Phoenix: Operation and Performance of a Cryogenic High-Resolution 1 – 5 micron Infrared Spectrograph

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ABSTRACT

At the 1998 SPIE meeting we described a cryogenic, high-resolution spectrograph (Phoenix) for use in the 1 – 5 μm region. At that time Phoenix had been used at Kitt Peak for about a year. In the intervening two years we have worked extensively with the instrument and have modified a few aspects of the design to bring the operational characteristics more closely into agreement with the original specifications. Changes to the instrument since 1998 that resulted in significant improvements in performance will be discussed. We will review the current operational characteristics of the spectrograph. Phoenix is a facility instrument of the National Optical Astronomy Observatory with use planned at Gemini South and CTIO.

Keywords: infrared spectrograph, cryogenic spectrograph, echelle spectrograph, high resolution spectroscopy, infrared array detectors, optical materials

1. INTRODUCTION

Phoenix is a cryogenic, high-resolution spectrograph designed for the f/15 Cassegrain foci of NOAO telescopes, including the Kitt Peak 2.1 m and 4 m telescopes, the CTIO 4 m, SOAR, and the Gemini 8 m telescopes. First light for this instrument was in June 1996. A report[1] was presented at the 1998 SPIE meeting on the design, construction, and performance after approximately one year of use. Operations since then have resulted in considerable insight into the operation of the instrument. As a result of this experience a few mechanical and electrical parts were replaced. It was also necessary to replace the grating because of a materials incompatibility, but no redesign was required. We will report on these experiences. After three years of use a solid understanding of the characteristics of the instrument has been developed, and we will also report on the instrumental performance.

In discussing any instrument it is important to recall that the design is a compromise between scientific goals, engineering constraints, and budget realities. Phoenix exists in its current form because of these often competing influences. The scientific requirements mandated by the KPNO user community demanded a high-resolution IR spectrometer with resolving power ($R=\lambda/\Delta\lambda$) of 100,000 over the 1 – 5 μm wavelength range.

Significant engineering constraints were the size and weight of the spectrograph with the limiting requirement that the spectrograph be carried on the 2.1 m telescope. As a result the weight had to be less than a ton and the vacuum enclosure could not extend more than 1 m below the telescope focal plane. Other constraints were the size and groove spacings of available gratings and the pixel size and count in infrared array detectors.

Budget was a critical aspect of the Phoenix design. Limited funds dictated building as simple an instrument as possible that was capable of achieving the scientific goals. At that time other observatory instruments were costing about $2,000,000 and this was a budget goal. Cryogenic instruments are by nature more complex than similar instruments operating under ambient conditions and the final cost, including the modifications described in this paper and various handling, mounting, and calibration fixtures was $2,700,000.

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2. PHOENIX OPTICS/MECHANICS

The basic features of Phoenix are given in our 1998 SPIE paper[1]. At the heart of the instrument is a spectrograph designed for operation in cryogenic conditions. The spectrograph is surrounded by fixed temperature and floating temperature radiation shields and held in a vacuum vessel. Cooling is supplied by a pair of closed cycle refrigerators. No liquid cryogens are used during the cooling phase or normal operation. The detector is sensitive to photons with wavelengths as long as 5.6 μm, so the instrument must be cooled below liquid nitrogen temperatures, with 68 K the warmest temperature possible without increasing the background radiation on the detector. The seven operable mechanisms are driven by externally mounted motors with flexible drive shafts that pierce the evacuated dewar. Also mounted on the outside of the instrument are the motor controller and array electronics, as well as the cryogenic refrigerators. The second stage of the cold heads extends $\sim$26 cm into the cooled interior of the dewar.

Most features of Phoenix are unchanged since construction and the original report. The three parts of the instrument that have changed, the mechanism control, the grating drive mechanism, and the grating substrate, are reported on in this section. While the refrigeration is largely unchanged, we will discuss the refrigeration because some upgrades have taken place. We will also report on operational experience with the order sorting filters.

