SpeX Upgrade for the IRTF

1. Overview and Motivation

The objective of this proposal is to upgrade the NASA Infrared Telescope Facility (IRTF) 0.8–5.5 μm medium-resolution spectrograph, SpeX, with a higher performance near-infrared array and modern array controller. The upgrade will help keep SpeX scientifically productive as it moves into its second decade of operation by improving sensitivity and wavelength coverage, and reducing operational risk by replacing its obsolete array controller. This will involve replacing the current Aladdin 3 1024x1042 InSb array with a 2048x2048 Hawaii 2RG (H2RG) array and the ten-year-old Digital Signal Processor-based (DSP) array controller with an off-the-shelf configurable controller developed for the Pan-STARRS Project. The Motorola DSPs used in the original controller are no longer made and the continued functioning of the controller (and therefore SpeX) depends on the decreasing supply of spare DSP boards we hold (two). With the improvement in read noise, dark current and short wavelength QE (<1.2 μm) through the use of the H2RG array, the gain in sensitivity averages 0.75 magnitudes (or a factor of three in speed) in the short wavelength (0.8-2.5 μm) observing modes, while the larger format and smaller pixels increases simultaneous wavelength coverage and sampling (for better airglow emission line subtraction and telluric absorption feature division) in all observing modes. Apart from a new detector mount and wiring, no other changes to the cryostat are required. The optics are unchanged. To carry out the upgrade SpeX would be off the telescope for one observing semester (six months).

The IRTF is a national facility with 50% of observing time dedicated to NASA mission support and solar system science, and 50% of observing time available to non-solar system science. Telescope observing time is oversubscribed by about a factor of two. Since it was commissioned in May 2000, SpeX has been the workhorse instrument of IRTF. It is currently averaging about 60% of all observing proposals to IRTF and 60% of observing time over the past two years, and because of its versatility, SpeX also has an important role in monitoring and maintaining telescope performance (e.g. measuring image quality and emissivity).

Scientifically SpeX has been a highly productive instrument for IRTF. According to the IRTF Bibliography over 250 papers have cited SpeX data. The upgrade will mostly benefit observing programs that are currently limited by array read noise and dark current (specifically persistence or residual image). In general these are programs that target point sources for spectroscopy (R=50-2000) at short wavelengths ($\lambda < 2.5$ μm). These programs make up over 50% of all SpeX observing. Two particularly active areas of research are programs to characterize asteroids and other small solar system bodies, and programs to identify and characterize low-mass stellar and sub-stellar objects. Small bodies are characterized by measuring solid-state features with the low-resolution prism mode (R~100). Low-mass stellar and sub-stellar objects are identified from spectral energy distributions (SEDs – dominated by molecular features) measured with the prism (R~100) and characterized by measuring atomic and molecular features with the medium-resolution short cross-dispersed (SXD) mode (R~1000). There are also many programs using the SXD mode for stellar and extra-galactic science. By observing fainter targets or larger samples, all these programs will benefit significantly from the factor of three increase in speed that the higher performance array will bring. In addition all other SpeX programs will benefit from the wider simultaneous wavelength cover and better sampling added by the larger array format.

The broader impact of the proposed upgrade is to ensure that the IRTF remains competitive. Forty percent of observing proposals to IRTF have graduate student involvement and over ten percent have a graduate student as PI. Consequently IRTF and SpeX make a significant contribution to graduate student training. Maintaining SpeX is also important for several other projects. The IRTF NEO program not only uses SpeX for spectroscopy, but also plans to use its optical output port to mount a CCD camera for simultaneous infrared and optical photometry. MIT is proposing to mount a CCD camera onto the optical port for simultaneous optical and infrared high-speed occultation photometry and the UH Pan-STARRS project is planning extensive use of SpeX to follow-up red objects found in its surveys. Lessons learned from low background operation of the H2RG array will be of interest to other instrumentation groups. All these efforts are required to maintain SpeX as an effective and working instrument into its second decade of operation.

2. Instrument Description

SpeX (Rayner et al. 2003) is a medium-resolution 0.8- 5.5 µm cryogenic spectrograph and imager. NSF funded the project in 1995 and the instrument has been in operation on IRTF since mid-2000. The design uses prism cross-dispersers and gratings to provide a resolving powers of R=2000 simultaneously across 0.8-2.4 µm, and R=2500 across 2.0-4.1 µm, 2.15-5.0 µm or 2.3-5.4 µm, with a 0.3x15 arcsec-long slit. Selectable wider slits give lower resolving powers. A high-throughput low-resolution R~100 prism mode is also provided for faint object and occultation spectroscopy across 0.8-2.5 µm. An internal K-mirror field rotator allows spectra to be acquired at the parallactic angle to remove the effects atmospheric dispersion which are significant at $\lambda < 2.5$ µm, Single-order 60 arc-second-long-slit modes with resolving powers up to R~2000 are available for extended objects. The spectrograph employs an Aladdin 3 1024x1024 InSb array, and uses narrow slits and a spatial scale of 0.15 arc-second/pixel for optimum sensitivity on point sources. An autonomous infrared slit-viewer is used for object acquisition, infrared guiding, and scientific imaging in the wavelength range 0.8--5.5µm . The imager employs an Aladdin 2 512x512 InSb array that covers a 60x60 arc-second field of view at 0.12 arc-second/pixel.

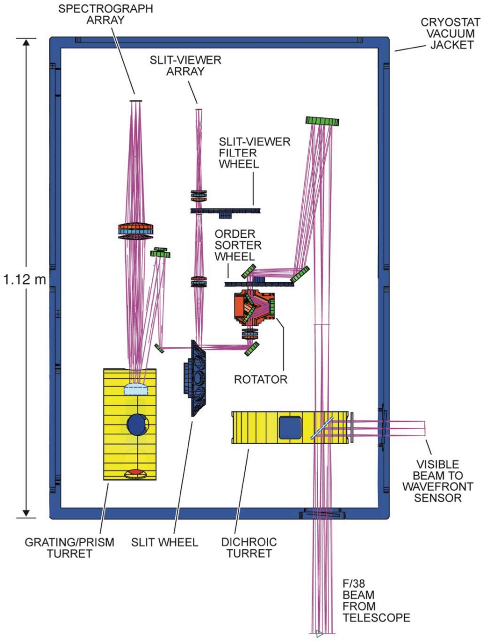

Figure 1. Optical Layout

The optics are cooled to ~75K using a liquid nitrogen can and the detectors are cooled to 30K using the second stage of a closed-cycle cooler. The first stage of the cooler cools a radiation shield to ~120K to minimize the heat load of the liquid nitrogen sink.

