Matthew J. Richter, Kimberly A. Ennico, Mark E. McKelvey and Andreas Seifahrt, "Status of the Echelon-cross-Echelle Spectrograph for SOFIA", Proc. SPIE 7735, 77356Q (2010).



http://dx.doi.org/10.1117/12.856515

# Status of the echelon-cross-echelle spectrograph for SOFIA

Matthew J. Richter[a], Kimberley A. Ennico[b], Mark E. McKelvey[b] and Andreas Seifahrt[a]

[a]UC Davis Physics Department, 1 Shields Ave, Davis, CA 95616, USA
[b]NASA Ames Research Center, Moffett Field, CA, 94035 USA

## ABSTRACT

The Echelon-cross-Echelle Spectrograph (EXES) is one of the first generation instruments for the Stratospheric Observatory for Infrared Astronomy (SOFIA). It operates at high, medium, and low spectral resolution in the wavelength region 4.5 to 28.3 microns using a 1024x1024 Si:As detector array. From SOFIA, the high spectral resolution mode (R $\approx$ 100,000) will provide truly unique data given the improved atmospheric transmission. We are currently involved with system testing in preparation for our first ground-based telescope run to occur in Jan 2011 at the NASA IRTF 3m. We present the current status of EXES including lab results in our high and medium resolution modes, our plans for ground-based observing, and our expectations for operations on SOFIA.

**Keywords:** SOFIA, astronomical instruments, mid-infrared, spectroscopy

## 1. INTRODUCTION

The Stratospheric Observatory for Infrared Astronomy (SOFIA) is a platform capable of bringing large instruments above 99% of the atmospheric water vapor. From this altitude, where the pressure is roughly one quarter that of sea level, transmission through the atmosphere is much better, particularly in the infrared. One scientific niche enabled by SOFIA is high-resolution spectroscopy at wavelengths unavailable from ground-based observatories. We are building the Echelon-cross-echelle spectrograph (EXES) to exploit this opportunity for unique science in the mid-infrared part of the spectrum.

The main emphasis of EXES, a PI class instrument, is high spectral resolution in the mid-infrared, roughly 4.5 microns to 28.3 microns. Using a large, coarsely-ruled grating, we will achieve R $\approx$ 100,000 in our standard observing mode. Medium and low spectral resolution science modes are also available. In addition, we have non-science imaging and pupil imaging.

During the last two years, a collaboration between UC Davis and NASA Ames has taken leadership responsibility for EXES from the original PI, Prof. John Lacy of UT Austin. All existing hardware shipped to NASA Ames in July of 2009. Over the past year, the new team has grown familiar with the instrument and we have made significant progress toward completing EXES. We have proposed for and received telescope time at the NASA Infrared Telescope Facility 3m on Mauna Kea. Our observing run is scheduled for Jan 2011.

Elements of EXES have been described in a series of past proceedings[1–4] but the change of development team and system integration done in the lab provide an opportunity for a new overview of the instrument here. In Section 2 we will provide an overall description of the instrument design. In Section 3, we will discuss the current status and near-term plans.

Further author information: (Send correspondence to M.J.R.)
M.J.R.: E-mail: mjrichter@ucdavis.edu, Telephone: 1 530 752 2226
K.A.E: E-mail: Kimberly.Ennico@nasa.gov, Telephone: 1 650 604 6067
M.E.M.: E-mail: mark.e.mckelvey@nasa.gov, Telephone 1 650 604 3196
A.S.: E-mail: seifahrt@physics.ucdavis.edu, Telephone 1 530 554 4504

Ground-based and Airborne Instrumentation for Astronomy III, edited by Ian S. McLean,
Suzanne K. Ramsay, Hideki Takami, Proc. of SPIE Vol. 7735, 77356Q · © 2010
SPIE · CCC code: 0277-786X/10/$18 · doi: 10.1117/12.856515

