrinus, Lupus, Chamaeleon, Perseus, Orion, Cygnus, and Monoceros (ordered by distance, 150-800 pc).

The outflows survey might best be undertaken by a small team, with the data flowing to an open database for subsequent use by the community. This model is similar to the present NOAO Survey Proposal format. Clearly target fields would have the greatest subsequent utility by being keyed to the IMF survey fields.

Table 4. The Star Formation Region Surveys

Parameter	Strawman MCC IMF Survey	Narrowband Outflows Survey
Area	165 sq deg: 145 sq deg halo, 20 sq deg center, 2 sq deg core	20 sq deg in each of three regions
Filters	I J H Ks	1.64 μm [Fe II], 2.12 μm H2, 2.14 μm continuum, 2.17 μm Br γ
Depth	I=22, J=20, H=19, Ks=18 with SNR=50, halo + center; J=22, H=21, Ks=20, SNR=30 in cores	3600 sec/pointing, estimated from previous work
Sky Locations	See text for MCC list	Centers of IMF survey regions
Facilities	NEWFIRM (I + wide IR) 6Pack (cloud cores)	NEWFIRM
Science Goals	IMF as function of mass, age, and environment	Outflow identification and physics; impact of outflows on turbulence
Number of Nights	13 optical, 50 IR (NEWFIRM); 5 IR (6Pack)	36 NEWFIRM

4.3 Operating Modes

Two operating modes are apparent from consideration of the science cases. The first is a survey mode for the planning and execution of large scale programs. These will require extensive community involvement (e.g., survey working groups) and will produce substantial public databases. Timely public release of readily accessible data will be an important measure of scientific success. The second operating mode is a general observer mode for the execution of small scale, short duration projects defined and carried out by a single Principal Investigator, perhaps with a few collaborators. This mode is how most 4 m science is done now. We expect that both types of program will be competitively selected. NEWFIRM as a national facility must support both without prejudice.

4.3.1 Survey Mode

In this operating mode large scale programs intended for general public use will be carried out. This may involve tens to hundreds of square degrees of sky observation, many nights of observing time distributed over a lengthy period, and public access to processed data. In this mode the instrument will operate in a pre-planned, systematic way with a minimum of real time decision-making during any night's observations. Filter and integration time changes are likely to be infrequent, and a given region of sky the only nightly target. The telescope and instrument should function semi-automatically for periods of hours with monitoring and occasional intervention by the observer—who may not be a PhD level expert astronomer.

The overall requirements for this operating mode are maximum data system efficiency and consistent observing and data reduction practices for the duration of a survey. Filter changes or telescope motions will probably not be significant overheads compared to detector readout time or data transfer. Consistency in observing and reduction practices will impact the user level software. For example, an appropriate observing protocol, once defined, may be frozen for the duration of the program as an observing macro. Data reduction procedures will need to be similarly defined and then frozen.

Substantial data sets will result from such survey programs, requiring a processing pipeline from raw data to fully reduced and archived data and extracted source catalogs. Three levels of processing can be identified: (1) a real time, "quick look" capability at the telescope to verify basic functionality; (2) overnight processing using procedures sufficient to verify the scientific utility of the previous night's data; (3) a final reduction process at the highest level of sophistication. The need to keep pace with the data flow means that data reduction cannot depend on extensive human interaction. The responsibility for developing appropriate tools and pipelines may be distributed between the NEWFIRM project and the NOAO Data Products Group, which will require careful management. Responsibility for delivery of fully reduced, archive ready data will rest with the Data Products Group.

Retention of raw data and data products in survey mode may use dedicated media or facilities not available to general observers, such as CD-ROM storage or a "disk farm", for efficiency and cost gains particular to this operating mode. Again, the areas of responsibility of the project and of other groups within the Observatory will need careful delineation.

A survey team's legitimate need for a proprietary data period will need to balanced against science enabled by rapid public access. This will be a policy issue for Observatory upper management, outside the scope or responsibility of the NEWFIRM project team.

4.3.2 General Observer Mode

In this operating mode an astronomer using the NEWFIRM instrument will conduct a limited program over a few nights with a specific immediate science goal. Various filters may be used, as well as a variety of integration times, on targets in any accessible part of the sky. All three—filter, integration time, telescope pointing—may be changed frequently. There may be extensive real time decision making and intervention by an expert astronomer as the observations proceed.

The overall requirement for this mode is maximum instrument system efficiency during data taking. Actions such as filter changes, large-angle telescope motions, and guider reset may be significant sources of overhead compared to data system actions. In addition to efficient hardware, user level software must allow clear, easy, rapid system interactions with protection against possibly harmful user errors. While a few standard observing protocols will be offered (and perhaps required, if the observer wishes to use automated processing functions), the user must be able to construct and use special purpose observing macros. The user may also wish to incorporate specific software reduction tools into customized reduction packages. Data reduction may be more time-consuming and more dependent on human interaction than for pipeline processed survey data. Responsibility for developing customized reductions, and carrying out the data reduction process, will rest with the science investigators.