An IRTF-designed array controller runs both the spectrograph and imaging InSb arrays. Cryostat-mounted electronics, consisting of preamps, analog to digital boards, clock, and bias boards, are fiber-optically coupled to the array controller, which resides in the telescope control room. The VME64-based array controller uses IXZ444 DSP boards (each containing four DSPs), and a single-board SPARC computer. One controller runs the spectrograph array, and a second runs the slit-viewer array. A PC-based instrument computer mounted on the mirror cell is used for motor and temperature control, and for monitoring tasks. The instrument is run from a graphical user interface running on a local workstation connected to the array controller and instrument computer by

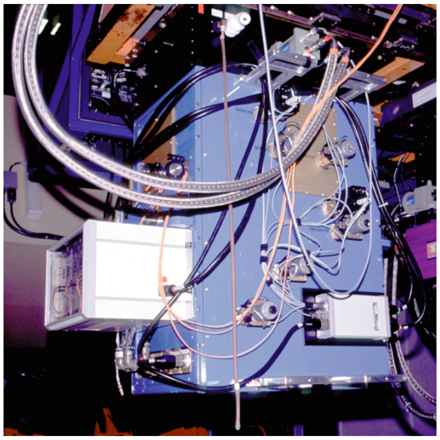

Figure 2. Cryostat on telescope

Ethernet. The majority of observers now run SpeX remotely from their home institutions via a VNC session.

SpeX data is reduced using Spextool (Cushing et al. 2004) which is a GUI-based reduction package written in IDL. Several other infrared spectrographs (including TripleSpec for APO and possibly the versions for Palomar and Keck, CorMASS, and ARIES for MMT) use or plan to use modified versions of Spextool for data reduction.

3. Performance Gains Resulting from the Proposed Upgrade

The performance of the Raytheon Aladdin 3 InSb currently in SpeX and the proposed Teledyne Hawaii 2RG is compared in Table 1. The read noise and dark current data for the H2RG comes from testing of arrays for JWST being done by Don Hall's detector group at the University of Hawaii in Hilo. Most of the gain in sensitivity comes from the improved read noise and dark current. Aladdin arrays are usually quoted as having dark currents ~ 0.1 e/s. However, once exposed to light the arrays suffer from persistence that manifests itself as an enhanced dark current. In our experience this effectively limits the dark current to > 1 e/s (Rayner et al. 2004).

Table 1. Comparison of array performance

	Current Array **:** ***Aladdin 3 InSb***	***Proposed Array : Teledyne H2RG***
Format	1024x1024	2048x2048
Pixel size	27 μm	18 μm
Peak QE	~ 0.95	~ 0.95
AR coating	Single layer (optimized for 1.6 μm)	Broad-band (multiple layer)
Wavelength range	~0.8-5.5 μm (substrate thinned)	~0.4-5.4 μm (substrate removed)
Full well	~ 10^5 e	~ 10^5 e
Dark current	> 1 e/s (persistence)	0.01 e/s
Read noise (multiple samples)	~ 15 e RMS	~ 5 e RMS

The Aladdin 3 InSb is sensitive across the range ~0.8-5.5 μm. The short wavelength sensitivity is limited by the amount of substrate thinning and the single-layer anti-reflection (AR) coating applied to the device by Raytheon. This coating is optimized for ~ 1.7 μm and consequently the AR has a maximum reflectance (36%) equal to bare InSb at 0.85 μm. SpeX is designed to work across 0.8-5.5 μm and the refractive optics are AR-coated (multiple layer) for this range. Since it difficult to get good performance over two octaves of wavelength the coatings are optimized for JHKLL′ and performance is not optimum below about 1μm. These two effects conspire to produce the decrease in throughput (telescope plus instrument, no slit seeing losses) measured at short wavelengths (see Figure 3).

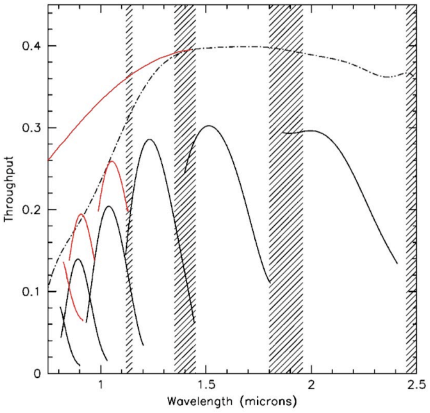

Figure 3. Measured thoughput of SXD mode (grey-solid lines) and prism mode (grey-hashed lines) compared to improved throughput with H2RG (red lines)

In contrast the H2RG has its substrate removed and is multi-layer AR-coated for good response across the ~0.4-5.4 μm. The

CMT detector material long wavelength cut-off at ~5.4 μm is slightly shorter than InSb. The expected improvement in short wavelength throughput with the H2RG is shown in Figure 3.

Using a model of the sky (ATRAN and sky emission lines), telescope, instrument (Figure 3), and detectors (Table 1), observing sensitivities have been calculated for the prism and SXD modes (see Table 2 and 3). The only difference is that a dark current of 0.1 e/s instead of 0.01 e/s has been used for the H2RG since this was the original instrument background requirement for SpeX and we plan no modifications to the light shields. The sky spectrum is smoothed to the resolution of the observing mode. The sensitivity models for the current configuration agree with actual measurements made on faint T dwarfs.

The sensitivity (magnitude relative to Vega) of the prism mode is given in Table 2. At a resolving power of R=100 the background is dominated by OH emission lines at H and less so at K. The sky background is much reduced at J and shorter wavelengths where the improvement in read noise, dark current and quantum efficiency is becomes more significant. 'Speed' is the relative decrease in integration time with the H2RG required to reach the current sensitivity.

Table 2. Prism mode sensitivity, 1 hour 50σ (R=100, 0.8″ slit, 0.7″ seeing)

	Y	*J*	*H*	*K*
Current	18.5	18.4	17.3	17.0
Upgrade	19.3	19.1	17.6	17.4
(Speed)	(x 4.0)	(x 3.0)	(x 1.6)	(x 2.0)

The sensitivity of the SXD mode is given in Table 3. At R=2000 most of the H-band is still dominated by OH emission lines and the sensitivity at H represents an average. In the K-band less than 50% of the pixels have OH emission and the sensitivity is given in clean regions. Similarly for the J- and Y-bands where the OH lines are even fewer and less intense, the sensitivity is given in clean regions.