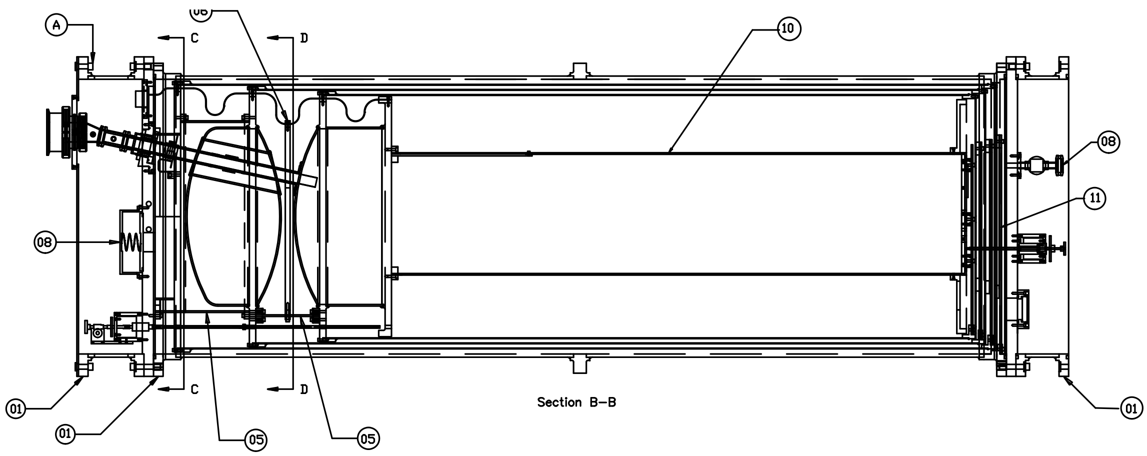


Figure 1. A view of the cryostat from the assembly drawing showing a side view of EXES as it will mount to SOFIA. The aft end is to the right and the entrance window can be seen toward the bottom of the aft end. The cryogen reservoirs are toward the forward (left) side of the drawing. The optics box is the large rectangle in the center of the drawing.

# 2. A DESCRIPTION OF EXES

## 2.1 Mechanical and Thermal Design

EXES is a liquid helium cooled instrument. The cryostat is a large, aluminum cylinder made by Precision Cryogenics. It is roughly 24 inches in diameter and 72 inches long. There is a stiffening ring at the midpoint of the cryostat shell to prevent bending of the cylinder. End rings are at both ends to protect external, warm mechanisms. The total weight of the cryostat, including components mounted to it, is roughly 600 pounds. The cryogen reservoirs are at the forward end, as mounted on SOFIA, with the window on the aft end toward the telescope. A view from the cryostat assembly drawing is shown in Figure 1.

There are two cryogen reservoirs, one for liquid nitrogen and one for liquid helium. Both reservoirs are cylindrical. The fill tubes extend toward the forward end plate and are offset vertically above the midline. The liquid nitrogen reservoir has two hemispherical end caps and an offset hole for the liquid helium fill tube. The liquid helium reservoir has a hemispherical end cap at the forward end and a flat work surface aft. Volumes, when full with the instrument as mounted on SOFIA, is roughly 8 liters.

We have three layers of radiation shielding within EXES. The first layer is a vapor cooled shield tied only to the cryogen fill tubes. The second level of shielding is attached to the liquid nitrogen reservoir and the third is attached to the liquid helium reservoir. All optics, except for the entrance window/lens, are attached to the liquid helium level. We do have baffling tubes connected to the liquid nitrogen level to reduce thermal emission impinging on the internal optics.

We use G10 fiberglass standoffs to separate the various cryogenic levels within EXES. At the aft end, each connection is made using interlocking triangles to increase the conduction length between surfaces. The vapor cooled shield has a nearly continuous ring of G10 at the forward end. It had to be nearly continuous to permit assembly. A continuous G10 cylinder connects the vapor cooled shield and the liquid nitrogen radiation shield. Between the liquid nitrogen and liquid helium levels, we use G10 structures shaped like an X.[3]

Mechanical feedthroughs for motors and adjustment of optics are done with ferrofluidics and fiberglass shafts. All mechanisms use warm stepper motors.

Within the liquid helium level, we have a rigid optics box constructed out of aluminum. The optics are all tied to the optics box. The detector headerboard is isolated with G10 fiberglass and actively maintained at a uniform temperature.

## 2.2 Optics

The optics consist of an entrance window/lens, foreoptics, three wheels housing the slits, deckers, and filters, a high resolution chamber, and a cross-dispersion chamber.

The entrance window/lens forms an image of the SOFIA secondary at the liquid helium cold stop within our foreoptics. It is roughly 12 inches from a telescope focus and changes the incoming f/# from the telescope somewhat. The lens is 2 inches in diameter. The choice of material for this lens depends on the wavelengths of interest during a given cooldown cycle. For observations at wavelengths less than 15 microns, we will use ZnSe. For longer wavelengths, we will use either KRS-5 or CsI. KBr is also a possibility, provided we do not wish to observe past 24 microns. It is not possible to change the entrance window without warming the entire instrument up to room temperature and breaking the cryostat vacuum.

The foreoptics are designed to take the incoming SOFIA f/19 beam and adapt it to the instrument's f/10 focal ratio. As mentioned above, the entrance window plays a small role in this process. After coming to a focus, the beam expands through a pupil, the location of our cold stop, to an ellipsoidal mirror. The ellipsoid changes the beam to f/10 and sends the light off two flats to a focus on the slit. We note that a possible upgrade to the instrument would involve replacing the first of these two foreoptic flats with a dichroic that would feed a small, K band imaging system to enable guiding off infrared light.

