DEVELOPMENT OF A CRYOGENIC DIFFRACTION GRATING SPECTROMETER

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INTRODUCTION

The SPace Infrared telescope for Cosmology and Astrophysics (SPICA) is a joint ESA/JAXA space observatory class mission [1] in which the primary mirror will be actively cooled below 8 K to minimize self-emission. Recent advances in far-infrared detector technology have led to increases in raw sensitivity of more than an order of magnitude over previous state-of-the-art detectors. With such sensitivity, photon noise becomes the dominant noise component, even when using cryogenically cooled optics, unless a method of restricting the spectral bandpass is employed. One such method is to use a low-resolution cryogenic diffraction grating spectrometer to post-disperse the signal from a high-resolution instrument, such as a Fourier transform spectrometer (FTS). The SpicA FAR-infrared Instrument (SAFARI) is based on a Post-Dispersed Polarizing Fourier Transform Spectrometer (PDPFTS) design, which limits the instantaneous spectral bandwidth falling on its ultra-sensitive detectors (NEP $\approx 2 \times 10^{-19}\mathrm{W}/\sqrt{\mathrm{Hz}}$). This poster describes the development and verification of a cryogenic grating spectrometer which operates at 4 K and was used to post-disperse the output of a room temperature polarizing FTS.

Grating Concept

The prototype diffraction grating spectrometer is based on the Czerny-Turner monochromator configuration which is governed by the grating equation [2]:

$$m\lambda = 2d(\sin(\theta)\cos\phi), \tag{1}$$

where m is the order of diffraction, d is the slit spacing, λ is the wavelength of the incident light, θ is the angle of incidence, and 2ϕ is the deviation angle. Inside the 4 K vacuum chamber, the grating is mounted in an aluminum housing on a pivot driven by a cryogenic Phytron stepper motor through worm gear reduction. The incident collimated beam (Figure 1 [grey])is reflected by a fold mirror onto the grating which disperses the radiation onto a 15° off-axis parabolic mirror, which in turn focusses the light on the exit slit of the spectrometer located on the feedhorn of a 0.3 K composite bolometer detector.

The grating was designed to operate over a wavelength range from 285-500 μm chosen close to the long-wavelength end of SAFARI and for which an extensive suite of test equipment is available. The theoretical resolving power, R, was calculated under the assumption that it was slit width limited [3]:

$$R = \frac{\lambda m r}{dw\cos(\phi+\theta)}, \tag{2}$$

where w, the width of the entrance slit, was chosen to achieve a resolving power of R $\approx$100 at 392.5 μm. A common method for maximizing efficiency of a reflecting grating is to blaze the grating according to the condition [3]:

$$m\lambda_B = 2d\sin\theta_B, \tag{3}$$

where θ_B is the blaze angle measured between the grating plane and the face of the groove, and λ_B is the wavelength where the grating produces maximum efficiency.

DESIGN

The design specifications for the grating, which is used in the first order, are listed in Table 1. The grating was donated by Blue Sky Spectroscopy Inc.. It was fabricated from RSA 6061 aluminum and ruled with a single point diamond machine under a specialized thermalization process to minimize internal stress [4]. The grooves embodied a sawtooth profile and were blazed to achieve a maximum efficiency at 392.5 μm, corresponding to a blaze angle of 39.4° [3].

Table 1: Design specifications for the grating spectrometer designed to operate in the 285 - 500 μm region.

Parameter	Value
Grating dimensions, (width x length)	105 mm x 50 mm
Slit spacing, d	312 μm
Deviation angle, 2ϕ	15°
Entrance slit width, w	5.0 mm
Exit slit width, w″	4.0 mm
Blaze angle, θ_B	39.4°

The enclosure that will house the grating has been redesigned as shown in Figure 1 and Blue Sky Spectroscopy Inc. has donated it to our group. Improvements from the previous design include: a monolithic grating enclosure (teal); a larger diameter filter (50 mm) (brown); a new diffraction grating (yellow) that features a plane mirror mounted to the rear side (red) free to rotate 360°; and a retractable baffle (blue) that will block stray light within the grating enclosure from reaching the detector. A thermal filter (pink) is mounted at the interface between the 4 K and 0.3 K enclosures. The exit slit (green) is mounted on the feedhorn of a 0.3 K composite bolometer detector (gold). The cryogenic stepper motor (orange) drives the worm and gear system and rotates the grating around the axis indicated by the black arrow. The grating assembly is clamped to the 4 K baseplate of a test-facility cryostat [5]. The monolithic design and choice of material of the enclosure minimize misalignments (e.g., gear drive and optics) as the system is cooled to cryogenic temperatures. The bottom of the enclosure has three extruded square pads that serve as a three-point contact between the enclosure and the 4 K plate. When the system is coupled to a Fourier transform spectrometer and viewing the mirror, a single measurement of the entire band is obtained which serves to calibrate the efficiency of the grating as a function of wavelength.