Table 3. SXD mode sensitivity, 1 hour 50σ (R=2000, 0.3″ slit, 0.7″ seeing)

	Y	*J*	*H*	*K*
Current	14.9	14.8	13.9	14.1
Upgrade	15.8	15.5	14.2	14.8
(Speed)	(x 4.0)	(x 3.0)	(x 1.7)	(x 3.0)

These sensitivity estimates do not take into account image quality improvements that are currently underway at IRTF. NSF is funding replacement of the telescope secondary mirror with a new mirror matched to the primary in order to remove spherical aberration. In good seeing conditions and with the smallest slits used in SpeX (0.3″) the sensitivity can be expected to improve a further few tenths of a magnitude. Furthermore, the finer sampling provided by the smaller pixels of the H2RG array (0.1″/pixel versus 0.15″/pixel) will reduce the effects of under sampling in optimal spectral extraction. The better sampling will also improve OH emission line subtraction.

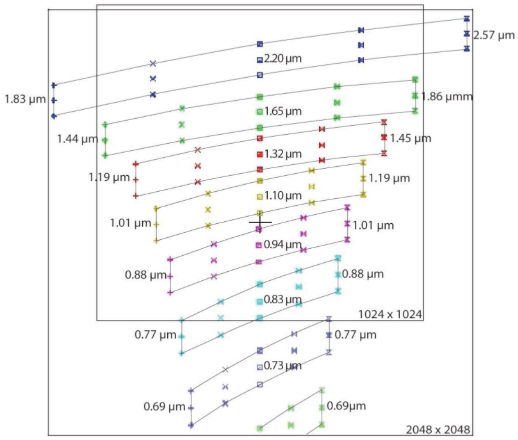

Figure 4. Improved SXD wavelength coverage.

Although the 2048x 2048 H2RG array (36.86x36.86 mm) is bigger than the 1024x 1024 Aladdin 3 array (27.65x27.65 mm) the optics are sufficiently oversized to illuminate it all without any vignetting. The image quality over the full field of the H2RG also supports full illumination (spot RMS better than 36 μm compared to the smallest slit width of 54 μm at the array). Consequently there are significant gains in simultaneous wavelength coverage without any need to modify the existing optics of baffles (with the exception of the baffles which are part of the array mount). The current simultaneous wavelength coverage in the SXD mode is 0.82 μm to 2.42 μm with a gap at 1.80 μm to 1.86 μm in the telluric absorption band. This compromise was made early on in the original design in order to reach R=2000 with the 1024x1024 InSb array. With the HR2G the simultaneous wavelength coverage is ~0.7 mm to 2.57 μm, providing complete coverage from the far optical (depending on brightness) to the end of the CO band-head sequence at ~2.5 μm (the atmospheric cut off). Figure 4 compares the wavelength coverage available with the two arrays. (Note that the arrays are physically centered on the optical axis and stepping the grating turret controls the vertical positioning of the grating orders. The plot just shows the extent of the wavelength coverage.)

In the prism mode the size of the arrays does not limit the wavelength coverage. In the long cross-dispersed (LXD) modes, the larger array simultaneously covers the KLL′M′ bands. This requires two positions of the grating turret with the current array. Due to high background in the M′ band few non-planetary projects can make use of this feature. However, programs doing slit scans of bright planets (Venus, Mars, Jupiter, and Saturn) to construct spectral image cubes (x, y, λ) can make very effective use of the additional coverage.

4. Improved Science with SpeX

The observing programs that will benefit most from the SpeX upgrade are those using the prism (R~100-250) and SXD (R~750-2000) modes at wavelengths ~0.8-2.5 μm where the increase in sensitivity due to improved detector performance is most significant. The broader simultaneous wavelength coverage resulting from the larger array format will also benefit the SXD and LXD (R~950-2500 and ~2-5 μm). Consequently, all science will be improved. Typically 35% of observing programs use the prism mode, 35 % the SXD mode, 25% the LXD modes, and a smaller percentage the long slit (single order) and imaging modes. The prism mode is used predominantly for solid-state features (small bodies and asteroids) and spectral energy distributions (low-mass stellar and sub-stellar objects, faint extragalactic objects). The SXD mode is used mostly to study atomic and molecular features in stars, embedded objects, and bright extragalactic objects, and the LXD mode is used mostly to study atomic and molecular features in stars, deeply embedded objects, and planetary atmospheres. The following sections highlight some of the programs that will benefit most from the proposed upgrade.

4.1 Near-Earth Objects (NEOs) and Small Solar System Bodies

The prism mode is ideal for observations of NEOs, main-belt asteroids, and Trojan asteroids. No other facility provides this combination of resolving power and wide spectral coverage. Since many of the objects targeted for this work are near the limiting magnitude of IRTF the upgrade will allow many more objects to be observed. Flexible scheduling and rapid response of IRTF also help overall efficiency. The IRTF is routinely scheduled for short remote observing periods (typically one to two hours), in which an observer at a remote location can conduct the observations. Since the IRTF is committed to supporting NASA missions and its broad objectives in planetary exploration, the scheduling of the telescope can be optimized for NEO characterization. Currently one night per semester near new moon is scheduled for spectroscopy of any available NEO with SpeX.

Characterization of the surface composition is essential to assessing and reducing the overall impact risk of NEOs. The surface composition provides a first guess at the bulk composition and porosity of the NEO. Characterization also provides a long-term benefit of better understanding NEOs as future stepping-stones to solar system exploration and the exploitation of space resources. Scientific goals for characterizing and understanding the physical properties of NEOs fully overlap with the information and measurements needed for any risk reduction planning.

To quantify the number of additional NEOs one might expect to observe with an upgraded SpeX, we show in Figure 5 the number of NEOs one can expect to observe as a function of V magnitude. We require a S/N of about 50 to obtain good classification of NEOs. This corresponds to requiring an NEO brighter than V=16.5. From Figure 5, this corresponds to about 250 NEOs being observable within 5 years. With the detector upgrade we can expect to go about 0.7 magnitudes fainter at J. This corresponds to an increase of 130 objects per year (50% increase).

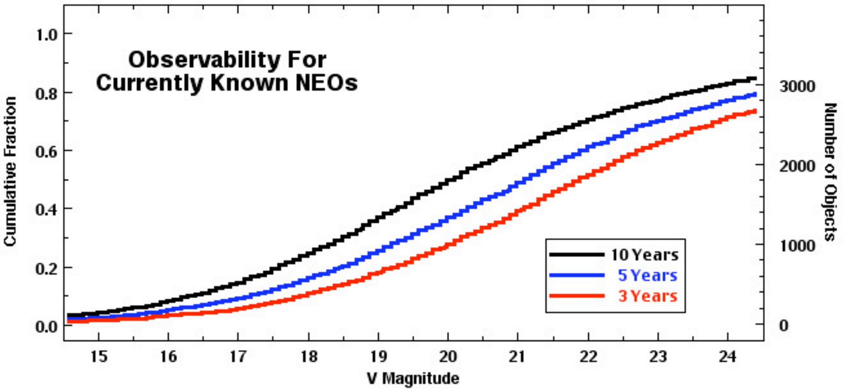

Figure 5. Analysis of NEO observability for 3800 objects known as of January 1, 2006 (R. Binzel and K.Y. Shah, private communication). The magnitude recorded for each object is the brightest opportunity it presents within a time interval of the next 3, 5, or 10 years. This figure depicts what fraction of the total known population can be measured at the V magnitude given on the x-axis. As an example, if allowed to operate to a V = 17.0 mag limit for 10 years, an estimated 15% of all currently known objects can be observed with a signal-to-noise of 50. We expect the number of potential targets to increase dramatically when the NEO survey program Pan-STARRS begins operations next year.