As the beam comes to a focus at the slit plane, it passes enters our slit/filter cassette. This is a series of three wheels on a common axle. The wheels contain filters to isolate grating orders, deckers to determine the length of the slit, and slits of varying widths. The filter wheel has 12 spots, which will force us to load the filter wheel specifically for each cooldown cycle given planned observations. In order to increase the number of filters available, we have broader filters for our low resolution mode in 4 of the decker wheel slots. The decker wheel has a total of 11 features that include continuously variable slit lengths, fixed length slits, pinholes, and an open position. The decker wheel permits slits ranging from $1''$ to $180''$ on SOFIA. In our high-resolution, cross-dispersed mode, we will typically use the continuously variable length slits to maximize the slit length on the array. The continuously variable slits permit lengths between $4''$ and $40''$ on SOFIA. There are actually three continuously variable decker arcs that take advantage of the high resolution grating out-of-plane angle to adjust the what wavelength falls at the peak of the blaze function. The slit wheel contains six slits for typical observations that range in velocity resolution from 1.5 km/s to 6 km/s in steps roughly corresponding to factors of 1.33. There is also a very wide slit, $9.4''$ on SOFIA, intended for flux calibration. Additionally, the slit wheel contains apertures for optical tests.

After the slit wheel, the beam hits our flip mirror mechanism. The flip mirror is used to choose between resolution modes by either directing the beam into the echelon chamber or into the cross-dispersion chamber. Two flat mirrors are attached to the same gear train; rotating the mechanism simultaneously moves one into position and the other out of the beam.

In high-resolution mode, the beam enters the echelon chamber. It expands to an off-axis hyperboloid mirror that serves as both the collimator and camera mirror for our high resolution echelon grating. The echelon,[5] is a very coarse, steeply-ruled grating built by Hyperfine, Inc.[6] We acquired it some time ago and it is described in earlier proceedings.[3] The dispersed light is focused by the off-axis hyperboloid and bounces off a flat into the cross-dispersion chamber.

The cross-dispersion chamber is conceptually identical to the echelon chamber. The light expands from the input to an off-axis paraboloid that again serves as both collimator and camera mirror. The collimated beam is sent to the cross-dispersion grating (discussed below) which disperses the light in the plane of the grating. The camera mirror sends the light to our detector. When operating in single-order, long-slit spectral modes – our medium and low resolution science modes – the light never enters the cross-dispersion chamber and the slit is rotated by the flip mirror mechanism.

The echelle grating currently in EXES is a stock replica from Richardson Grating Lab on loan from UT Austin. It has 31.6 lines/mm and is an R2 grating. We will replace this grating with a custom aluminum grating from Bach Research. The custom grating will have the unique property that the grooves are efficient in the infrared in both positive and negative orders. With this grating, which is sized to permit rotation through 0 degree angle of incidence, we will have medium and low resolution cross dispersion available through a single mechanism. We consider it critical that we be able to switch between medium and low resolution cross-dispersion (and long-slit) modes. Since the adjustment feedthroughs for the camera/collimator mirrors are not available during SOFIA flights, we felt utilizing same grating face for both modes was the best way of ensuring the modes hit the detector in the same location. The cross-dispersion grating will be turned face-on to give us a low efficiency mirror for imaging modes.

In front of the detector is a wheel providing a lens for imaging the pupil through the instrument and a dark slide for isolating the detector. This wheel would also, if desired, be available for transmissive optics to adjust the plate scale on the detector.

### 2.3 Detector

The detector is a Raytheon Vision Systems Si:As array with $1024^2$ pixels. The detector material is bonded to a SB 226 multiplexer. This array was designed for operation at space background levels, as is required at the high spectral resolution of EXES. This particular detector's performance has been described elsewhere.[7]

We mount the array in EXES within a separate enclosure to reduce scattered light. The headerboard is thermally isolated from the rest of the optics box with G10 standoffs to permit active temperature control of the array. We use a Lakeshore temperature controller for this purpose.

Because the photon fluxes in our low resolution mode will be significantly above the level intended for the array, we expect to clock out only a subsection of the array in this mode, as well as in imaging modes. To accommodate this, the array is positioned such that medium and low resolution dispersion runs along rows. We anticipate using half to one quarter of the array, which will still provide slits close to $60''$ in length.

The electronics package we use to run the array was delivered by T. Herter's group at Cornell University.[8] We have adapted the system to operate the SB 226 in the lab and will be optimizing operations with EXES over time.

### 2.4 Software

The software for EXES will be largely based on the existing software used for our TEXES instrument.[9] The overall system can be divided into array operations, instrument monitoring and control, data quicklook, and pipeline data reduction. In addition, there is a user interface that will facilitate easy interaction between the first two subsystems as well as incorporating telescope interactions.

The array operations software are part of the electronics system. We will be adapting this software to provide readout schemes matched to EXES photon fluxes. This includes variations in the timing patterns and use of the coadder buffers. The software runs on a PC running Windows XP that we denote the instrument computer. This is the one component of the software where our group has the least familiarity; we are still interacting with the Cornell University group as we gain experience.

