The FIRE infrared spectrometer at Magellan: construction and commissioning

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The FIRE Infrared Spectrometer at Magellan: Construction and Commissioning

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ABSTRACT
We describe the construction and commissioning of FIRE, a new 0.8-2.5 µm echelle spectrometer for the Magellan/Baade 6.5 meter telescope. FIRE delivers continuous spectra over its full bandpass with nominal spectral resolution \( R = 6000 \). Additionally it offers a longslit mode dispersed by the prisms alone, covering the full \( z \) to \( K \) bands at \( R \sim 350 \). FIRE was installed at Magellan in March 2010 and is now performing shared-risk science observations. It is delivering sharp image quality and its throughput is sufficient to allow early observations of high redshift quasars and faint brown dwarfs. This paper outlines several of the new or unique design choices we employed in FIRE’s construction, as well as early returns from its on-sky performance.

1. INTRODUCTION

FIRE (the Folded-port InfraRed Echellette) is a new medium-resolution near infrared spectrometer, designed specifically for studies of quasar absorption lines at high redshift and radial velocity studies of low luminosity brown dwarfs. It delivers \( R = 6000 \) spectra over a range of 21 orders, covering the full \( z \) to \( K \) bands in a single exposure. It is therefore suitable for a wide variety of general purpose observations, and will be available as a facility instrument for the Magellan community starting in 2010B.

FIRE mounts on the center f/11 auxiliary Nasmyth port of the Magellan I (Baade) telescope, and achieved first light in March 2010. Operating at \( \Delta v = 50 \) km/s for a slit matched to the median Magellan seeing (0.6′′), it resolves out much of the terrestrial OH background, leaving \(~ 80\%\) of each spectrum free of OH contamination and permitting sensitive observations in the dark inter-line continuum regions.

In the best seeing conditions, a narrow slit may be used to achieve spectral resolution as high as \( R = 10,000 \). Magellan’s other infrared spectrograph (MMIRS\(^1\)) is a multi-object instrument that is available during campaigns with the wide field F/5 secondary. The user community indicated additional demand for low-resolution, high throughput single order IR spectroscopy during periods when MMIRS is not on the telescope. To meet this need, FIRE may be reconfigured by replacing its echelle grating with a flat mirror, yielding longslit \( R \sim 300 \) spectra dispersed with the prisms alone.

Details regarding the FIRE’s design philosophy and preliminary layout are described in a previous SPIE proceedings document.\(^2\) The present contribution presents a full discussion of the instrument’s construction, user interface, and on-sky performance. Section 2 describes the instrument subsystems; Section 3 describes software design and data reduction methods, and 4 describes preliminary measurements of instrument performance made during commissioning observations.
2. INSTRUMENT CONSTRUCTION

FIRE’s optical design employs a 50mm collimated beam, which was deliberately kept small in order to constrain the total size of the cryostat. This decision was made in order to reduce complexity, cost, and build time, but also because of stringent weight and moment restrictions for instruments at the Magellan folded ports. Another implication of folded port operation is limited access for servicing, which drove our cooling design towards a closed-cycle refrigerator. This required significant infrastructure development on site during installation, but eliminates the long-term need for regular cryogen fills. By accepting the additional engineering investment for folded port instrument development, we gain a dedicated port on the telescope. FIRE runs continuously without instrument changes, during both dark and bright observing time. This is extremely beneficial for scheduling, particularly for target-of-opportunity science programs (e.g. gamma-ray burst follow up).

2.1 Cryostat and Optical Bench

Figure 1 shows the assembled FIRE instrument dewar. The cryostat is approximately 35 inches in diameter, and 20 inches deep, constructed of welded aluminum by Atlas UHV (Port Townshend, WA). The optical package resides on a 6061 aluminum optical bench, roughly 30 inches round by 2 inches thick. The bench is substantially light weighted, and thermally stabilized by liquid nitrogen immersion and uphill quench in a high-temperature steam bath before final machining.

The bench, whose cold mass approaches 150 pounds when fully loaded, is suspended mechanically in the dewar using four cryogenic grade G10 flexures. The flexures mount to a warm support ring, which forms a vacuum flange and does not deflect upon evacuation of the dewar. The ring indexes directly to the telescope structure and may be articulated to align FIRE’s cold stop with the telescope pupil.