The known close approach of asteroid (99942) Apophis in April 2029 (6 Earth radii miss distance) highlights the insights one can obtain by observing a potentially hazardous asteroid in advance of its encounter with the Earth. The reflectance spectrum of Apophis was observed with the Magellan 6.5 m telescope at visible wavelengths and with the IRTF and SpeX at near-infrared wavelengths (see Figure 6). Also shown in Figure 6 is the comparison to spectral and mineralogical characteristics of likely meteorite analogs. Apophis is found to be an Sq-class asteroid that most closely resembles LL ordinary chondrite meteorites in terms of its spectral characteristics and in terms of its interpreted olivine and pyroxene abundances.

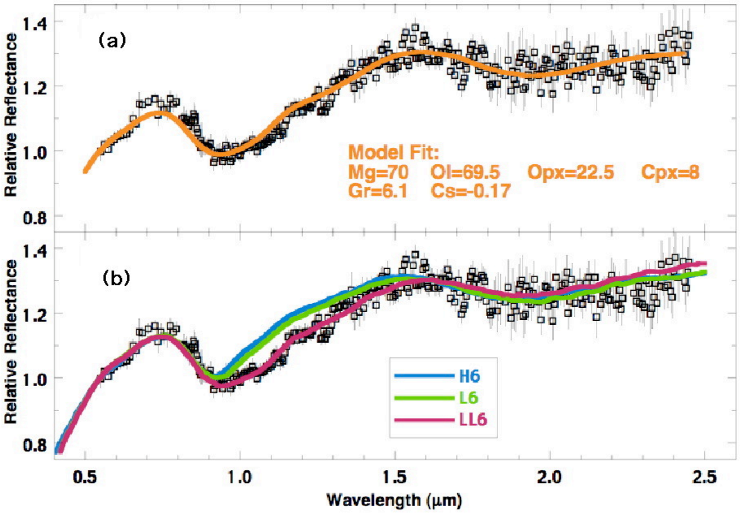

Figure 6. Combined visible and near-infrared reflectance spectrum of asteroid (99942) Apophis, normalized to unity at 0.55 µm (data points) (from Binzel et al. in press). Mineralogical model fit to Apophis is shown in panel (a). The model constituents include olivine (Ol), orthopyroxene (Opx), and clinopyroxene (Cpx). Additional free parameters in the model are Mg-number (Mg), grain size parameter (Gr), and a space weathering slope parameter (Cs). The LL ordinary chondrite class meteorite is the best match to the Apophis data. In panel (b) the direct comparison between the reflectance spectrum of Apophis and laboratory reflectance spectra of ordinary chondrite meteorites is shown. The best match corresponds to LL ordinary chondrites.

We note that an LL-chondrite interpretation for Apophis is consistent with that for (25143) Itokawa, for which in situ spacecraft measurements are available. Using Itokawa as an analogy, this suggests a "best guess" total porosity of 40% for Apophis. Using this best guess yields a mass estimate of 2 x 10^{10} kg and a kinetic energy estimate of 375 Mt of TNT for its potential hazard. Actual unknowns, most notably in the total porosity, allow uncertainties in these mass and energy estimates to be as large as a factor of two or three.

Although we have emphasized NEO observations here, there are active observational programs to study main-belt asteroids and the Trojan asteroids. A major goal in main-belt asteroid research is to understand the extent of the asteroid families (asteroids with a common parent body). Infrared spectroscopy is required to determine which asteroids belong to any particular family. As the brighter asteroids have already been observed, the detector upgrade will permit finding the smaller members of asteroid families. Spectroscopy of the Trojan asteroids is aimed at understanding the origin of these asteroids by looking for variations in the surface composition of these objects.

4.2 Ultracool Brown Dwarfs

Over the past decade, the first digital wide-field sky surveys (SDSS, 2MASS, and DENIS) have enabled a fundamental leap in studying the solar neighborhood and spawned the field of substellar astrophysics. Hundreds of very low-mass stars and brown dwarfs have been identified in these surveys. These so-called ultracool dwarfs (T_{eff} ~ 700-2400 K) populate the new spectral types L and T. SpeX has played a major role in classifying and studying these objects (e.g. Burgasser et al. 2006). Indeed the NIR T dwarf spectral classification scheme is based entirely on data obtained with SpeX (Burgasser et al. 2007, see Figure 7).

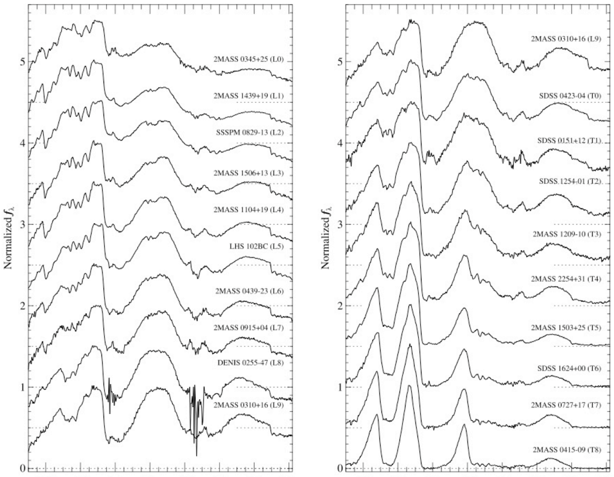

Figure 7. SpeX spectral templates for L (left) and T dwarfs (right) from Burgasser *et al.* 2007.

Identification and characterization of even cooler objects is now a major observational goal for a number of upcoming surveys, including the operating UKIDSS survey (2005 start; 0.95-2.4 μm), the imminent Pan-STARRS-1 survey (2008 start; 0.5-1.05 μm), and the WISE satellite (2009 start; 3-28 μm). Through multi-epoch, wide-field imaging covering most/all of the sky, these surveys are primed to discover hundreds of objects even colder than the coolest known T dwarfs. Indeed, the first discoveries from UKIDSS have already found an exceptionally cold late-T dwarfs with T_{eff} ~650 K (Warren et al. 2007). One key science goal is the discovery of objects cold enough to warrant a new spectral designation, the "Y dwarfs". Several possible triggers have been suggested by theory for a new spectral class, e.g., the appearance of NH_3 in the NIR near T_{eff}~600 K or the disappearance of the alkali lines near T_{eff} ~500 K, but observational discovery will determine the answer. Such objects are considered the missing link between T dwarfs and Jupiter.