The instrument monitoring and control software makes extensive use of Labview software available from National Instruments. We run Labview on the instrument computer. Socket communication permits interaction with the user interface operating on a separate computer. This system monitors the environmental health of the system including temperatures and pressures, and the current location of mechanisms, recorded in terms of resistance on potentiometers. Motions of motors are given in terms of motor number, number of steps, maximum speed, and direction. Warnings and alarms will be incorporated within the software regarding parameters that have limits or that may require attention.

The user interface is intended to make running the instrument while observing as simple as possible. It will incorporate lessons learned over the decade of ground-based observing we have done with TEXES. It operates on the user computer and connects via socket to the instrument computer. To specify a particular instrument configuration, the user inputs the instrument mode, central wavenumber, and observing mode. The user interface will provide standard values for the locations of all mechanisms for that observation (filter wheel, decker wheel, slit wheel, flip mirror, cross-dispersion grating angle), suggested detector parameters such as integration time and clocking pattern, and typical telescope parameters for the observing mode. Standard EXES observing modes will include nodding a point source along the slit, nodding an extended object off the slit, and creating a data

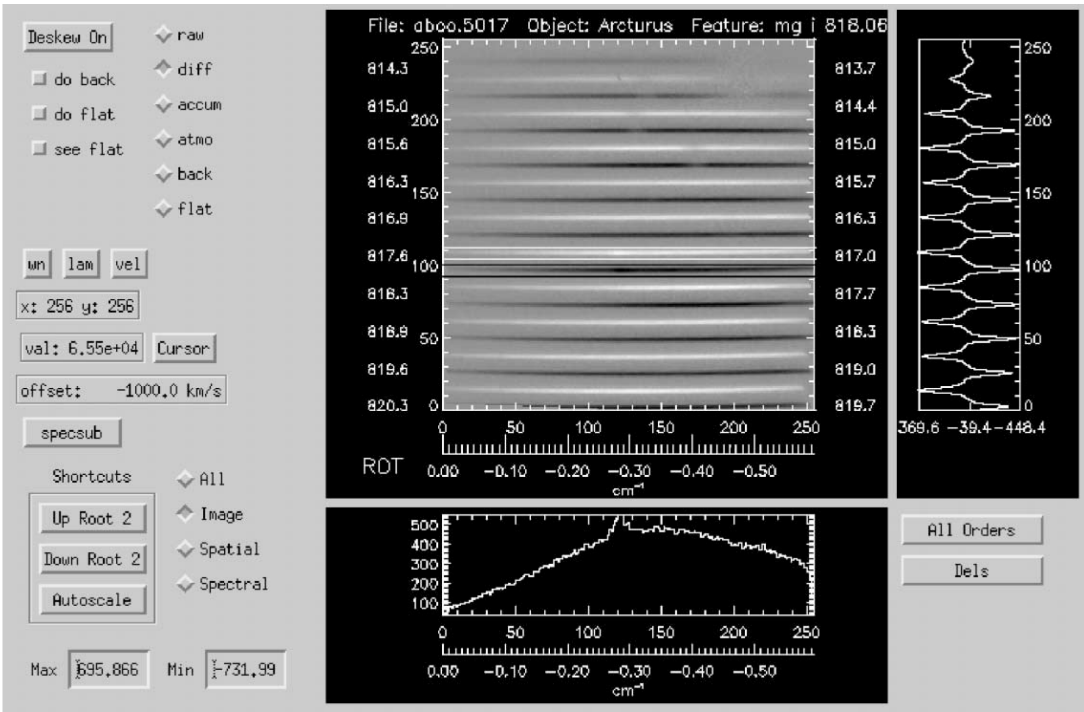


Figure 2. An illustration of the quicklook GUI as implemented on TEXES. The GUI displays the array, in this case displaying a difference between two nod positions after a fast rectification based on our knowledge of the instrument. To the right is a spatial profile made by summing over the spectral dimension. The light and dark lines near pixel 100 denote regions for summing over spatial directions to display a spectrum in the lower region. For EXES, we will modify the software for the larger array and build on the functionality to improve the capabilities.

cube by stepping the slit across the object. The user will verify these suggested parameters before the user interface software issues commands. For non-standard observations in the lab or on the telescope, the user can override the suggested parameters. The user interface will coordinate data taking with telescope motion as well as provide alarms and warnings in addition to those intrinsic to the labview software.

The quicklook is written in IDL and provides an easy tool for evaluation of each recorded frame. The GUI displays the full array – either the most recent raw frame, sky subtracted frame, or a sum over many differenced frames – as well as simple spatial and spectral sums (Figure 2). The user can specify the display level and the extraction locations as required to examine details. Corresponding calibration images can also be displayed and it is possible to apply first order flat fields and sky corrections. The quicklook can present data cubes as spectrally summed maps. It will also display background counts in strip chart format as a way of monitoring the sky fluctuations. The quicklook operates on the user computer and receives the data from the instrument computer either over a socket or through mounting the data disk in read-only mode.