2.1. Motor Control

The mechanisms in Phoenix are driven by motors mounted on the outside of the vacuum enclosure. Linkage from these mechanisms penetrates the dewar walls via ferromagnetic feed throughs. Thermal insulation is provided by the use of sections of thin wall fiberglass tubing in the linkage. The alternate design of cryogenic motors was rejected principally because the engineering staff had considerable experience with the warm motor design[2]. While operationally there is no question that these two options are equivalent, we feel strongly that warm motors were a good choice. Linkage connections to the outside of the dewar makes possible the simple, routine measurement of torques to monitor the mechanism performance. It is also possible to manually turn the mechanisms and this has proved useful on more than one occasion.

However, at first light it was obvious that the motor control was not sufficient for an instrument of this complexity. The original motor control system used components built in house and was capable of turning one mechanism at a time at a fixed rate. Three of the mechanisms contain pawls for latching the mechanism into position. The use of a pawl requires backing into place after passing the latch. The one speed of the existing motors would move forward too slowly but backward too rapidly frequently jamming the mechanism. Although new controllers for the existing motors could be designed in house, it was more economical to adapt commercially available motors with integrated controllers. We selected OEM750 motors by Compumotor, which feature a high level RS-232 command interface. We linked the RS-232 control lines to an external ethernet with an EDAS-1025E interface from Intelligent Instrumentation in Tucson.

The replacement of the motors required redesigning the motor mounts, which were upgraded to allow replacement of the motor without disturbing the feed through and breaking the vacuum seal. The motors were also mounted in sealed containers to prevent problems with dust and moisture. The Phoenix motor interface was mounted on the outside of the dewar with a switching power supply used to distribute power to the EDAS interface and seven Compumotors.

The Kitt Peak standard operational control for IR instruments, known as WildFire, is a combination of VME-chassis transputer-based electronics and user interface software running on a Sun computer. Motor control had been implemented with custom electronics controlled via the transputers; the change to Compumotors moved the problem from electronic engineering to software. A separate stand-alone program was written first, using a configuration file to specify the desired behavior for various mechanisms. This allowed software development even when the instrument was not available. Careful separation of functionality from specifics makes this a very versatile control program adaptable for use with future instruments. A socket interface was then added to provide a second command and response path via the existing Tcl-based user interface. The program now runs as a background daemon, keeping its own independent command interface for maintenance. This approach was so successful that a second configuration option was added to the motor control program to handle the serial line interface to the comparison lamp mechanism. However, the current slide mechanisms are not motorized, so the user still has to make a pilgrimage to the instrument for calibration exposures. One problem, discovered in telescope tests and now being addressed, is an inability to cope with noise on any of the control lines, which can lead to loss of motor control for as much as 90s while the daemon is restarted.

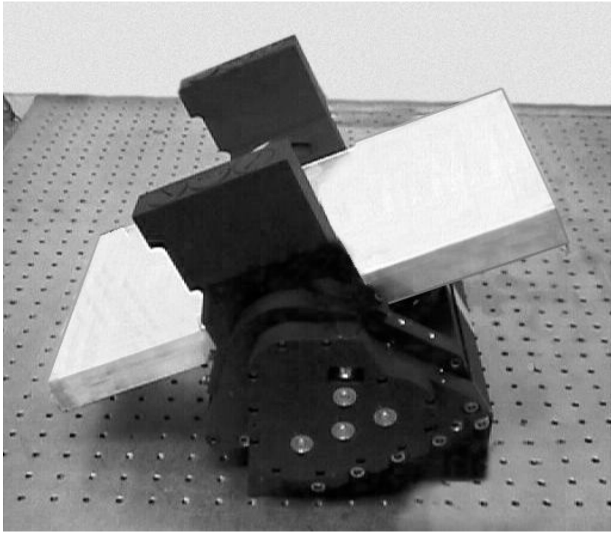

Figure 1. The planetary drive gear box is shown on the side of the grating mount. Counter weights extend above the grating. The counter weights are cylinders of tungsten held in the aluminum boxes. All surfaces that could potentially cause unwanted reflections are bead blasted and finished with hard black anodizing. The grating is 20 x 40 cm.