The investigators must be provided with the raw data in its entirety, and any reduced data produced during an observing run, on some medium which is transportable, widely used, and low cost. Data transfer via electronic means will likely be impractical due to the data volume. However, such transfer for limited amounts of data, e.g. compressed images for inspection by remote co-investigators as a run progresses, will be required for effective scientific use of the instrument. General observers will need access at the telescope to sufficient computing power and data storage to take, inspect, and analyze data. We expect this will be the same data system as used for survey programs, with the exception of perhaps different data storage areas.

General observer data shall remain proprietary for a period defined by AURA policy, which presently is one year from the date the data were obtained. Raw data may then be made publicly accessible. Observers will be encouraged to submit reduced data sets for the public archive.

5. NEWFIRM Instrument System Requirements

The scientific drivers and example programs, and the operating modes, described above lead to the following top level, science driven, instrument and system requirements for NEWFIRM. Some of these will be further justified or developed in other documents. Some are still rather loose at this stage to permit various cost/performance trades and optimizations as the instrument definition proceeds.

5.1 The telescope

In order to achieve the sensitivity required for very deep imaging in many of the scientific programs, NEWFIRM shall be designed for the NOAO 4-m telescopes at KPNO (Mayall telescope) and CTIO (Blanco telescope). A choice between prime focus or f/8 Ritchey-Chretien focus shall be made on the basis of scientific performance, instrument cost, and operational impact.

Subsequently, the project has been directed to put NEWFIRM at the f/8 focus of the 4 m telescopes. The design unvignetted focal plane of these telescopes at f/8 is 40 arcminutes in diameter.

5.2 The camera

Under this heading we consider field of view, per pixel sampling, wavelength coverage and spectral resolution, image quality, throughput, and noise. We do not consider optical design; this is a question of engineering implementation.

Since IR arrays are available in discrete sizes with factor-of-two jumps (512 x 512, 1024 x 1024, 2048 x 2048), field of view and pixel sampling are closely coupled. Detector cost places a practical limit on the total number of pixels. Multiside buttable IR arrays are under development but not yet available. The first generation is unlikely to be buttable on all four sides. These considerations place some constraints on science driven requirements.

5.2.1 Field of view

All of the survey science emphasizes coverage of large total fields (many square degrees), while a substantial fraction benefits from contiguous, uniform (in signal-to-noise) coverage. Operationally, telescope time required is directly proportional to field area per pointing covered without duplication.

NEWFIRM shall have a minimum 20 x 20 arcminute field of view per pointing, with 30 x 30 arcminutes as a goal. This total area may be achieved as a mosaic of smaller separate areas. Focal plane geometry shall seek to maximize efficiency for uniform coverage of large contiguous areas. A single filled focal plane is a goal. Rotation of the field of view is not required. NEWFIRM shall be fixed with the sides of its FOV oriented to the cardinal points.

5.2.2 Pixel sampling

Survey science pulls this requirement in opposing directions. The extragalactic imaging science emphasizes detections at modest photometric accuracy over the largest possible area per pointing. This leads to coarse per pixel sampling. The galactic stellar science requires better photometric accuracy, which implies finer sampling of the delivered point spread function. Both are feeding multiobject spectroscopic followup, which requires substantially sub-arcsecond precision in image centroids for placement of small slitlets. Various methods have been developed, for both data taking and data reduction, to improve photometric and astrometric accuracy with undersampled images. The optimal choice may require science trades and may require certain observing modes and data reduction strategies to be supported. This must be investigated further.

For the present, we take the photometric precision requirement to be ±0.03 mag rms and the astrometric requirement to be point source centroid precision of ±0.03 arcsec rms in X and in Y. Limits on precision set by pixel sampling induced systematics (not photon Poisson noise) must allow these requirements to be met.

For purposes of this document, NEWFIRM shall have per pixel sampling between 0.30 arcsec and 0.44 arcsec per pixel, with the high end of this range preferred.

This is consistent with the field of view specification. Both assume a 4096 x 4096 total pixel area as a practical constraint due to detector cost and likely technology improvements.

5.2.3 Wavelength coverage

The JHK bands support the great majority of science. Operation in the sub-micron “z” band enables some further science gain; however, this could also be achieved with optical CCD imagers. The science gain from extension to the L band (3-4 microns) is modest while the engineering requirements on the instrument and data system become quite severe.

NEWFIRM shall operate over 1.1 to 2.4 microns. Extension to 0.85 microns is a goal.

5.2.4 Spectral resolution

The majority of science programs can be carried out with broadband filters. There is also a significant component requiring intermediate and narrowband filters, $10 < R < 100$. In the most accurately quantified programs, Sec. 4.2, the proportion of telescope nights for narrowband science is ≈ 1/4 to 1/3 of the total.