The pipeline reduction software will come from our TEXES pipeline reduction software. This program is written in fortran and has been used and improved over nearly a decade. Data reduction is done via a script with parameter choices that can vary depending on observing mode, source characteristics, and observation quality. The user is currently asked for input when setting the wavelength scale, using Earth's atmospheric lines, but we envision using correlation techniques with model atmospheres to automate this process. We will work toward modeling of the sky emission in an attempt to permit accurate telluric correction without the need for observations of a featureless continuum source. In practice, the pipeline reduction software enables nearly real time, high quality reduction of our complex, cross-dispersed spectra.

# 3. CURRENT STATUS

## 3.1 EXES Development Team

Before granting approval for the current development team to take responsibility for EXES, NASA required us to present a detailed plan for completion. The plan included a master schedule based on identified tasks and resources, detailed budget with reserves, and a risk assessment with mitigation strategies. The development team for EXES includes personnel at UC Davis and NASA Ames, taking advantage of special capabilities of available at each facility. These include extensive experience with high-resolution, mid-IR spectral observations and instrument development, mid-IR detector testing and characterization, technical engineering, systems engineering, and project management. The hardware is based at NASA Ames, where the bulk of the personnel associated with the project reside.

Approval was granted to our collaboration in April, 2009. The existing hardware shipped to Ames in late June, 2009. We have had six cold cycles during the past year.

## 3.2 Thermal Performance

Shortly after transferring hardware to Ames, we equipped EXES with diode temperature sensors. They can be positioned in various locations depending on goals for each cold cycle. In Figure 3, we show measurements from our second cooldown. In this cooldown, we had a sensor on the vapor-cooled shield (top trace), the liquid nitrogen shield base (middle trace near 77 K), the detector and cross-dispersion grating mount (two bottom traces).

As expected given the large size of EXES, cooling the instrument to cryogenic temperatures takes time. We used roughly 160 liters of liquid nitrogen and 85 liters of liquid helium to reach equilibrium temperatures. The cross-dispersion grating is poorly tied to the cryogens and took $\sim$45 hours to cool below 100 K. We will improve this with a flexure added to the mounting shaft when we install our custom cross-dispersion grating. We experimented in this cooldown with using pumped nitrogen in the liquid helium reservoir to reduce the use of liquid helium. While this process did reduce liquid helium usage, it also caused operational challenges in terms of removing the solid nitrogen. Our liquid helium hold time was 29 hours in normal operation and $>$37 hours if we pumped on the liquid nitrogen reservoir. The liquid nitrogen hold time was $>$36 hours.

## 3.3 Optical Performance

During the past year, we have begun testing the EXES optical system as a whole. We are able to do this warm and cold. These tests have helped us to align the internal optics, assess our current status, plan for use on the telescope, and gain familiarity with the instrument.

Warm optical tests are done with a visible laser. We put a laser fiber near the telescope focus within the EXES foreoptics and allow the beam to overfill the cold stop. Using the slit wheel as a knife edge, we can adjust the location of the laser input to provide a sharp focus at the slit wheel.

The expanding beam is directed toward either the echelon grating or the cross-dispersion grating, depending on which mode we choose to test. The current cross-dispersion grating works well at optical wavelengths and we are able to separate laser modes from the diode laser. We have steered the beam to fill the grating and adjusted the detector focal position to bring us within the middle of the travel available on the adjustment screws for the cross-dispersion chamber. We have also measured our collimation in the cross-dispersion chamber by sending the beam out of the optics box and measuring its size as it travels several meters across the room. At current time, we have a slightly converging beam in this chamber, roughly f/2500.

The echelon grating does not function well at visible wavelengths. The laser light in a given laser mode essentially fills the single slit pattern of a single groove. The various laser modes are still separated by the cross disperser (Figure 4). Although we are uncertain of the overall diagnostic value of warm observations using the echelon, we are able to doing alignment of the optics in this mode. We have corrected slight offsets in the illumination of the collimator/camera mirror and made adjustments such that the beam fills the cross-dispersion grating in both modes.