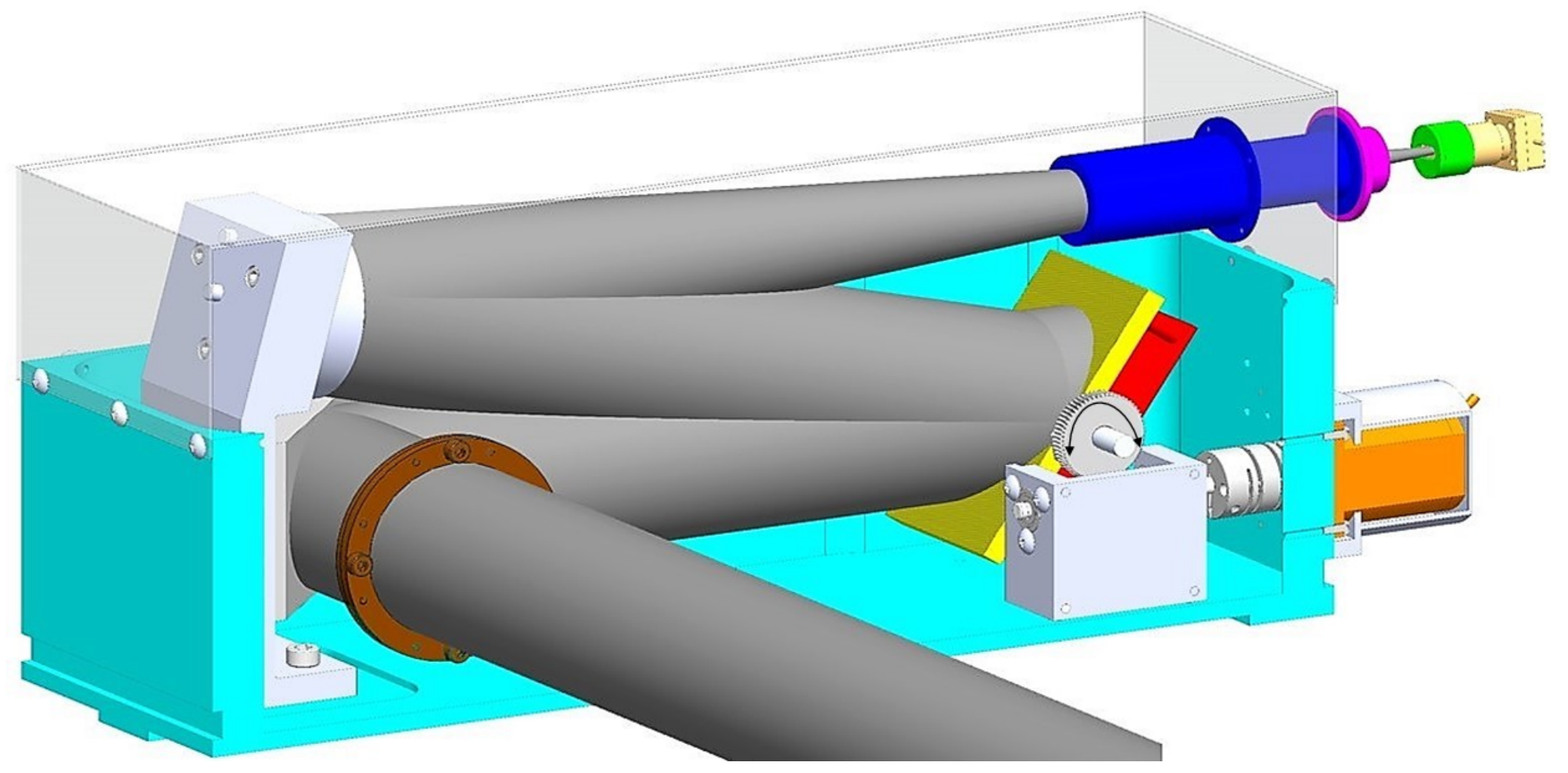

Figure 1: Cut-away view of the prototype grating spectrometer CAD model. See text for details.