NEWFIRM shall provide spectral resolution capability of $5 < R < 100$. Filters shall be the standard J H K_S K bands plus narrowband filters defined by science programs. Enough filters shall be cryogenically available at any one time to serve both broadband and narrowband science programs.

5.2.5 Image quality

The median delivered image quality of the Mayall telescope is estimated as 1.0 arcsec (J) and 0.8 arcsec (K) for point source FWHM. The Blanco telescope is perhaps 0.1-0.2 arcsec better. Degradation of the delivered image quality has negative science impacts: on star-galaxy separation, on point source photometry in crowded fields, and on resolution of complex morphology. Geometric distortion at field edges makes it difficult to stitch together image mosaics while preserving photometric and astrometric precision. It also degrades precision enhancements achieved by microstepping, since the fractional pixel step at distorted field edges and corners will differ from that over most of the field.

NEWFIRM shall not degrade the telescope delivered image quality by more than 10% in terms of enlargement of the point source FWHM. This includes all instrumental effects: optical performance, pixelization, instrument flexure, and guiding error. Edge of field distortion shall be sufficiently small to permit NEWFIRM to meet requirements for photometric and astrometric precision given in 5.2.2 after distortion correction.

5.2.6 Instrument throughput

Survey efficiency depends on both field of view and instrument sensitivity. Sensitivity is directly dependent on throughput: the fraction of photons arriving at the entrance aperture of the telescope which are converted to photoelectrons at the detector. Throughput depends on the transmissive (or reflective) efficiency of the telescope mirrors, camera optics, and filter, and the conversion efficiency of the detector.

We do not foresee any technological advances in optical coatings, filter performance, or per-pixel performance of detectors that will give NEWFIRM an edge over predecessor IR cameras. Therefore we set as a requirement that NEWFIRM have throughput at least equal to that demonstrated with other IR cameras at NOAO and elsewhere: 0.30 system throughput. Allocating nominal values to the telescope mirrors (0.90), filter (0.80), and detector (0.6), we require a camera optics throughput of 0.70 or better.

Higher values for all of these elements, and resulting highest feasible system throughput, are goals.

5.3 The detector

Field of view is a very strong science driver. NEWFIRM gains its performance advantage for IR survey science from increased field of view achieved by deploying more pixels compared to previous IR cameras. The FOV requirement (Sec. 5.2.1) may be satisfied by multiple, separate arrays, or by a filled focal plane achieved by mosaicing arrays. The largest monolithic format likely to be available is 2048 x 2048. This is in production in HgCdTe (Rockwell) and in development in InSb and HgCdTe (Raytheon). The complexity of deploying multiple smaller format devices (e.g. 1K x 1K) makes this alternative unacceptable. Both manufacturers are developing two-side-buttable architectures to support a 4096 x 4096 mosaic format.

The present per pixel performance of IR arrays is adequate for the required scientific performance. InSb has the advantage of higher detective quantum efficiency and perhaps more uniform intrapixel response, but is not yet marketed in the required format. With NEWFIRM's field size there will be bright stars in nearly every image. Therefore the most attractive technical advance for detectors would be improved immunity to retained charge ("memory") effects caused by bright sources. However we have no science need to support detector development aimed at per pixel performance improvements.

NEWFIRM shall use a 2048 x 2048 monolithic array geometry, and four such elements to meet its field of view requirement. Deployment as a filled 4096 x 4096 array mosaic is a goal. Present per pixel performance in either HgCdTe or InSb sensor material is acceptable. Improved immunity to retained charge effects, at no cost to the project, is a goal. There is no requirement or prejudice as to choice of sensor material or manufacturer.

5.4 Calibration facilities

Achieving the sensitivity and photometric precision required for NEWFIRM science goals requires calibrations to remove the instrument signature. Instrument calibration for IR imaging consists of defining the instrument response to a uniform input ("flatfielding"), determining detector dark current at integration times used for science data, and measuring read noise and other noise characteristics for data quality assurance. Experience shows that flatfields are best determined by some combination of imaging data from the sky and from images of an illuminated target external to the telescope ("white spot") provided by the facility. The only special need for calibrations is the ability to shield the detector from all external photon input for dark current and electronic noise measurements.

The NEWFIRM camera shall provide an internal cryogenic dark slide, at the pupil plane or closer to the detector, to permit "zero background" detector characterization. No other calibration facilities shall be provided.