2.2. Grating Mechanism

As originally built the Phoenix grating pivoted on two large (64 mm diameter) tapered roller bearings. The positioning was done with a worm screw working on a gear at approximately the diameter of the bearing. For a high resolution echelle spectrograph changes in position of the grating of less than an arcsecond result in measurable motion of the spectrum. Three problems were found with the original grating mechanism. First, the worm gear was not capable of holding the grating in position. This had been corrected by installing a solenoid operated brake on the grating. The grating is heavy (8.8 kg) but is counter balanced with tungsten weights (Figure 1). However, the solenoid was very difficult to adjust so that the braking force was adequate. Second, while tapered roller bearings work well under cryogenic conditions, due to the nature of the mechanism the bearing never moved more than a few degrees (typically ± 1 degree). As a result the dry lubricant used in the bearing accumulated on one side of the rollers. These lumps produced undesirable non-linearities in the action of the drive. Third, belleville washers were used to hold the tapered roller bearings in place. The force exerted by these washers was large at cryogenic temperatures and there was concern that the grating mount and even the grating itself could be distorted.

To solve these difficulties with the grating mechanism the entire assembly was redesigned and rebuilt. Precision machined conical bushings replaced the tapered roller bearings. The drive mechanism was a challenge because it had to fit in the available space envelope. A sine bar drive, preferable for a grating of this size and weight, could not be used for this reason. The worm drive was replaced with a planetary gear system with a large mechanical advantage. The gear box and grating drive are shown in Figure 1.

The planetary gear system allows accurate and repeatable positioning of the grating anywhere over the full $\pm 7°$ range of positions. Using this drive it has been possible to position the grating with angular precision of about 30 arcsecond. This is equal to a few percent of the spectroscopic coverage in a single exposure. Stability of the grating depends on the grating being relatively well balanced and there being very little play in the planetary gear train. In operation the only problem has been a tendency for grating drift resulting from unreleased torsional forces in the gear train. We have succeeded in removing most of the wind up in the gear train by reversing the motion of the grating drive by a few motor steps after the grating has reached the desired position.

2.3. The Grating

A major design decision concerned the substrate for the large mirrors and grating. The spectrograph employs a 20 cm diameter Ritchey-Chrétien primary in the collimator/camera and a 20x40 cm echelle grating. There are two distinct choices for optical materials in a cryogenic instrument. Glasses, fused silica, and ceramics (e.g. Zerodur) provide one set of choices. These materials can be worked with traditional optics shop techniques and the cryogenic properties are well known. However, these materials are difficult to cool, having thermal conductivities ~ 1 W/m-K. Glass and ceramics with higher alkali oxide content also suffer from delayed elasticity[3]. Alternatively, metals are frequently used, including aluminum, copper (with and without electroless nickel plating), and beryllium.

Unlike glasses, metals are excellent thermal conductors (conductivities of multiple 100 W/m-K at 77K) and can be diamond turned to produce complex figures. However, dimensional stability[4] and possible hysteresis when subject to repeated cryogenic cycling[5] are issues with metals. Microyield strength of these materials when subject to high g-loads in handling was also a concern.

Since it was known that the instrument would have to endure perhaps hundreds of thermal cycles over its lifetime and also would experience considerable stress from shipping, we found the risk involved in using aluminum optics undesirable. There was also concern about scattered light resulting from a diamond turned finish degrading the 1 μm region performance. An attractive alternative material was silicon. Silicon is a hard, glassy material used extensively in optics for both high-index infrared lenses and infrared filter substrates. The thermal conductivity, specific heat, and elastic moduli of silicon indicated that silicon would work well for the substrates of large cryogenic mirrors[6]. The dimensional stability of silicon is much better than that of metal mirrors[6].

The three major optical elements in Phoenix, the two collimator mirrors and the grating substrate, were fabricated out of silicon[6]. The collimator mirrors were a successful design. These mirrors work well through the visible allowing use of visible light for alignment and calibration. The figures have proven very stable with thermal cycling. The only difficulty, which was foreseen during the design phase, results from the silicon optics being mounted in a collimator support structure made of aluminum. The coefficient of expansion of the aluminum and silicon are quite different so the collimator must be held at a constant temperature if it is to remain in focus. The collimator temperature is regulated by the closed cycle refrigeration. If the refrigeration is functioning normally the collimator does remain in focus. However, the operation of the refrigerators has not been as trouble free as predicted (see below).