RESULTS

The results presented here were obtained using the new grating housed in an enclosure that was designed by a previous student [6]. A tunable pseudo-monochromatic source was provided by a photomixer, illuminated by two continuous-wave lasers operating in the 1550 nm band such that their difference frequency occurred in the terahertz region. The frequencies of the individual lasers were adjusted by varying their current and temperature to enable tunable radiation across the terahertz band. For a given setting of the photomixer frequency, the grating was scanned in 0.03° (0.1425 μm) increments at $\pm$ 2.0° ($\pm$ 9.5 μm) around the corresponding photomixer wavelength, in order to determine the spectral response function (SRF) of the grating as a function of angle (wavelength).

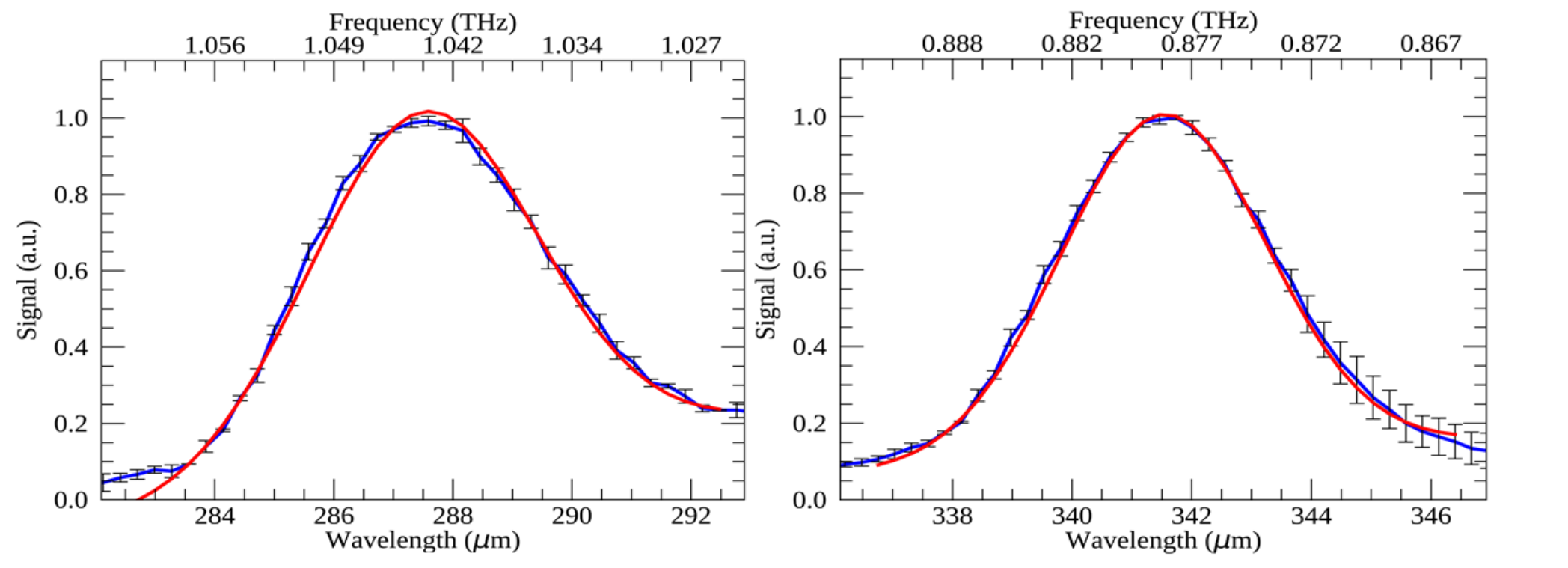

Figure 2: The blue curve shows the average of three independent scans and the red curve shows the best fit Gaussian profile. The plot on the left shows the photomixer set to a frequency of 1.04 THz and the right plot is the photomixer set to 0.878 THz.