5.5 The guider

As noted above, degradation of the delivered image quality is undesirable. Experience has shown that unguided, open loop tracking with the 4 m telescopes and the pixel scales under consideration preserves image quality satisfactorily for exposure times up to tens of seconds. NEWFIRM exposures will be considerably longer than this in the shorter wavelength broadband filters (J, potentially z) and narrowband filters. Guide star lock at predetermined positions may also be used for telescope position control when building up mosaics of large areas. Therefore an instrument guider capability is required. This guider must not have any obstructions inserted into the science field, for reasons of both image obscuration and harmful thermal background. Instrument rotation is not required

Table IV gives the number of stars at the north galactic pole brighter than a given V limit in 10 square arcmin (from the Bahcall and Soneira model, numbers from the UKIRT WFCAM project). Poisson statistics dictate a total accessible guider field of ~25 square arcmin to ensure the availability of a guide star at V ~ 17-18. This magnitude limit is consistent with the performance of CCD guide cameras currently used at the Mayall 4 m for MOSAIC guiding.

Table V: Number of Stars at the Galactic North Pole Brighter than the Specified V Limit

V Limit	N
16	0.7
17	1.1
18	1.8
19	2.7

The majority of stars at this apparent magnitude are of late spectral type; and red filtering is desirable to reduce effects of blue scattered moonlight. So red sensitivity (and/or use of a red filter) is desirable for the sensor. Information showing the accessibility of R~16 guide stars over several square degrees in the ρ Oph dark cloud region (kindly provided by the UKIRT WFCAM project) suggests that a radius from science field center of 0.5 degree may be necessary for guide star acquisition in this and similar regions.

Science requirements call for the coarsest pixel sampling consistent with identified levels of photometric and astrometric accuracy. Some of the data taking methods developed for improved photometric and astrometric accuracy with coarse pixel sampling involve precise offsetting of the telescope by sub-pixel steps ("microstepping") on the order of 1/10 pixel. This will be treated further in a separate document. This sets a requirement for the guider to be capable of supporting this mode.

The 4m primary is presently actively corrected in bending moments to provide best possible images. The f/8 secondary will soon be corrected in tilt. In order to establish nightly calibrations for wavefront correction, special imaging sensors are being fitted to the present rotator-guider assembly. Ultimately this may provide continuous closed loop active correction, including secondary despace (focus) control. It would be advantageous for this capability to be present in a new guider, if one is otherwise needed for NEWFIRM. However, there are alternative methods of carrying out the calibrations and checking focus without special sensors.

NEWFIRM is required to have a guide capability external to the science field that (a) has sufficient field of view and sensitivity to insure acquisition of a guide star anywhere in the sky, including galactic poles and dark clouds, under full Moon illumination; (b) has sufficient resolution and precision to allow guider controlled offsets at the 1/10 science pixel level; (c) maintains the image quality specification of 5.2.5; (d) minimizes overhead for guide star acquisition and lock. Provision of means for active optics calibration and continuous correction is a goal. The present 4 m guiders are acceptable if they meet these requirements.

5.6 Instrument control

For present purposes, "instrument control" includes a variety of functions: electronic operation of the IR arrays including data readout and analog-to-digital conversion; monitoring and control of instrument functions and status; interactions with the observing environment (telescope, dome, guider); and interactions with the astronomer user. Science and operating mode determined requirements have to do with ability to operate in all science bandpasses, noise, survey efficiency, and ease of use.

Readout time shall be sufficiently fast to enable imaging in broadband K. Readout noise shall be low enough that data remain background noise limited in all filters. System overheads (time during which signal collection does not occur) shall be minimized, with survey efficiency equal to current instruments (70-80%) as a requirement. User interaction shall allow clear, easy, rapid system interactions with protection against possibly harmful user errors. Definition and execution of automated observing sequences shall be enabled. The user interfaces of instruments presently in use at NOAO (MOSAIC, Osiris, FLAMINGOS) are examples of acceptable implementations.

5.7 Data system

The data handling tasks are collection, processing, storage, evaluation, and delivery of imaging data subsequent to conversion to digital format. Science and operations defined requirements are for speed, flexibility, and adequate levels of sophistication.

Data handling shall not increase system overhead beyond the level specified in Sec. 5.5, and shall not degrade individual input frames in terms of noise or spatial resolution. The data system shall provide images and metrics for real time data quality assurance. It shall provide image processing tools for user defined image manipulation and assessment while observing, and subsequently for off-line reductions. It shall support survey mode observing with an automated pipeline processing system capable of keeping up with the nightly data stream, and incorporating the highest level of sophistication compatible with automation and high throughput. The data system shall provide suitable storage media and retrieval facilities for survey mode and for general user mode operations; these may be different for the two modes.

5.8 System noise

Greatest sensitivity per unit observing time is achieved when the data noise level is set by Poisson fluctuations of the background sky level. Other noise sources are: warm sources external to the camera, background thermal photons originating in the camera, thermal noise in the detector, electronics noise in the detector readout and subsequent data system electronics, and data degradation by insufficient digitization of analog data. Since some significant noise sources are independent of integration time (e.g. read noise), a long integration time may reach the background sky noise limit when a short one does not. However the stability of the background sky itself sets an upper limit to integration time before systematic effects predominate. Experience with IR cameras at the 4 m sites indicates that ~5 minutes is a reasonable upper limit.