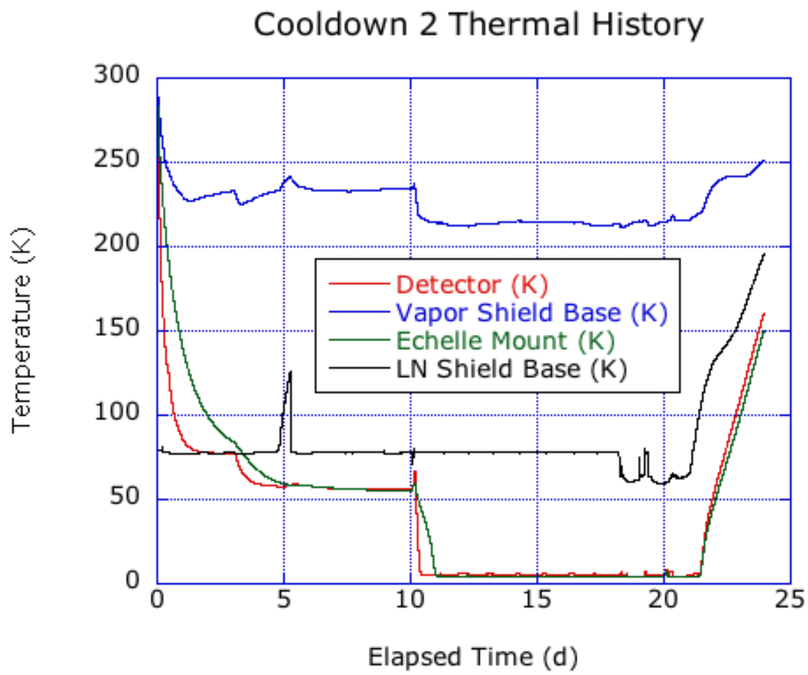


Figure 3. Temperatures in EXES during our second cold cycle. The sensors are located on the vapor-cooled shield, the liquid nitrogen shield, the detector and the cross-disperseion grating. The period from day 5 to day 10 was spent waiting for the solid nitrogen in the liquid helium reservoir to evaporate. Near the end of the cooldown, we pumped on the liquid nitrogen to measure the improvement in liquid helium hold time.

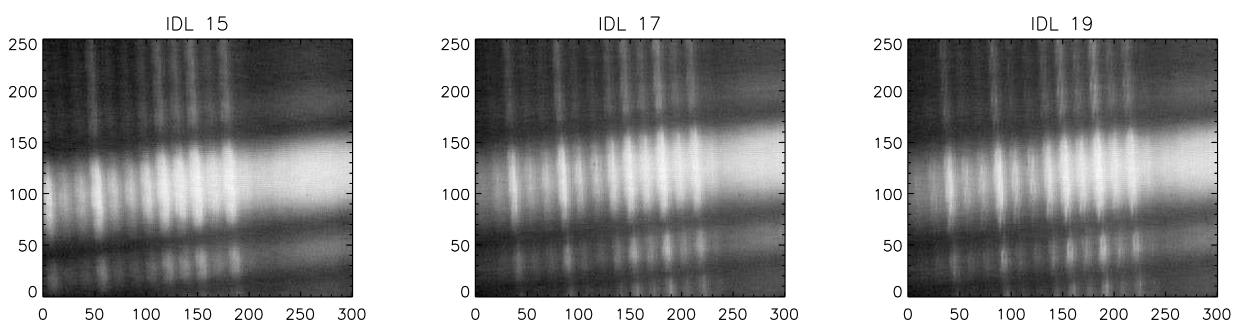


Figure 4. An example of warm testing of EXES using an input laser and a bare multiplexer. The different laser modes are spaced horizontally due to the cross-dispersion grating. Nearly vertical gaps are seen between the laser modes. The echelon single slit diffraction pattern is seen running vertically for each of the laser modes. In the visible, the angular width of the echelon order is quite small and only covers ∼80 pixels from null to null. When we observe in the infrared, the echelon orders will fill the grating much better with continuous coverage in a single setting possible to almost 20 microns. The figure shows the same input for three positions of the echelon collimator/camera mirror.

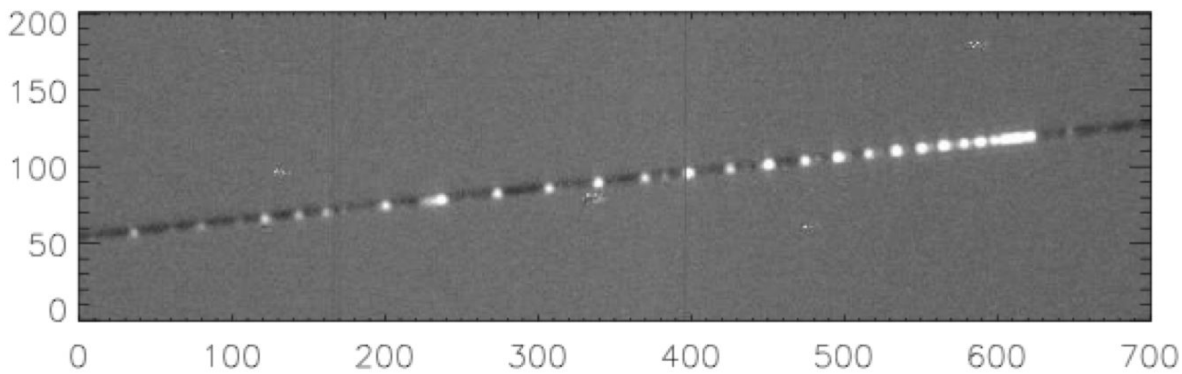


Figure 5. Medium resolution observation of the $C_2H_2$ Q branch near 13.7 microns. We show just a portion of the detector array in the figure. See text for a description of the observation.