Our proposed SpeX upgrade will enable the spectroscopic follow-up needed to take full advantage of these surveys. While these projects will yield many photometrically identified candidates, spectroscopy is essential for confirmation and to determine their physical properties (effective temperature, surface gravity, and metallicity). Even at low spectral resolution, strong water, methane, and molecular hydrogen absorption can be used to spectrally classify objects and diagnose their physical properties, either by comparison to the known T dwarf and/or against state-of-the-art atmospheric models (e.g. Burgasser et al. 2006, Liu et al. 2007, Leggett et al. 2007).

SpeX's prism mode (R~100) is a unique capability, providing high throughput and broad wavelength coverage. The latter is especially useful since the SEDs of the coolest T dwarfs peak in the Y and J-bands, and this is predicted by current models to be the case for even cooler objects. Toward this end, the proposed upgrade will especially boost the sensitivity at these wavelengths (+0.8 mag at Y-band, equivalent to a 4x increase in observing efficiency). As a reference point, models by Baraffe et al (2003) predict that a 1 Gyr brown dwarf of T=500 K will have a mass of 10 M_{Jup} and a J-band absolute magnitude of 19.2. The upgraded SpeX should be able to obtained S/N=50 data in 1 hour on-source. Simulations of the solar neighborhood by Burgasser (2004) suggest about 100 objects of such low temperature within 10 pc, for an $\alpha=0$ slope to the initial mass function (Metchev et al. 2007).

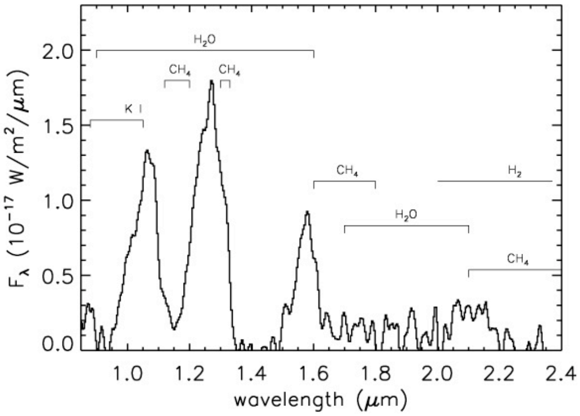

Figure 8. Faint T7.5 dwarf observed with prism mode

An example of SpeX's current value for faint-object spectroscopy is seen in Figure 8, which shows an ultracool (T7.5) dwarf recently confirmed from the UKIDSS survey (Chiu et al. 2007, MNRAS, submitted). With IR magnitudes of YJH = {19.9, 18.8, 18.6}, to our knowledge this is among the faintest brown dwarf spectra of ever published from any telescope. This spectrum was obtained in only 1~hour of on-source integration with SpeX. The prism mode of SpeX makes IRTF competitive with existing spectrographs on 8-10 meter telescopes for low-resolution near-infrared spectroscopy.

4.3 Extragalactic Science

The majority of extragalactic science programs done on IRTF use the SXD mode of SpeX (R=750-2000, 0.8-2.4 μm). These programs exploit not only the multiplex advantage afforded by the broad wavelength coverage of the SXD mode, but also the high overall observing efficiency that results from the use of the infrared slit-viewer/guider in SpeX. Slewing the telescope, object identification, slit positioning (including position angle selection using the internal k-mirror), and the start of guiding can be accomplished within a few minutes, a significant advantage for programs observing many targets. Typical observing programs include a variety of projects requiring relatively large samples of quasars, active galactic nuclei (AGNs) and starburst galaxies. These programs benefit significantly not only from the ~0.75 magnitude increase in sensitivity, either by observing larger samples (x3 increase in speed) or fainter targets, but also from the increase in wavelength coverage resulting from the use of a larger array.

SpeX can be used to study optically selected starburst galaxies for tracers of star formation in the near NIR. Recent models show that TP-AGB stars should dominate the NIR spectra of 0.3 to 3 Gyr old stellar populations (Maraston 2005, see Figure 9). Riffel et al. (2007) used SpeX to construct a 0.8-2.4 μm spectral atlas of AGNs and they found the CN absorption band at 1.1 μm that is attributed to TP-AGB stars (see Figure 10). A sample of starburst galaxies can be used to test these models and develop an independent method of searching for star formation in galaxies insensitive to dust or continuum dilution by an AGN.

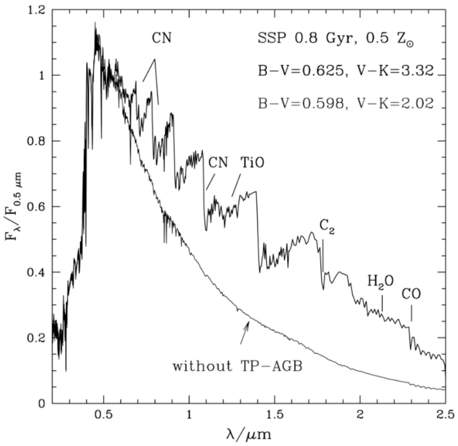

Figure 9. Effect of TP-AGB phase on SED

This technique can also be used to probe star formation in more distant quasar host galaxies. The detection of CN and other tracers of young stellar populations such as Ca and C_2 would confirm the presence of a young stellar population with ages between 0.3 and 3 Gyr in these objects. Such observations would also address the connection between AGNs and starbursts. Given a typical sample quasar magnitude of K~15 and a S/N~50 for unambiguous detection of CN, the upgraded performance is required to reach a reasonable sample size at R~1000 (integration time about one hour). The expanded wavelength coverage stretches from the CN bands at ~0.7 μm to the complete CO band-head at 2.3-2.5 μm.