During normal operation, the cryocooler’s cold head (a CTI1050 single stage unit) runs at a temperature of 65K, lifting approximately 65W to maintain the bench an equilibrium of 90-100K. We included a single-layer passive thermal blanket, constructed of aluminized Kapton dressed on a thermally isolated space frame, to reduce
radiative loads. The cryocooler is vibrationally isolated from the rest of the dewar via sorbothane gaskets and vacuum bellows seals. Its cold surface couples to the optical bench via two 1 cm thick by 2.5 cm wide stacks of OFHC copper. A large activated charcoal getter attached to the cold head cryopumps on the dewar, in concert with a Varian StarCell 40 ion pump. We routinely achieve vacuum levels of $10^{-8} - 10^{-9}$ Torr. The long term “hold time” (essentially the period of vacuum integrity) is not yet known, through our experience thus far shows it is at least several months. We attribute part of the cleanliness to the elimination of any thermal or vacuum greases on the dewar. Careful attention to fabrication and protection of flanges and O-rings permits high-vacuum operation without the need for greased seals.

2.2 Optical Fabrication and Assembly

We employed a subsystems approach to the realization of FIRE’s optical train, which was designed and optimized by R. Bernstein. The only powered optical elements in the instrument are a pre-slit Offner relay, the collimator, and the camera. Internal alignment of these systems is challenging, but the relative alignment of the subsystems is fairly forgiving. The sensitive internal alignment of the camera was performed and verified by Jenoptik (formerly Coastal Optical, Jupiter, FL) as part of the fabrication contract. We aligned the internal Offner relay elements in our lab as described in Section 2.2.1. The relative alignments of all subassemblies were then verified using an alignment telescope fixture, indexed to precision-drilled holes in the optical bench.

2.2.1 Pre-Slit Optics

FIRE employs a cold, 1:1 Offner relay in front of the slit to provide an achromatic Lyot stop. This also ensures that diffraction effects from the spectrograph slit, which scatter light into a beam faster than the f/11 beam from the telescope, do not introduce unbaffled thermal backgrounds.

The Offner relay is an athermal design, achieved by constructing both the mirrors and housing from 6061-T6 alloy. The mirrors are diamond-turned spheres, figured on specialized RSA-6061 aluminum substrates. The RSA alloy is specifically designed to yield improved surface roughness on diamond turning, which we deemed important given FIRE’s coverage in the “far-optical” z band. The delivered optics achieved surface RMS roughness of $R_q = 32.18$ Å for the primary and pupil mirrors, respectively. This yields an integrated scatter of 0.16% and 0.08% for the two surfaces. This performance is superior to standard aluminum; it is...
somewhat more rough than electroless nickel coated substrates but does not suffer from any bimetallic bending stress on cool down.

We aligned the Offner internally using a laser bore sight and knife edge. Measurements of the MTF made using a USAF test target (at room temperature) showed contrast on spatial scales corresponding to 0.02″. Cold performance was verified with stellar images through the telescope, which registered FWHM values better than 0.30″ in good seeing. The Offner’s usable field of view is limited to ~1 arcminute because of off-axis aberrations.

2.2.2 Slit Viewing Camera

Since many of FIRE’s most interesting science targets are not visible at optical wavelengths, an infrared slit viewing capability was deemed a high priority for target acquisition. To this end we included a small, custom-built 2.75:1 reimager to project the 1×1 arcminute slit plane onto a subraster of an engineering grade HAWAII-2RG sensor.

The slit viewer is a fixed filter design using an MKO-J bandpass. Designs incorporating filter wheels were ruled out because of severe space restrictions in our dewar, owing to a small clearance between the folded port mounting flange and the telescope’s focal plane. The optical design is all-spherical and refracting, with two doublets of CaF$_2$ and S-FTM-16, and an Infrasil 301 field flattener. Its lenses are radially loaded into precision-machined cells with integrated wire-EDM flexures. This design maintains an athermal centration of the optics. The axial lens stack up is maintained with spacers of varying materials to compensate for thermal contraction, and loaded with leaf springs.

In practice, the slit viewer is used in “manual” mode where images are obtained individually for locating targets and placing objects on the slit. In principle it may also be used for guiding. However, the observatory provides separate optical pickoff mirrors in front of the instrument package for guiding and wavefront sensing. We use the pickoff systems for guiding, and only servo on the slit view occasionally, to check for flexure between the observatory guider and the cold mass during long integrations.