Minimizing noise has various implications. The camera must prevent direct or scattered light from warm external surfaces from reaching the detector. The camera must be sufficiently cold that its own thermal contribution to the background is very small. The detector must be operated cold enough to inhibit thermal generation of electrons. Read noise, in the detector multiplexer and subsequent off-array electronics, must be small. Analog-to-digital conversion must have sufficient range, typically 15-16 bits. The system noise budget must track all these contributions.

The instrument system is required to be background sky noise limited in all filters. The contribution of all other noise sources shall be no more than 5% of the background sky noise. Integration time of up to 5 minutes may be used to achieve this.

6. NEWFIRM Instrument System Overview

In this section we briefly describe the instrument system concept presented at Conceptual Design Review. Our purpose is to demonstrate that the top level scientific and operational requirements are met, and to provide a reference concept for subsequent definition of observing scenarios in Sec. 7. References back to top level requirements are indicated in italicized brackets, thus: *[5.3]*. The Appendix tabulates various performance estimates and their implications. This further demonstrates that this concept adequately performs the target science.

6.1 The telescope

The instrument is operated at the f/8 focus of either 4 m telescope *[5.1]*.

6.2 The camera

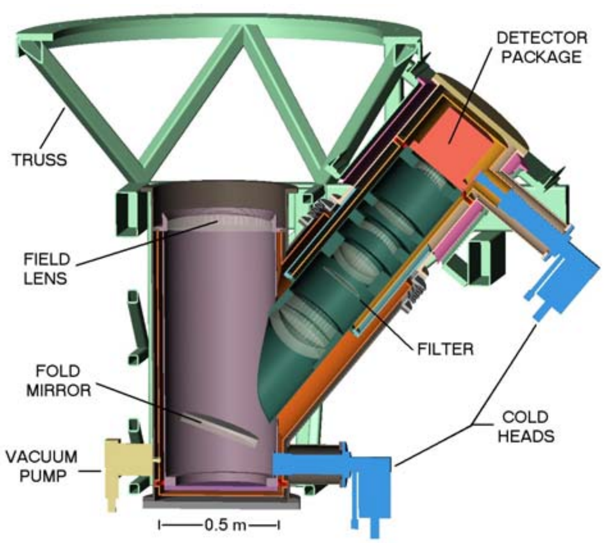

Figure XX. NEWFIRM camera concept.

The camera optical system is a refractive, collimator-camera design with cryogenic filters placed at a cold pupil stop. The dewar is cooled to cryogenic temperature with closed cycle coolers *[5.8]*. The telescope focal plane is outside the cryogenic envelope and is defined by a warm reflective field stop. Cold internal baffles normal to the optical axis are placed along the science beam to trap scattered light. Internal surfaces are blackened. The cavity from pupil stop to detector is light tight except for the aperture necessary for the science beam *[5.8]*.

The plate scale is 0.4 arcsec per pixel *[5.2.2]*. The total field of view is 27.3 x 27.3 arcminutes *[5.2.1]*, realized with a 2 x 2 mosaic of four 2048 x 2048 pixel detectors *[5.3]*. This produces a single field with a cross shaped gap. Gap width is 3% of total linear dimension.

The camera is equipped with cryogenic IR filters as follows. Broadband J H K_S K, a cold dark slide, narrowband (1% resolution) 1.64 µm [Fe II], 2.12 µm H_2, 2.14 µm continuum, 2.17 µm Br γ, plus spaces available for 5 additional filters *[5.2.3, 5.2.4, 5.4]*.

Image quality is 80% geometric energy within a 2 x 2 pixel area, and maximum distortion of 2% at field corners *[5.2.5]*.

The system throughput is 0.3, including telescope (0.9), optics (0.7), filter (0.8), and detector quantum efficiency (0.6) *[5.2.6]*.

6.3 The detector

There are four, 2048 x 2048 IR arrays mounted as a physical mosaic. Each is electrically independent. Synchronization for data taking is effected by the array controller. The detectors are equivalent to Rockwell HAWAII 2 detectors in per pixel performance (see Appendix) *[5.3]*. They are operated at 80 K for suppression of thermally generated electrons *[5.8]*.

6.4 Calibration facilities

A cold dark slide is provided in the filter wheel. The telescope facilities already provide an illuminated target ("white spot") in each dome *[5.4]*.

6.5 The guider

The guider is an external, warm unit mounted on the front of the dewar ahead of the telescope focal plane. It contains two CCD cameras similar to those used with MOSAIC, capable of guding on R=16 stars under full Moon sky illumination (30 degrees or greater distance from full Moon). The cameras access opposite sides of the science field of view; each accesses a strip of 2 x 25 arcmin dimension. Each can be independently positioned. The guide signal is derived from either one, software selected via instrument control. The guider can position the telescope with an angular precision of ±0.05 science pixels *[5.5]*.