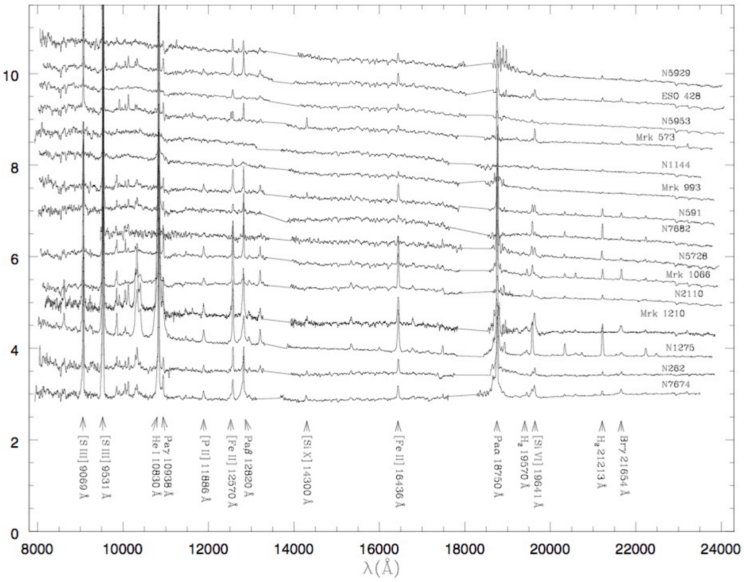

Figure 10. Seyfert 2 galaxies observed with SXD mode and showing 1.1 μm CN band

In related work, it is generally accepted that the onset of AGN activity is closely related to the formation of galaxies through mergers. While buried AGN are found in merging ultra-luminous infrared galaxies, the morphologies of luminous, blue quasars show no signs of interactions. A population of highly reddened quasars may represent the missing link in this evolutionary picture. This population of reddened quasars is being uncovered using radio and NIR surveys (Glikman et al. 2007). SpeX can be used to confirm the nature of the candidates (broad lines R~1000) and investigate for the first time the links between quasar activity and its environment during their phase of co-formation. Given a typical quasar magnitude of K~15, increased sensitivity is of great benefit.

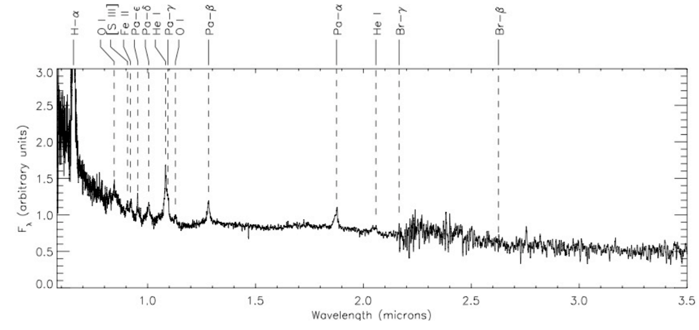

Figure 11. Composite of 27 quasar spectra (shifted to z=0) observed with SXD and LXD modes (Glikman et al. 2006)

The Pan-STARRS 1 System will be a significant machine for discovering high redshift quasars (z ~6-7). Over 100 candidates are expected to be found in the demonstration 5000 square degree survey requiring only a few nights of operation. It is planned to use SpeX extensively on the brighter sources (J<18) to weed out brown dwarfs (!) and other interlopers and measure their redshifts. The upgraded sensitivity would significantly increase the speed of this work.

5. Technical Case

The goal of the proposed upgrade to SpeX is to improve sensitivity and simultaneous wavelength coverage, and to reduce operational risk by replacing the obsolescent array controller (very limited spares). This is achieved by replacing the current Raytheon Aladdin 3 1024x1024 InSb array with the higher performance and larger format Teledyne 2048x2048 Hawaii 2RG array (see Table 1), and by running the new array with an optimized state-of-the-art controller. The new controller will also run the guider/slit-viewer array but this array will not be replaced.

5.1 H2RG Array Requirements

The H2RG array will be procured from Teledyne. Given the work being done to qualify these arrays for JWST the prospects for getting an array of the required high performance (see Table 1) are excellent. Changes to the array mount, wiring, and array controller are required to meet this performance.

The IRTF facility infrared camera, NSFCAM, was upgraded with new optics and a H2RG array in 2005 (NSFCAM2). The upgrade was successful except that the H2RG provided free to IRTF from Don Hall's grant to characterize H2RG devices for JWST is only of engineering grade and is being replaced. The array controller used in NSFCAM2 is an upgraded version of the one used in SpeX, replacing the DSPs with Field Programmable Gate Arrays (FPGAs), for the functions and pixel clocking and pixel output accumulation. NSFCAM2 is an imager and therefore the noise performance of the array controller (~ 20 e RMS) does not need to meet the low noise (low background) requirements of a spectrograph. Significantly better performance is required for the proposed H2RG array controller in SpeX (~ 2 e RMS). The new array controller for SpeX was developed for the Pan-STARRs Project. It is available off-the-shelf and meets all the requirements. This is achieved through a fully programmable design. Improved design methods also ensure better impedance matching in the controller boards and wiring (see Section 5.3). Full programmability of the controller is required to switch between fast read out (~ 1 s) of the array for bright objects where read noise is not a concern to slow read out (~ 5 s) of the array for faint objects where low read noise is critical.

5.2 H2RG Array Mount and Wiring

The H2RG mount developed for NSFCAM2 is too big to fit into the space available for the detector package in the SpeX spectrograph box (see Figure 12). Although the new array is double the format the smaller pixels mean that the array itself is not too big to fit (36.9x36.9 mm compared to 27.7x27.7 mm). Although this requires a new array mount the array mount design in SpeX is modular and is easily replaced with no other changes to the spectrograph box (see Figure 13). The wiring harness path to the arrays will also remain unchanged but the wiring to both arrays will be replaced to interface with the new controller. The only changes required will be to the cryostat vacuum jacket electrical connectors.

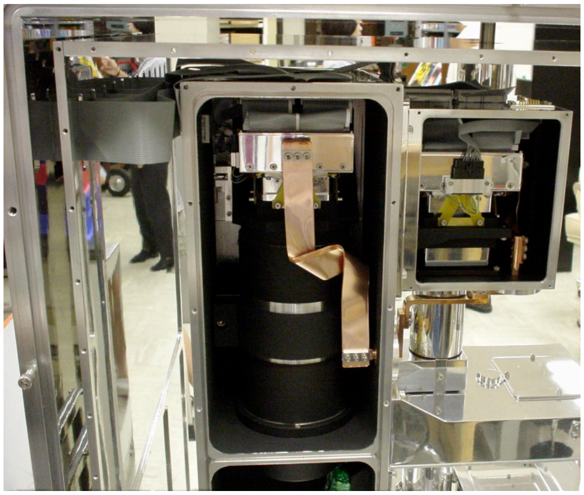

Figure 12. Location of spectrograph array in spectrograph box (center) and path of wiring harness to cryostat vacuum jacket. (Guider array is on the right.)