The choice of a silicon grating substrate, on the other hand, created a major problem for the instrument. The grating is replicated in an epoxy layer on the substrate by Spectronics using a proprietary process. On the first cool down small spirals of the replication epoxy violently separated from the grating blank peeling up a layer of the grating substrate (Figure 2). Subsequent investigation showed that the epoxy had a coefficient of thermal expansion (CTE) near 45 ppm/K, very different from the few ppm/K CTE of silicon. Degradation of the grating surface continued on each thermal cycle but was limited mainly to the corners of the grating and resulted in no detectable loss of signal in operation. However, after about two years of use the grating substrate crazed over its entire surface (Figure 3). This was a sudden catastrophic event that occurred after the grating was cold. We had been concerned about the grating from the first cool down. However, a great deal of our concern was about 'bimetallic' distortion of the blank. Subsequent analysis never detected any distortion of the blank and optical problems attributed to this were discovered to result from alignment and mounting problems with other optical elements in the collimator.

Several other groups have had success with cryogenic applications using aluminum grating blanks[7]. Despite a lack of engineering data for an aluminum-epoxy interface and concerns about the stability and microyield of aluminum (especially in the replication process), an aluminum substrate seemed most likely to produce a successful grating. An aluminum blank was cut to the same shape as the silicon blank using stock from the center of a 6061-T6 boule. The shape for the blank was generated, the blank uphill quenched, and then final machining was done. Two blanks were produced and compared by optical tests at room and cryogenic temperatures. Both blanks had excellent room temperature to cryogenic temperature stability, with figure changes of ~1 μm over a temperature change of 250 K. One blank was sent to Spectronics for replication and was installed in Phoenix. To date there have been no problems. The aluminum to epoxy bond has not degraded and the grating surface figure is flat to optical requirements and stable.

2.4. Refrigeration

Phoenix is cooled with two closed cycle coolers run from a single compressor. The first stages of the cold heads are connected with multiple thick copper braids to the collimator assembly (Figure 4). The second stage of the cold heads is connected with a thin copper braid to the detector mount. Temperature sensing diodes and resistive heaters on the detector mount are used in a feed back system to maintain the detector temperature at 30$\pm$0.1 K. The rest of the instrument has an equilibrium temperature near 50 K. The instrument requires three days to cool from room

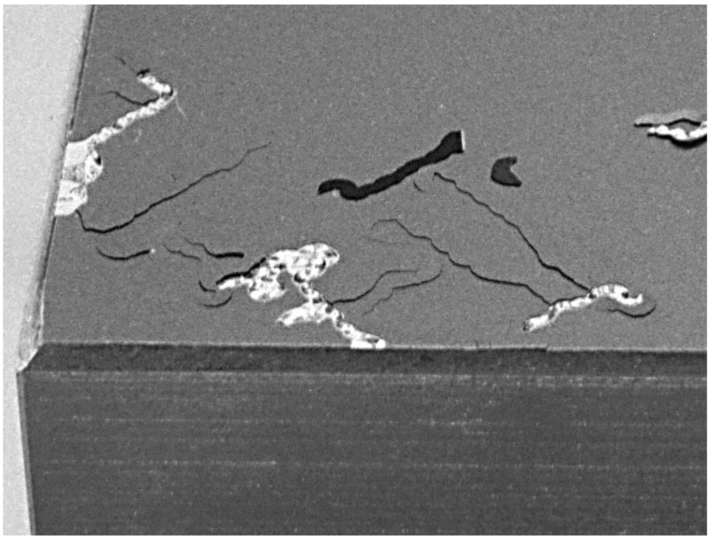

Figure 2. A close up of the corner of the silicon grating blank showing the debonding of the epoxy replica and the silicon substrate. The debonding fractures extended into the substrate. Debonding occurred mainly on the corners and to a much smaller degree along the edges of the grating. Debonding occurred in small areas on every thermal cycle. The grating surface shown here is approximately 5 cm wide by 3 cm deep.