6.6 Instrument control

Array control uses an NOAO MONSOON controller (B. Starr, MONSOON Image Acquisition System concept definition document, to be posted to NOAO Website) which meets all requirements for readout speed *[5.6]*, low noise *[5.8]*., etc. Upper level control and communications, including the user interface, is accomplished in a Labview environment. This is based on proprietary software and is similar to the implementation for the CTIO IR imager ISPI (http://www.ctio.noao.edu/instruments/ir_instruments/ispi/, click on "software") *[5.6]*.

6.7 Data system

The data handling system (DHS) is based on the existing DHS for the NOAO CCD Mosaic camera. The DHS architecture consists of modular components (processes) connected by a message bus. IRAF components are used for data processing and image display. Other components provide an instrument interface, a data capture service, a control GUI, and a sequencer. Provision is made for real time quick-look and quick-reduce capabilities, and offline pipeline processing. GUI's are provided for user interfacing. Stored data products include raw data frames, processed and calibrated data frames, mosaics up to ~3 x 3 telescope pointings (~1.5 x 1.5 degrees), calibration frames used for processing, variance (noise) frames and other data quality metrics *[5.7]*. 16 or 32 bit digitization is used as appropriate to preserve the data signal-to-noise ratio *[5.8]*.The data system is more fully described at http://www.noao.edu/ets/newfirm/CODR.htm, click on "Data Processing and Handling".

One possible pipeline processing methodology is shown here.

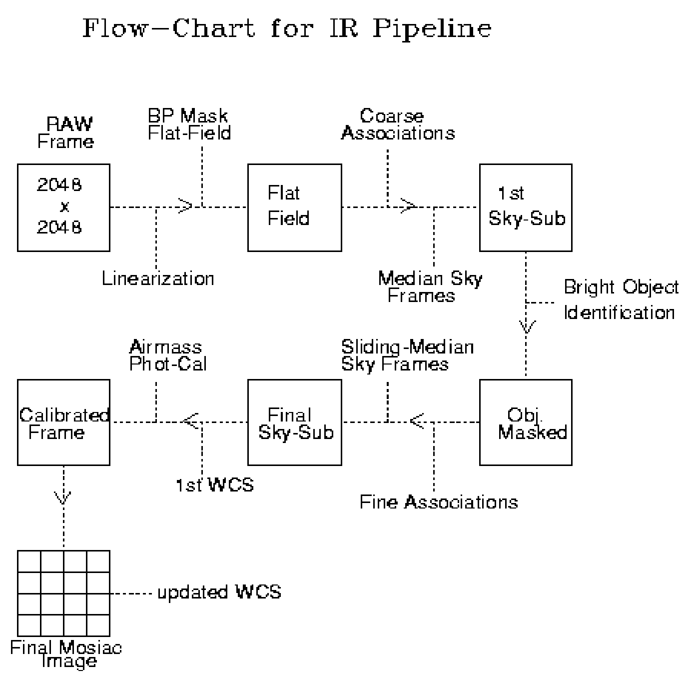

Fig. XX. IR pipeline used to reduce data for Las Campanas Infrared Survey (courtesy Pat McCarthy, OCIW)

6.8 System noise

The camera cold pupil stop and cold baffling block external warm background outside the science beam. Camera internal temperature will be low enough that internal thermal emission is negligible (≈150 K). The detector operates at 80 K, which suppresses thermal electron generation. The multiplexer has adequately low read noise. The array controller electronic noise is specified so low as to be negligible for NEWFIRM. The data system has adequate dynamic range to avoid digitization noise *[5.8]*.

7. NEWFIRM Observing Scenarios

In this section we present the sequences of actions which would be undertaken by the science observer (and/or the instrument system, in an automated fashion) to plan, obtain and reduce data for various kinds of science programs. We shall exemplify extragalactic and galactic science, both “survey” and “general observer” modes, and some range of observing conditions. We present three scenarios that illustrate a range of end use science, and the resulting differences and similarities in execution. Since NEWFIRM is a simple instrument, there are many commonalities in planning, preparation, setup and calibrations, observing and reduction protocols. Any given data set will probably be used for multiple scientific purposes, some identified in advance and others not.

For the planning, calibration, and observing steps, there are resources and tools which can be used or adapted to the purpose, e.g. Digital Sky Survey, Gemini Observing Tool. There will be appropriate macro creation tools and predefined macros for specific purposes, e.g. focus, guide star acquisition, dome flats, that can then be built into observing sequences.

For data reduction and analysis we presume the availability of software tools on three levels with increasing degrees of automation:

1) Quick-look: to verify that the telescope and instrument are functioning normally, and that observing conditions are acceptable; may have highly interactive tools, e.g. focus check.