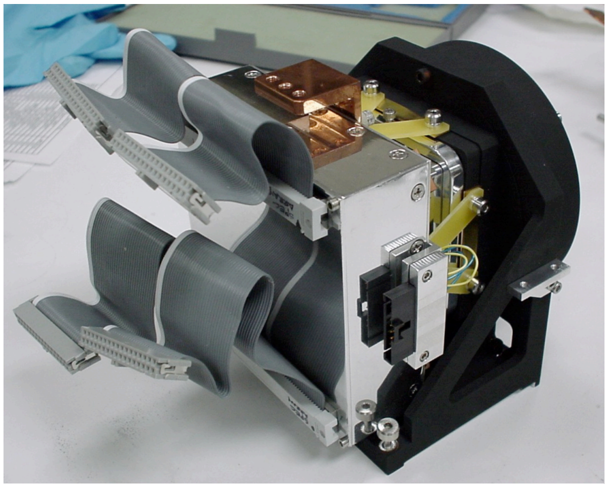

Figure 13. Spectrograph array mount removed from cryostat.

As explained in Section 3 no changes are required to the instrument optics to use the new array. The H2RG array is operated slightly warmer (38 K) than the Aladdin 3 InSb array (30 K) so apart from a simple change in the array mount cooling strap (see Figure 12) to meet the slower cool down requirement and fine tuning of the temperature controller, no changes are needed.

5.3 New Array Controller

We will use a scaled version of the STARGRASP controller developed by Peter Onaka and his group for the Pan-STARRS 1.4 giga-pixel camera now working successfully on Haleakala. STARGRASP was designed to be an off-the-shelf array controller with high channel density, high-speed data acquisition, extreme scalability, low cost and flexible operation. There are three subsystems, the cryostat-mounted chassis, a power supply and a computer connected via a local area network.

The controller chassis has multiple slots that each house a board-set. Each board-set consists of a PowerPC CPU and large FPGA, 512 MB DRAM, 16 10Mhz 16-bit ADCs, and programmable bias and clock level generators, which handles the generation of array biases and clocks and the amplification, digitization and pixel data transport to the computer (called a pixelserver). Control and data transport is accomplished over a 1 gigabit fiber Ethernet interface. The software running on the PowerPC CPU is open source C code. The power supply is an Ethernet controllable multiple output system that supplies the necessary voltages to the controller chassis. The LINUX computer is completely off-the-shelf with no additional plug-in boards and there is no particular favored vendor.

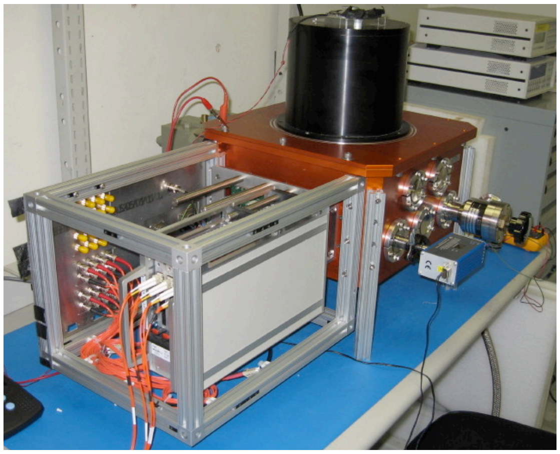

Figure 14. A STARGRASP controller of the same size needed to run SpeX testing a CCD focal plane in the UH Pan-STARRS lab.

The STARGRASP array controller scaled to run the 2048x2048 H2RG spectrograph array and 512x512 InSb guider array in SpeX requires four board-sets. A four board-set controller of the type required to run

SpeX is shown in Figure 14. Compared to the current controller the volume is reduced by a factor of three and the power dissipation from 300W to 75W.

The STARGRASP controllable offers several significant gains over earlier controllers. New design tools were used to control trace lengths on the electronic boards allowing better impedance matching between the controller and array. Noise levels of ~ 2 e RMS are being consistently delivered. All array voltages (bias and clock signals) are software controlled. The clock pattern generation is also generated by software and fed into the FPGA. This ability allows much quicker and easier array optimization tests to be performed and the option to use different clocking modes and speeds to optimize read noise against read out speed for different observing modes. The new controller is also much less costly so we are able to buy substantial spare parts and avoid vendor end of life problems.

Even without the upgrade of the spectrograph with a H2RG array **the SpeX array controller must be replaced if SpeX is to remain operational beyond the next few years** due to limited spares of the now obsolete DSPs used in the current controller.

5.3 Software

The general control software and software control tools for the STARGRASP controller are already written and come as part of the controller purchase. The C code required to clock and run the H2RG array will need to be written but tools are provided for this purpose. The software written to control the H2RG in NSFCAM2 is not useable because it was developed for a different controller. All of this development will first be done with the MUX and then the H2RG array in a lab test system independently of the instrument. Further optimization will be done once the array is installed in SpeX.

The IDL-based Spextool data reduction package (Cushing et al. 2004) will have to be modified. Although spectral order finding and spectral extraction is automatic, the code does require approximate starting positions and so recalibration will be required. New instrument profiles and bad pixels maps will need to be obtained and incorporated into the code together with corrections for non-linearity of the new array (Vacca et al. 2004).

5.4 Expanded instrument capabilities

Once the new array and controller are achieving low background performance other new instrument capabilities can be considered. These include replacing the gratings in the cross-dispersed modes to double the resolving power to R=4000 (which requires good low-background performance). This also means halving the slit length to accommodate the extra orders. However, it is expected that the H2RG array will be more background stable than the Aladdin arrays. Consequently, AB nodding in the slit will not be required, data can be reduced like CCD data, and so a shorter slit is acceptable. Another possibility is to use OH rejection filters to reduce sky background. These filters are currently too thick (~1mm per line) to remove enough lines to be useful but progress is being made. These options can be considered once better noise performance is achieved. For now IRTF users want better sensitivity rather than higher resolving power.

6. Project Management and Budget

6.1 Project Manager.

The PI, John Rayner, will provide overall leadership and management for the project. The project manager will conduct weekly progress meetings, help set priorities, monitor expenditures, and expedite work required to meet established milestones. He will also provide the day-to-day oversight of the technical staff.

6.2 IRTF Oversight.

Co-I and IRTF Director, Alan Tokunaga, will consult with Rayner on issues affecting IRTF. Particular attention will be paid to the scheduling of SpeX downtime to install the H2RG array and new controller since SpeX is most heavily instrument on IRTF. Rayner will work with Tokunaga on allocating IRTF staff resources.

6.3 Project Scientist.

Rayner will act as Project Scientist for the upgrade. He will be responsible for setting the science requirements and ensuring that they are met. He will also be responsible for testing the array in the lab and will conduct the commissioning of the upgraded instrument on the telescope.