2.2.3 Spectrograph Optics

After passing through the slit, the f/11 beam is collimated by an off-axis paraboloid. The OAP is figured onto a Zerodur substrate and coated with protected gold. It delivers a 50 mm collimated beam to the prism assembly, which is shown in Figure 3.

Optical design of the prisms was a particular challenge because the linear dimension of the H2RG sensor is large, the camera is relatively fast, and the chromatic dispersion of glasses in the infrared is low. Moreover the most dispersive near-IR glass—ZnSe—is only available in limited thicknesses. Many prisms are therefore
required to achieve the angular deviation needed to span the full detector. Our solution incorporates a train of four prisms, two used in double-pass, for a total of six passes. Half are through ZnSe and half through Infrasil 301, which was chosen to balance the partial dispersion across the detector and minimize wavelength variation in anamorphic compression of the beam.

FIRE’s camera consists of three 92mm diameter lenses (CaF$_2$, S-FTM-16, CaF$_2$), and a small Infrasil 301 field flattener. The camera lenses were fabricated, assembled, and aligned into a barrel by Jenoptik (Jupiter, FL). Two of the CaF$_2$ surfaces are even aspheres. These were manufactured by rough turning the aspheric shapes on a diamond lathe, and post-polishing with a magneto-rheostatic (MRF) finishing machine. All other surfaces are conventionally polished spheres.

The lenses are individually mounted in cells using cryogenically qualified elastomeric materials. Like other opto-mechanical elements, the lens barrel and cells were constructed of 6061-T6 aluminum, to provide a good thermal match to the optical bench.

Great care was taken to construct both warm and cold models of the camera. The cold model was used in design optimization, while the warm model was used for fabrication and testing. Rather than employing the standard Zemax-supplied tools for thermal analysis, we explicitly modified the design configurations using custom glass catalogs constructed from the CHARMS database and integrated thermal expansion properties of each material at cryogenic temperatures taken from the NIST Cryogenics Database or the general literature.

For testing purposes, we generated theoretical models of the warm MTF, and a theoretical OPD diagram for interferometric analysis of the optical assembly. Warm interferometric tests at 1064 nm were compared with the theoretical models as a basis for acceptance of the camera package.

2.2.4 Detectors and SIDECAR Readout

FIRE contains two 2.5 micron cutoff HAWAII-2RG arrays: one science-grade device for the spectrograph, and one engineering-grade device for the slit viewing camera. Both are read out using the Teledyne SIDECAR ASIC and associated cryogenic development kit. We performed a full set of test procedures for each array in the University of Rochester’s detector lab. Each array was tested first using a set of standard array control electronics with known low noise characteristics, to provide a baseline. Then, the same sensors were coupled to the SIDECAR to assess the difference in performance and explore techniques to bring the two measurements into agreement (i.e. achieving detector-limited performance).

The detectors themselves are of excellent quality. After correcting for inter-pixel capacitance effects, we measure a quantum efficiency of 88-95% across the $J/H/K$ bands. Their dark current signal is negligible, on order of a few counts per pixel per hour. These characteristics all exceed the original goals laid out for the project, with a direct positive impact on FIRE’s sensitivity.

Read noise is the limiting factor in FIRE’s detector performance (excluding the sky). To match the SIDECAR noise performance with that of the control electronics, we experimented extensively with schemes to isolate power inputs to the SIDECAR system and JADE2 USB controller. Our final solution incorporates a commercial USB-to-fiberoptic converter, powered from the same supply as the JADE2 analog power input. The input power was heavily filtered to reduce common mode noise before being fed to the signal chain. Then, the signal path itself was completely isolated from the dewar ground using nylon or G10 standoffs, all the way to the HAWAII-2RG sensor. With these adjustments, the SIDECAR performed as well as in the Rochester test dewar, and in its highest preamp gain setting, even slightly better. In the lab, we achieved optimal noise performance of 16-18 e$^-$ RMS per CDS read; on the telescope the noise levels are 10-20% higher. We are continuing to work on grounding schemes to bring the noise back to the baseline lab level.

3. SOFTWARE IMPLEMENTATION

The FIRE software suite contains three principal modules. The first module is dedicated to instrument control, the second controls the guider and communicates with the TCS, and the third encompasses data reduction tools.
Figure 4. Screen shot of the FIRE control software suite. A simple set of control commands are issues through the pull down menus and entry fields at upper left. Other windows are used for pressure and temperature telemetry, as well as data viewing.