2) Quick-reduce: to verify that the best protocols are being used for obtaining the data, to check S/N and other characteristics of a data set, and to verify that data are “complete” for subsequent automated processing; likely pipeline-based but with shortcuts such as predefined calibration frames (e.g. flatfields)

3) Pipeline reduction: to provide fully reduced, science ready data products which have been processed in a uniform way and are ready for posting to an archive; the best processing methodologies consistent with fully automated operation

There will also be image manipulation and analysis tools, e.g. in IRAF or IDL, that permit the observer to manually retrieve, manipulate, and interrogate images from the disk. This will be done “offline”, that is, not serially as part of the observing procedures. We expect this to be most useful in non-survey observing programs.

7.1 A deep, large-area extragalactic survey with broadband filters

Science motivation: identification of faint small high-z galaxies

Science flowdown: star-galaxy separation requires good and uniform image quality; achieving moderate S/N (10-20) on faintest possible sources requires high precision sky subtraction and flatfielding; photometric redshifts require photometrically calibrated images; followup observations require good positional information; clustering analyses are best done with fully and uniformly sampled large contiguous areas.

Ancillary science: complementary high-redshift science (e.g. a program aimed at large scale structure definition can also identify individual galaxies of interest outside of its target redshift regime); faint stellar objects in the Galactic halo; distant supernova search or other faint, time-variable phenomena in calibration fields (requires rapid data turnaround).

In what follows we identify 14 steps from idea to science, and qualitatively describe the activities at each step. Actual on-sky experience with NEWFIRM will no doubt greatly aid the definition of observing protocols for sky subtraction, flatfielding, and photometric standards after the first observing runs. We will assume such information exists.

1. Pre-run planning: from the science goals, determine requirements on data and schema for resulting protocols.
   a. Amount of sky to cover, to what depth, in what bands.
   b. Final photometric accuracy required, to set S/N requirements and constraint the protocols for sky subtraction, flatfielding, and photometric calibration.
   c. How to achieve S/N (or required total integration time) through combination of coadded integrations and dithered images.
   d. How to do photometric calibration, e.g. through combination of standard stars or fields, internal fields observed repeatedly, transference of 2MASS magnitudes, transference from data set to standards via observations on another telescope.
   e. How to do sky subtraction, e.g. from data, from reference “empty” sky positions, or some combination.
   f. How to do flatfielding, e.g. from data, reference sky positions, dome flats, or some combination.
   g. Astrometric accuracy required; how to extract relative and absolute astrometry.
   h. How to deal with variable seeing and transparency; under what conditions will data be rejected, and how will program plan accommodate this.

2. Pre-run preparation: this turns the plan into quantified, detailed inputs for highly automated observing.
   a. Determine overall mapping pattern and precise field pointings on sky.
   b. Determine precise dither pattern to be used at every pointing
   c. Identify guide stars for each field, determine corresponding guider X-Y positions, check for guider out-of-range conditions
   d. Iterate mapping pattern if necessary to provide guide star at every pointing
   e. Identify reference sky fields for sky and/or flatfield frames
   f. Identify standard stars/fields, and/or reference fields contained in map
   g. Fix sequence for each night’s observations (calibrations, standards, sky fields,program fields…, standards, sky, program fields…, end of night calibrations)

h. Identify steps at which quick-look intervention is required before proceeding
i. Use observing tool to convert input information into observing macros

Now we are ready to go to the telescope!

3. Daytime setup and calibrations: for system performance assessment and for subsequent data reduction steps. These activities will be executed by standard macros in the NEWFIRM package. This will be a **requirement** for subsequent pipeline reductions.
   a. Dark current exposures at times corresponding to a few standardized integration times; ~10 images at each exposure time (~1 hour)
   b. Dome flats, lamps on – lamps off, accumulating a total of 100,000 electrons in differenced frames; ~10 frames in each filter (~30 minutes)
   c. Execute quick reduction and comparison macros for comparison with standard archived frames; dark current normal? Responsivity normal?
   d. Quick data set for approximate gain and noise derivation and check against standard values; one filter only, plus darks; ~10 minutes
   e. Linearity curve data set, verify gain, noise, linearity; very time intensive; done occasionally by instrument scientist

4. Twilight calibrations: if required by flatfielding strategy
   a. Obtain twilight sky flats using standard observing macro
   b. May need to watch sky levels carefully to meet needs of reduction strategy

5. Start of night setup
   a. Check instrument-to-telescope boresight with substantially out-of-focus image (look for roundness, vignetting, centration of central obscuration)
   b. Do initial focus in each filter using focus macro (~5 minutes/filter)
   c. Check resulting filter-to-filter offsets against standard values, determine best-fit starting focus values
   d. Establish telescope absolute pointing across sky (telescope operator, using telescope macro) (~10 minutes)
   e. Establish telescope to detector relative pointing; default position on detector nominally at center of array mosaic
   f. Confirm correct operation of new mapping and dithering macros by trial with suitable stellar field