We have also conducted performance tests at infrared wavelengths. These tests involve both continuum observations, such as looking at the room, and observations of a gas cell.

Our gas cell is a simple cylinder made of PVC with vacuum tight end caps and two vacuum pumping ports. One end cap holds a window and the other holds a mirror. The gas cell is filled with the desired gas, $C_2H_2$ is our most commonly used gas, placed in front of the entrance window, and pumped to low pressure. The mirror at the end of the gas cell results in lowered background emission since much of the beam originates within the cryogenic regions of EXES. The gas is at room temperature and so its spectral features show up in emission. With the gas cell we are able to investigate the spectral resolution of EXES for the first time.

We first present results for medium resolution mode in Figure 5. The emission lines seen are mostly part of the $C_2H_2$ Q-branch. We have subtracted a continuum image to make fitting the line spots easier. The aperture used was a pinhole with a nominal diameter of 108 microns (4 pixels). At this wavelength, 13.7 microns, diffraction contributes significantly to the final image size. When we convolve the pinhole size with the Airy function expected at this wavelength, we predict the FWHM of the pinholes should be 5.5 pixels. Fitting to the spots with two-dimensional Gaussians, we find measured FWHM of 5.1 to 5.6 pixels. With the typical slit expected for this wavelength setting, this translates to a resolving power of R=22,000. Our spectral coverage is 0.7% at this setting. It will change with the cross-dispersion grating angle.

In Figure 6, we show a high spectral resolution observation of the $C_2H_2$ Q branch from the gas cell. The main lines are all resolved and some excited bands are also present. We can extract a simple spectrum from this image by summing along columns. To minimize the broadening caused by summing the tilted spectrum, we sum over four rows. The extraction and a subsequent Gaussian fit to the lines present is shown in Figure 7. The profiles are well-represented by a Gaussian. From these data, we can determine the spectral resolution is R=110,000. This is the best spectral resolution we have obtained to date. We found, however, that the high resolution mode suffers from astigmatism at this point. At the circle of least confusion, we find a resolving power or R=65,000 and spots that are roughly twice as large as predicted by diffraction.

### 3.4 Preparations for Ground-based Observing

EXES projects were awarded five nights of observing time at the NASA Infrared Telescope Facility (IRTF) in January 2011. The projects are monitoring of Io's $SO_2$ atmosphere (PI: J. Spencer); working toward completion of a spectral line survey of Titan (PI: H. Roe); and mapping Venus in lines of $SO_2$ and HDO. All of these projects can be done with TEXES, which will serve as a back-up instrument should EXES perform below expectations.

We have developed optical and mechanical mounting plans for EXES. We will mount at the Cassegrain focus of the IRTF. To avoid spilling cryogens, the cryostat will be mounted at a 45° angle. In this manner, we will

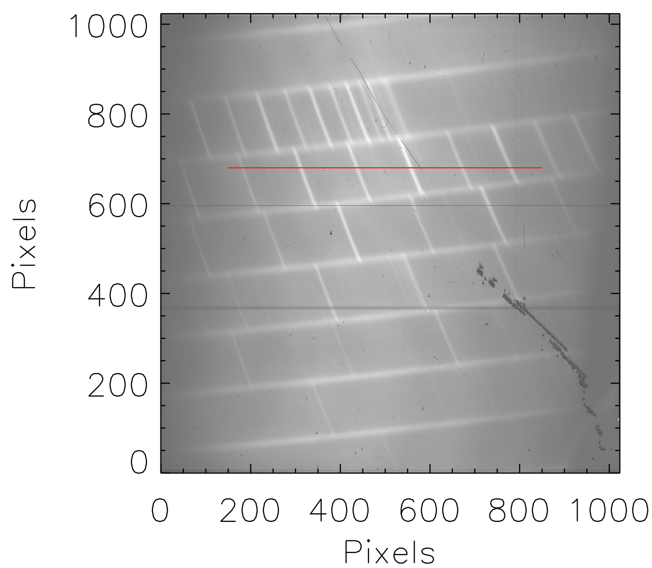


Figure 6. The detector array with EXES in the high resolution mode and looking at the $C_2H_2$ Q branch using the gas cell. Echelon spectral orders run mostly horizontal. Cross dispersion and the spatial direction are mostly vertical. The bright lines running along the edge of the echelon orders are due to the slit used being slightly too long for this grating setting; a shorter slit would have been a better choice. The wavelength increases to the right in each echelon order and increases vertically in the cross dispersion direction.