3.1 Instrument Control

FIRE’s instrument control software is a multi-threaded application written in C. It is intended for use in a Macintosh OSX environment, and uses the Cocoa graphics package to realize windows and controls.

The vast majority of the code base was written by Christoph Birk of Carnegie Observatories, in support of the FourStar project. He kindly provided versions of his code in alpha and beta forms, and helped guide us in implementing tasks specific to FIRE. Given FIRE’s limited options for user control, the interface is quite simple. Observers use drop down menus to select between echelle and prism modes, select slits and detector gain, and run calibration sequences.

Telemetry with remote devices (e.g. temperature controllers, ion pumps, motor controllers) is achieved using simple serial commands. Communication with the detector hosts is more complex. For low level control of the detector, we use the HxRG IDL package supplied by Teledyne with the SIDECAR development kit. This software runs only in a Windows environment, in conflict with observatory standards for mac-based computing. As a workaround, Teledyne incorporated a simple socket server capability into the HxRG code. Our control software opens a client-side thread to the HxRG and sets detector parameters and initiates exposures through this link.

3.2 Slit Viewing Software

The slit viewer is controlled by an IDL widget, descended directly from the public “atv” package developed by A. Barth. The standard atv release includes tools for image display, scaling, zooming, and normal manipulations, as well as simple photometry and image quality analysis.

*http://cryogenics.nist.gov/MPropsMAY/material properties.htm
3.3 Data Reduction

The data reduction pipeline for FIRE builds upon the MASE pipeline\(^8\) for the Magellan/MagE instrument.\(^9\) It is still in beta testing stage, but now produces flux calibrated and combined spectra in both echelle and longslit modes. For each frame, we generate a 2D wavelength map using fits of the background OH lines and/or arc lamp spectra. These maps are in turn used to generate a 2D model of the night sky. The sky model for each order is parameterized by a fast-varying bspine function in the wavelength direction that is also allowed to vary slowly in the spatial direction to correct for illumination effects. We do not use pairwise subtraction as a default; provided that the sky subtraction code leaves small residuals, this leads to a \(\sqrt{2}\) improvement in signal-to-noise ratio.

A fast boxcar extraction is performed to estimate the signal-to-noise ratio (SNR) in each order. Then, orders are optimally extracted in order of decreasing SNR. For orders with high SNR, the weighting is determined by fitting a non-parametric spline to the object’s spatial profile. Intermediate SNR orders are fit with a Gaussian function, and low SNR orders use a Gaussian as determined by fits to adjacent orders. For orders with little or no flux, object positions are estimated by examining the slit position in adjacent orders, or using a standard star as a crutch.
After extraction, a telluric correction is applied. We have incorporated the “xtellcor” routines from Spextool into the FIRE pipeline for this purpose. This software generates reddened model atmospheres of A0V stars and allows the user to scale absorption features appropriately to calibrate out science exposures. This procedure also provides a flux calibration accurate at the ~5% level. Finally, the spectra are combined onto a single wavelength grid and corrected for heliocentric velocity variations.

An example reduced spectrum is shown in Figure 10. Although substantial work remains to be done on the pipeline, the software is well past the point required for assessing data quality and is in fact close to producing science-quality output.

4. COMMISSIONING PERFORMANCE

FIRE’s first light was obtained in March 2010 and has subsequently been in use for 11 additional nights at Magellan. Figure 5 shows an example spectrum of a bright star to illustrate the spectral layout of the orders. We obtained a modest amount of calibration data during this run for the purpose of characterizing image quality and instrument throughput. The following sections describe these measurements in greater detail.

4.1 Image Quality

During the third night that FIRE was on the telescope, we experienced a period of good seeing. We used this time to sharpen the instrument’s focus with respect to the telescope. Internal focus had been verified using a pinhole mask in the lab, indicating an instrument-induced blur of ≤ 1 pixel (0.15") consistent with FIRE’s design specifications. A proper focus of with respect to the observatory’s Shack-Hartmann camera (which controls the telescope primary and secondary) provides an end-to-end test of the full system.

Figure 7 shows the results of this test. Spatial cuts were made across the trace of a bright star (the one shown in Figure 6), in four different locations in the focal plane. One position is at array center, one is at the
We measure a FWHM of 0.29 arcseconds from the array center to the most extreme field angles seen by the camera. This meets the requirements set out for best-case natural seeing conditions at Magellan.