6.4 Schedule.

The anticipated length of the upgrade project is two years (see Table 4). Following funding we will procure the array and array contoller. The assembly and testing of the array controller together with the design and fabrication of the array mounts will be done within the first six months. There will then follow six months of testing and characterization of the array in the lab test dewar. Only following successful completion of this phase will SpeX downtime be scheduled. Since the telescope is scheduled in six month observers semesters a pause is built into the schedule at this point to reduce overall risk to the observing schedule. SpeX will be removed from the observing schedule for six months to complete the array and controller installation, for testing, and for re-commissioning.

Table 4. Upgrade schedule and effort

	Year 1				Year 2				Effort (man-weeks)
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	
Project Manager/Scientist	1 w	1 w	1 w	3 w	1 w	1 w	4 w	4 w	16 w
Senior Electrical engineer	2 w	2 w	4 w	2 w			4 w	2 w	16 w
Software (controller + array)	2 w	4 w	4 w	2 w			2 w	2 w	16 w
Mechanical engineer	4 w	4 w					2 w		10 w
Machine shop fabrication		8 w							8 w
Technician (ME+EE)	2 w	2 w	2 w	2 w			4 w		12 w
Software (modify data reduction)								4 w	4 w
Total effort (man weeks)	11 w	21 w	11 w	9 w	1 w	1 w	16 w	12 w	82 w
Procurement	🟦								
Build and test array controller	🟦	🟦							
Design array mount	🟦								
Fabricate array mount		🟦							
Test MUX and array in lab			🟦	🟦					
Schedule SpeX downtime					●				
Install controller/MUX in SpeX, test							🟦		
Install array in SpeX, commission								🟦	
Upgrade complete								🟥	

6.5 Budget.

The cost of the Teledyne HAWAII 2RG infrared array ($400k) and multiplexer ($10k) is based on a quotation from the vendor. The boards that make up the array controller are available off-the-shelf from the camera controller group at the IfA. The cost of the controller is $80k, and the cost of spare boards is $36k. We are also requesting additional boards so that we can maintain a stand-alone lab test system ($18k). The lab test dewar is already built. The lab test system is needed to fully characterize the array and controller before removing SpeX from the telescope. Our experience is that an independent test system is critical to trouble-sheet problems encountered at the telescope efficiently. Two array mounts will be built, one for the instrument and one for the lab test system. The total cost of hardware is $544k.

Our manpower requirements are based on work completed on very similar projects (array controller assembly and testing, array and controller software, array mount design and fabrication, cryostat wiring, SpeX data reduction software). The total manpower required is 82 weeks (1.7 man-years). The cost of the Project Manager/Scientist (Rayner) will be paid for by IRTF. The IRTF oversight effort provided by Tokunaga is not included in the manpower estimate and will be paid for by IRTF. The cost of the effort for which NSF funding is being requested (66 weeks) is $221k. This includes no contingency. Any additional resources required will be paid for by IRTF.

6.6 Experience, Resources, and Facilities.

The PI, John Rayner, will have overall responsibility for the upgrade project. Rayner was PI on SpeX and is also the astronomer responsible for its operation at IRTF. He is also currently Instrument Scientist for the Gemini Precision Radial Velocity Spectrograph. Senior Electronics Engineer Peter Onaka will be responsible for the array controller and array electronics. He developed the array controller currently being successfully used in the Pan-STARRS camera a scaled own version of which will be used for the upgrade. Onaka has worked on all previous IRTF facility instruments, including SpeX. Software Engineer Charles Lockhart worked on the array control software for the engineering grade H2RG array in NSFCAM2. Mechanical Engineer Vern Stahlberger has worked on all previous IRTF facility instruments, including SpeX. Mechanical and electrical technician Greg Ching was for technician for SpeX and several other facility-class instruments. Mike Cushing wrote the Spextool data reduction package and will be modifying it to work with the new array.

The array controller assembly and testing, and initial array testing will be done in the IRTF Lab in Honolulu. Fabrication of the array mounts will be done in the IFA machine shop in Honolulu. SpeX will be brought down to the IRTF Lab in Hilo for installation of the array and array controller, and for initial all-up testing. The instrument will be transferred back to the telescope for full commissioning.

7. Broader Impact

The proposed SpeX upgrade will help to keep the US astronomical infrastructure competitive by providing critical observing capability for the astronomical community. Since the IRTF is a national facility, the proposed work benefits a broad range of researchers at major research centers at universities and small colleges. Remote observing is used by 50-60% of the observers at the IRTF. Typically the observer will work at his or her institution, saving time and money in traveling to Hawaii. This type of remote observing allows undergraduate and graduate students to participate in conducting the observations and in much greater numbers than previously. Remote observing thus “levels the playing field” by providing convenient access for researchers at smaller institutions and departments (such as Rowan College, Ithaca College, Iona College, Univ. of Toledo, Cincinnati Univ., Univ. of North Dakota, Univ. of Central Florida). However, it is the policy of the IRTF that classical observing is welcomed and researchers often bring students to the observatory for training and inspiration. At the IRTF we recently had a very positive experience mentoring a Research Experiences for Undergraduates (REU) student who used SpeX for observations of asteroids. Forty percent of observing proposals have graduate student involvement and over ten percent have a graduate student as PI. Consequently the IRTF and SpeX make a significant contribution to undergraduate and graduate student training over a much broader range of institutions than a typical observatory.

Maintaining SpeX is important for several other projects. The IRTF NEO program as well as needing SpeX for spectroscopy plans on using the its optical output port to mount a CCD camera for simultaneous infrared and optical photometry. MIT is also proposing to mount a CCD camera onto the optical port for simultaneous optical and infrared optical high-speed occultation photometry. The UH Pan-STARRS project is also planning extensive use of SpeX to follow-up red objects found in its surveys. All these efforts are required to maintain SpeX as an effective and working instrument into its second decade of operation.

The PI, Mike Cushing and Bill Vacca are engaged in producing a 0.8-5 μm spectral library using SpeX. These data are being made available on the web in advance of publication (http://irtfweb.ifa.hawaii.edu/~spex/WebLibrary). Many programs from star formation, brown dwarf spectroscopy, and galaxy evolution will benefit from this spectral library. A major data reduction software package, Spextool, was developed to support the SpeX observations. This software is continuously updated and has been made available to other projects that wish to adapt it to their needs. The IRTF also makes available upon request the SpeX user interface software. Thus, the software developed for SpeX has had a very positive effect on instrumentation at other institutions.

The engineering work done optimizing the H2RG to work under low background conditions will have use beyond IRTF. Other groups will undoubtedly need to operate these arrays in spectrographs at low background. The controller is commercially available from the University of Hawaii and the code to run the array will be made freely available.