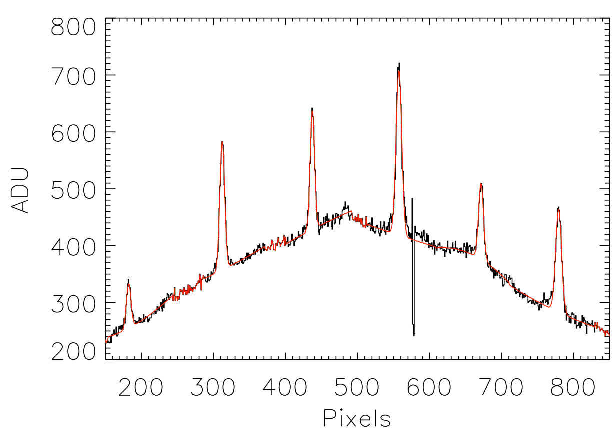


Figure 7. A sum over 4 rows and subsequent Gaussian fit to the emission lines. The data are replaced in fitted regions. The fits do a good job reproducing the data.

have access to most of the sky. We will use warm foreoptics to alter the IRTF input f/# and pupil to mimic those expected from SOFIA. The foreoptics consist of two powered mirrors and a flat turning mirror. We expect that the ground-based telescope run will help prepare us for observations on SOFIA in a more robust manner than is possible in the lab.

## ACKNOWLEDGMENTS

We thank Prof John Lacy for providing us with a wonderful instrument. MJR and AS are supported by NASA Collaborative Agreement NNX10AC27A.

## REFERENCES

[1] Richter, M. J., Lacy, J. H., Jaffe, D. T., Mar, D. J., Goertz, J., Moller, W. M., Strong, S., and Greathouse, T. K., "Development and future use of the echelon-cross-echelle spectrograph on SOFIA," in [*Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*], *Presented at the Society of Photo-Optical Instrumentation Engineers (SPIE) Conference* **6269** (July 2006).

[2] Richter, M. J., Lacy, J. H., Zhu, Q., Jaffe, D. T., Greathouse, T. K., Moerchen, M., Mar, D. J., and Knez, C., "High-resolution mid-infrared spectroscopy from SOFIA using EXES," in [*Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*], R. K. Melugin & H.-P. Roeser, ed., *Presented at the Society of Photo-Optical Instrumentation Engineers (SPIE) Conference* **4857**, 37–46 (Feb. 2003).

[3] Richter, M. J., Lacy, J. H., Jaffe, D. T., Greathouse, T. K., and Hemenway, M. K., "EXES: a progress report on the development of a high-resolution mid-infrared grating spectrograph for SOFIA," in [*Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*], R. K. Melugin & H.-P. Röser, ed., *Presented at the Society of Photo-Optical Instrumentation Engineers (SPIE) Conference* **4014**, 54–64 (June 2000).

[4] Richter, M. J., Lacy, J. H., Jaffe, D. T., Hemenway, M. K., and Yu, W., "EXES: an echelon cross echelle spectrograph for SOFIA," in [*Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*], A. M. Fowler, ed., *Presented at the Society of Photo-Optical Instrumentation Engineers (SPIE) Conference* **3354**, 962–972 (Aug. 1998).

[5] Michelson, A. A., "The Echelon Spectroscope," *The Astrophysical Journal* **8**, 37–+ (June 1898).

[6] Bach, K. G., Bach, B. W., and Bach, B. W., "Large-ruled monolithic echelle gratings," in [*Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*], R. K. Melugin & H.-P. Röser, ed., *Presented at the Society of Photo-Optical Instrumentation Engineers (SPIE) Conference* **4014**, 118–124 (June 2000).

[7] Ennico, K. A., McKelvey, M. E., McCreight, C. R., McMurray, Jr., R. E., Johnson, R., Hoffman, A. W., Love, P. J., and Lum, N. A., "Large Format Si:As IBC Array Performance for NGST and Future IR Space Telescope Applications," in [*Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*], J. C. Mather, ed., *Presented at the Society of Photo-Optical Instrumentation Engineers (SPIE) Conference* **4850**, 890–901 (Mar. 2003).

[8] Pirger, B. E., Schoenwald, J., Herter, T. L., Gull, G. E., Adams, J. D., Keller, L. D., Berthoud, M., Henderson, C., Stacy, G. J., and Nikola, T., "High-speed highly-flexible reconfigurable data acquisition system for astronomy," in [*Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*], *Presented at the Society of Photo-Optical Instrumentation Engineers (SPIE) Conference* **6276** (July 2006).

[9] Lacy, J. H., Richter, M. J., Greathouse, T. K., Jaffe, D. T., and Zhu, Q., "TEXES: A Sensitive High-Resolution Grating Spectrograph for the Mid-Infrared," *Publications of the Astronomical Society of the Pacific* **114**, 153–168 (Feb. 2002).