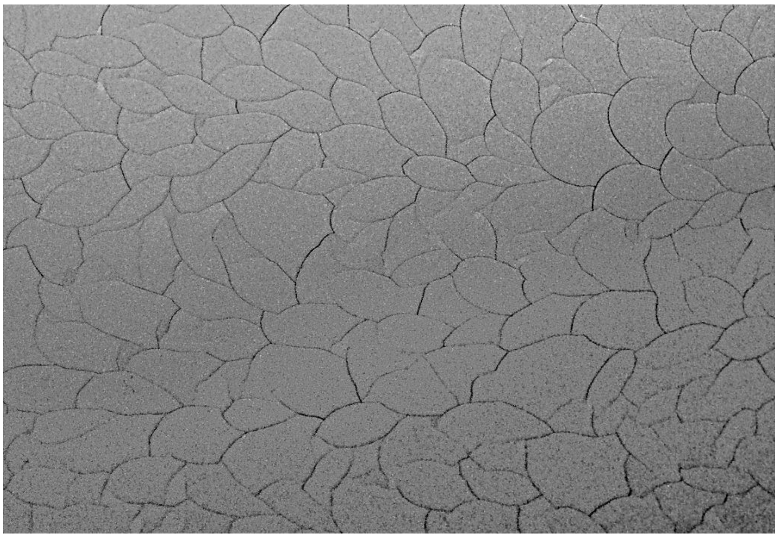

Figure 3. A close up of the grating surface showing crazing of the epoxy replica coating on the silicon substrate. The crazing occurred suddenly over the entire surface of the grating after the grating had been thermally cycled many times. The area of the grating shown is approximately 3.5 by 2.5 cm.

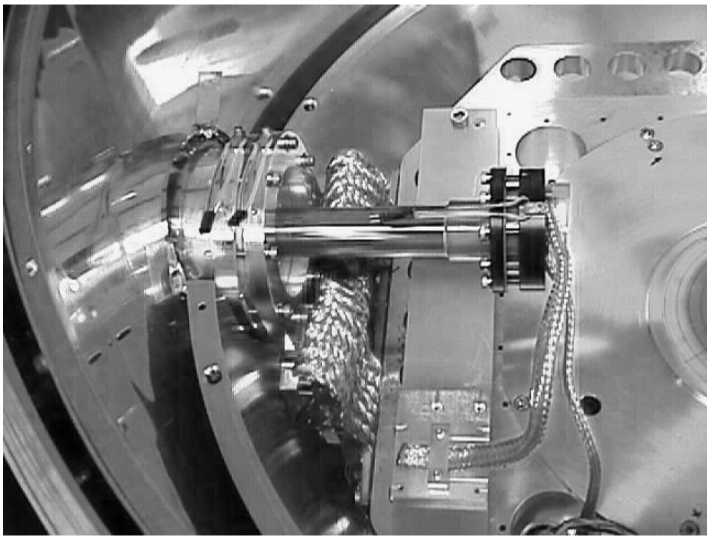

Figure 4. An interior view of a cold head installed in Phoenix. The clamps connecting the first and second stages to the flexible copper braid are shown. The connection between the copper braid off the first stage and the collimator can also be seen. The copper braids off the second stage connect to a getter box (which has been removed for this photograph) and the detector mount.

temperature to operating temperature. Warming to room temperature takes less than one day using resistive heaters mounted on the collimator. Typically, after warming with the heaters, the instrument is backfilled with warm dry nitrogen several hours before opening to prevent any possibility of thermally isolated components frosting.

The cold heads are mounted across the dewar from each other with only flexible connections into the dewar. Vibration damping material is used under the cold head mounting bolts and bellows extend the dewar vacuum enclosure to the cold head. Unlike previous NOAO instruments[2] the heads are not synchronized. No detectable vibration from the cold heads can be measured as image motion at the telescope. Similarly no vibrational motion of the grating can be measured.

The original Balzer 065 cold heads were replaced with Leybold 5/100-2-LV heads because the Leybold units provided more power, had fewer moving parts, and produced lower vibration. We found that the Balzer heads needed overhaul after approximately 4000 hours of use. The manufacturer specified lifetime is more than twice as long. The heads in Phoenix are mounted on their sides and this might contribute to shorter than expected lifetime. As a result of the design differences between the Balzer and Leybold heads, we felt the Leybold heads might have enhanced lifetime. We have not yet determined if this is the case. However, there is no question that it will be necessary to replace the cold heads many times during the lifetime of the instrument. In order to facilitate rapid swapping of the cold heads with unmodified, off-the-shelf cold heads, clamps were designed that attach quickly and easily to the first and second stages of the head (Figure 4). The clamps feature bimetallic parts that shrink to tighten the clamping force.