6. Standards: If observing standard stars/fields, get initial observations in all filters at end of initial setup observations; then interrupt observing sequence ~1 time/hour to do standard star or standard field in all filters (~10 minutes)
   a. Disable guider
   b. Go to standard star or field (presumes pointing adequate without explicit pointing check and positional adjustment)
   c. Guider not used, short exposures, noncritical pointing and dithering (guider would be used if experience shows need to microstep for standard stars)
   d. Use standards macro, incorporating dithering and filter changes, possibly

integration time changes
   e. Return to next program field
   f. Re-enable guider; proceed

7. Blank sky fields: For extragalactic program, assumed to be occasional and distinct process from program data sequence
   a. Interrupt observing sequence as protocol requires (< once an hour)
   b. Disable guider
   c. Go to preselected blank sky field
   d. Use blank sky macro that incorporates dithering and filter changes (~10 minutes)
   e. Guider not used, short exposures, noncritical pointing and dithering (guider would be used if experience shows need to microstep for blank sky fields)
   f. Return to next program field
   g. Re-enable guider; proceed

8. Observing protocol and sequence: for science data fields, producing a large mosaic
   a. Move to first field nominal position
   b. Verify field ID with short dithered pair of observations (<5 minutes)
   c. Center field with telescope motions; zero telescope pointing
   d. Acquire guide star from pre-selected list. Set guide camera to predetermined X-Y position and let guider lock steer the telescope.
   e. Enable guiding
   f. Execute observing macro
      i. Dither or microstep pattern executed under guider lock
      ii. Integration time at each position prespecified
      iii. Change filter, repeat
   g. While executing, preposition other guide camera for guide star acquisition in next field
   h. Disable guiding
   i. Offset telescope to next field position
   j. Acquire guide star
   k. Re-enable guiding
   l. Execute observing macro
   m. Metasequence including several field positions may be predefined as a supermacro

Proceed with mix of standard star, blank sky field, and science field sequences.

9. Real time checks: this includes use of “quick-look” tools to monitor observing conditions, and “quick-reduce” tools to verify observing protocols and data quality.
   a. Monitor focus, image quality, background level with automatically reported diagnostics
   b. Visual check via realtime display for pronounced anomalies in data
   c. Flag questionable data in image headers
   d. Adjust focus as observing proceeds; autofocus based on telescope environmental parameters (position, temperature), or observer initiated focus macro

   e. Use "quick-reduce" tools on first hour's data
      i. verify observing protocol completeness and correctness for final pipeline processing
      ii. verify data quality, e.g.. signal-to-noise, image FWHM

10. Retake data blocks if necessary: timescale ≥ 1 hour
    a. standard star sequence
    b. mosaic grid, e.g. 3 x 3 pointings

11. Default to a backup program if conditions deteriorate. Backup program(s) may share some calibration data with principal program, but will be independent science data sets with their own protocols.
    a. halt program observing
    b. start backup program
    c. decision made at most nightly

End of night and subsequent activities.

12. End of night calibrations
    a. Do final sets of standard stars/fields per "Standards" above
    b. Obtain twilight sky flats if flatfielding strategy requires them
    c. Execute telescope shutdown procedure
    d. Repeat dome flat sequences as required
    e. Repeat dark current sequences as required
    f. Pipe data to quick-reduce task with definition of flatfield data sets, etc. as required by task
    g. With the last two tasks driven by macros, observer can go to bed

13 . Data quality assessment next afternoon: Quick-reduce operates on night's data on time scale of hours while observer sleeps
   a. Preliminary reductions
      i. sky subtraction,
      ii. flatfielding,
      iii. registration and coaddition of dithered frames,
      iv. mosaic creation
   b. Interactive quality check
      i. S/N adequate?
      ii. Potential problems with photometric calibration?
      iii. Fields contaminated by
      iv. avoidable artifacts such as satellite trails?
   c. Identify fields to re-observe following night; unit field will be 3 x 3 grid, not individual elements
   d. If data complete and acceptable, pass to final pipeline

14. Pipeline reduction: a separate project being pursued in Data Products Group

a. Time scale of days
b. Automated
c. Details TBD, not discussed here

7.2 A targeted narrowband survey of Galactic molecular clouds

Science motivation: identify and trace morphology of molecular flows on degree scale, and obtain physical data on mechanical and radiative energy exchanges with ISM.
Science flowdown: star-galaxy separation requires good and uniform image quality; achieving moderate S/N (10-20) on faintest possible sources requires high precision sky subtraction and flatfielding; photometric redshifts require photometrically calibrated images; followup observations require good positional information; clustering analyses are best done with fully and uniformly sampled large contiguous areas.

Ancillary science: complementary high-redshift science (e.g. a program aimed at large scale structure definition can also identify individual galaxies of interest outside of its target redshift regime); faint stellar objects in the Galactic halo; distant supernova search or other faint, time-variable phenomena in calibration fields (requires rapid data turnaround).

Draft in progress from here forwards as of 01 May 2002

7.3 A “general observer” program for stellar photometry and variability [questionable photometric conditions?]