4.2 Sensitivity

We obtained spectra of the spectrophotometric standard GD71 in both longslit and echelle mode, to estimate the instrumental throughput. Relatively few spectrophotometric standards are calibrated as far as $K$; a handful are available from the HST calspec archive, and eventually the ESO X-shooter team will be releasing a new set of southern IR secondary standards. In the interim we use a combination of model atmospheres for our A0V telluric standards to achieve a low-accuracy flux calibration, bootstrapping as required from the (rare) primary standards for more accurate calibration.

Figures 8 and 9 illustrate our preliminary sensitivity estimates for the two modes. The plots show the zero point, defined as the AB magnitude yielding 1 count/second, as a function of wavelength. No corrections have been applied for slit losses, telescope losses, or airmass. This therefore represents a realistic observation, obtained in non-ideal conditions.

Nevertheless, the zero point appears to be fairly flat at 17th magnitude over most of FIRE's range, dropping off in the K band and the very blue. The slit was accidentally positioned far from the parallactic angle during these observations. This fact, coupled with the $J$ band filter in the slit viewing camera, may account for part of the rolloff to the red. Future testing should resolve this question when FIRE completes its commissioning period. The general zero point is consistent with our clear detection of signal in 10-15 minute exposures for sources as faint as $J = 19.7$ (Vega).

The bottom panel of Figure 8 shows an estimate of the instrument efficiency, where we have removed the effects of the three telescope mirrors and slit losses (though no airmass correction is applied). Over most of its bandpass, FIRE’s efficiency varies in the 20 – 25% range.

Figure 9 shows a preliminary zero point calculation for the prism-dispersed longslit mode. The zero point extends 3-3.5 magnitudes deeper in this configuration, consistent with its lower resolution, plus a correction of
Figure 8. Top: Preliminary zero point for the FIRE spectrograph in $R = 6000$ echelle mode. No corrections have been applied for airmass, slit, loss, or telescope losses, representing a realistic observing condition. However the slit was not oriented at the parallactic angle, which leads to extra losses in $K$ (since the slit viewer uses at $J$ filter). The zero point is expressed as the AB magnitude that yields one count per second. Corrections must be applied for objects measured in the Vega system. Bottom: Estimate of instrument efficiency, correcting for telescope and slit losses.

10 – 20% for the increased efficiency of the mirror relative to the echelle grating. This mode suffers however from a substantially increased sky background because of blending among the OH forest. During commissioning, we are exploring the tradeoff in ultimate sensitivity for observations made in both modes.

5. CONCLUSIONS

We have described the construction and commissioning program for FIRE, a new facility infrared spectrograph for Magellan. FIRE’s design philosophy is discussed in detail in an earlier companion paper, the present contribution follows up on this work and brings the project to conclusion. Although FIRE was originally designed for observations of high redshift QSOs and local brown dwarfs, it has already been scheduled for ~ 50 nights in 2010B, for observations ranging from supernovae, to gamma-ray bursts, high redshift Lyman alpha emitters and clusters, near earth asteroids, main belt asteroids, exoplanetary atmospheres, high redshift clusters, X-ray binaries, and more. As a facility instrument, FIRE is available to the Magellan community and (through the TSIP program) to the larger US community as well.

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Figure 9. Zero point for prism-dispersed longslit mode, defined as above for Echelle mode. The fainter zero point is consistent with the lower resolution of this mode $R \sim 350$, but this operation incurs a background penalty because of blended OH lines.

We benefited from useful discussions on visits to the IR labs at the University of Virginia and UCLA. Finally, the FourStar team, especially Eric Persson and Christoph Birk, were extremely generous with their time and resources in helping us develop our instrument and software designs. FIRE’s construction was supported by the NSF MRI program, under award number AST-0649190. We gratefully acknowledge additional support from the Curtis Marble Instrumentation Development Fund, MIT-Kavli Instrument Development Fund, and the MIT Department of Physics.

REFERENCES


Figure 10. Spectrum of a recently discovered $J = 16.5$ T dwarf, taken in $R = 6000$ echelle mode. No telluric correction is applied. Spectra with this resolution are appropriate for obtaining radial velocity measurements of faint brown dwarfs in the solar neighborhood.