We have gained considerable experience with the operation of cryogenic refrigerators in an observatory environment. The purity of the input gas is critical. Unlike the case in a laboratory environment the compressed helium line connections must frequently be broken to install or remove the instrument at the telescope. To maintain the purity of the helium entering the instrument cold heads, we have added extra adsorbing tanks at the instrument to supplement the tank at the compressor. We also use only alcohol to lubricate the threads of the fittings. The temperature of the gas arriving at the heads impacts operation but we have yet to confirm the manufacturer specifications. For the Balzer's heads the gas temperature is specified to be at least 10 C. We have encountered problems below 0 C. The gas moves through the heads quickly with a flow rate of 0.21 l/s. With the standard 0.5 inch inside diameter supply line into the head the gas velocity is 1.65 m/s. Any heating of the gas prior to entry into the heads must take this into account.

Since Phoenix does not have a thermally compensated collimator, instrument performance is critically dependent on the operation of the cooling system. Long term variations with periods of more than a few days are not important in Phoenix since the collimator focus can easily be checked every few nights and refocused if required. Since the coolers are run as a pair and are tied to the large mass of the collimator there is considerable thermal capacitance. However, temperature variations shorter than a few days and of more than a few degrees are devastating to the instrument performance. The most common cooler failure mode (with good gas purity) has been failure to cool below ~100 K but we have observed a cold head oscillate between normal operating temperate (~50 K) and ~100 K. We believe these problems to be related to input gas temperature as well as wear of the piston. Our investigation of these problems is continuing.

2.5. CVF

Phoenix has provision for discrete filters in the Lyot space and a circular variable filter (CVF) in front of the slit. The discrete filters are custom made, wedged to prevent fringing, well blocked out of the selected echelle order, and have high in band transmission. On the other hand the CVF is an unwedged filter selected from a catalog to have the appropriate band width. As might be expected, channel spectra are seen in spectra taken using the CVF. The channel spectra are quite strong and consequently little use has been made of the CVF, especially since the discrete filters cover all the frequently used wavelengths. Due to budget limitations during construction, the filter wheel has only 13 positions. One useful application of the CVF wheel has been as a backup position for discrete filters. One slot has an infrared neutral density filter intended to be used to reduce the count rate in imaging mode. This is especially useful in the thermal infrared since the shortest integration time allowed by the electronics (1 second) is near saturation on background radiation.

3. INSTRUMENT PERFORMANCE

Phoenix has been used extensively over the last three years on both the KPNO 2.1 m and 4 m telescopes. From first light Phoenix has been characterized by high throughput for a spectrograph. The slitless throughput in the 1.6 – 2.5 μm region is 13%. Initial observations suffered from high slit losses due to astigmatism in the collimator. After replacement of the grating the source of the astigmatism was tracked to the mounting and alignment of the collimator optics and was corrected. Slit losses are now dependent entirely on seeing, plate scale, and slit size. The two pixel slit width is 0.7 arcseconds on the 2.1 m and the four pixel slit width is 0.7 arcseconds on the 4 m. These are excellent matches to the image quality of these telescopes. Typical throughput including slit losses with a slit matched to image size is ~10%.

Resolution, R, as determined from the full width at half maximum of hollow cathode emission lines is at best 75000. The inverse linear dispersion is given by $\sigma/(2\ f_l\ \tan\theta)$, where σ is the wavenumber of interest, f_l is the focal length of the collimator and θ is the grating angle. The focal length of the Phoenix collimator is 1500 mm. The grating angle is typically within one degree of 63.°4 although considerably larger angles are possible in the 5 μm region at lower orders. The pixel size is 27 μm. Using these values (f_l=1500mm, R=75000, 27 μm pixels, and θ=63.°4), the sampling is 2.96 pixels per resolution element with the two pixel wide input slit.

The mechanical stability of the instrument, which is crucial to high-resolution spectroscopy, is excellent. Flexure of the spectrograph is of order 1 pixel within a zenith distance of 60°. All-sky radial velocity accuracy of 1 km s^{-1} has been obtained over the course of a night. In addition, there is no measurable flexure between the spectrograph slit and the external guiding CCD camera, ensuring a stable fiducial for acquisition and telescope guiding. The greatest challenge to stability is grating motion due to residual torque in the gear train.

Light leakage in the instrument is very small. There is no detectable light leak in the foreoptics of the instrument. When taking long spectral exposures, the brightest sections of the array see a background rate of 0.7 electron pixel^{-1} s^{-1}. The median background over the entire detector is 170 ADU pixel^{-1} in 1 hour, corresponding to 0.4 electron pixel^{-1} s^{-1}. We have not yet resolved this into array dark current versus light in the instrument, but any possible light leaks are in any case not limiting the performance. Furthermore, there are no ghosts or glints of starlight in the foreoptics. There is a low level ghost reflection in the collimator caused by reflection off a shiny surface near the detector, but this has not been a problem in reducing the data.

Data are taken using conventional long-slit IR spectroscopic techniques[8]. Point sources are observed at two or more positions along the slit. Adjacent observations are differenced to cancel out features such as dark current or sky emission common to the two exposures. These sky-subtracted images are then flattened using observations of

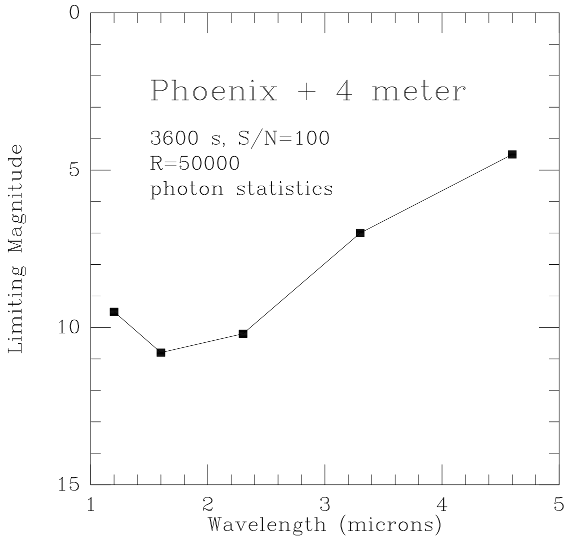

Figure 5. Performance of Phoenix at the Mayall 4-m was measured with the widest slit (R=45,000). This graph is based on measured count rates. As noted in the text the large number of high dark current pixels in the present InSb array can significantly degrade the extracted S/N

a flat field lamp with the same instrumental configuration. The off-plane Littrow configuration results in a loss of orthogonality between the dispersion and spatial axes; the dispersion axis is tilted by $2\overset{\circ}{.}75$ with respect to the array column axis. We have rotated the array to keep the spatial axis aligned with the rows of the array. This is of no consequence to the reduction, since standard extraction tasks (e.g. 'apall' in IRAF) derive the extraction aperture by an empirical fit to the spectrum. At the high resolution of Phoenix the night sky lines are still unresolved but fill very little of the spectral space. As a result the background cancels nicely when differencing images taken at different points along the slit, even with exposure times as long as 1 hour.

The major unsolved issue in observing with Phoenix is how to reduce noise arising from high dark current pixels in the array. While the dark current is statistically low, the array has many high dark current pixels. In very short exposures these pixels do not show up and extracted spectra will have signal-to-noise ratios in accord with the number of counts above background, integrated over a spatial cross cut of the spectrum, times the number of electrons per count. However, as the integration time increases over a few seconds, the signal-to-noise ratio quickly falls away from this expectation. For integration times of more than a few tens of seconds the S/N is about half of the above value. In principle the noisy pixels can be extracted from the image using routines developed to extract CCD data contaminated by cosmic rays. We have yet to experiment fully with these routines. In mid-2000 the array will be upgraded from the current first generation Aladdin array[9] to an Aladdin array from a recent foundry run. A new array should have fewer high dark current pixels.

Current instrument performance is approximated in Figure 5. These values are in agreement with the expectations for an instrument of this design[10]. Figure 5 is based on count rates corrected for high dark current pixels. Additional testing is required near the instrument wavelength limits.

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