Measurements at six photomixer frequencies were obtained. Figure 2 shows the SRF for two photomixer frequencies. Gaussian profiles were fitted to each measurement to determine the center wavelength, λ_c, and the standard deviation, σ, which were used to determine the resolving power, R, and full-width-half-maximum, $\Delta\lambda$.

$$R = \frac{\lambda_c}{\Delta\lambda}, \quad \Delta\lambda = 2\sqrt{2\ln(2\sigma)} \tag{4}$$

The measured (4) and theoretical (2) resolving powers are compared in Figure 3. The tunable range of the photomixer depends on the center wavelengths of the individual lasers that are used. In these preliminary tests, the lasers allowed tuning over the range of (0.878 – 1.04 THz). New lasers have been acquired that will be able to produce radiation over the entire range of the grating, 285 – 500 μm (1.05 – 0.600 THz), which will allow us to verify the grating's performance over the entire range.

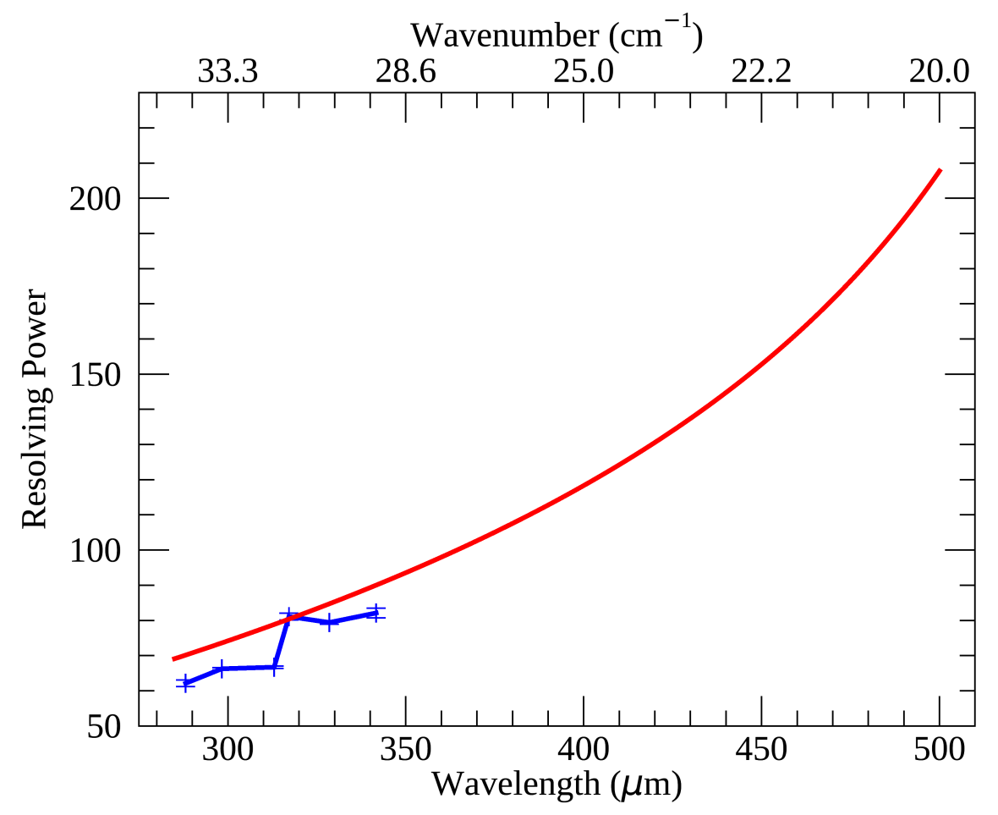

Figure 3: Experimental resolving power (blue) calculated from grating spectral response profiles using six photomixer settings. The theoretical resolving power (red) is described by (2).

Finally, preliminary measurements were obtained with the grating coupled to a polarizing FTS which was loaned by Blue Sky Spectroscopy Inc.. The grating was used to post-disperse the signal from a room temperature polarizing FTS with one port viewing a $\approx$1200 K blackbody source and the other viewing a room temperature blackbody. The grating was stepped through angular positions in 0.12° (0.57 μm) increments around the atmospheric water absorption line at 32.954 cm^{-1} and the FTS was operated with a resolution of 0.0343 cm^{-1}. The measured spectrum is compared with a theoretical atmospheric model [7] for the conditions in the laboratory in Figure 4. These measurements illustrate the capability of the post-dispersed FTS to reconstruct a broad spectral feature by stitching together individual grating profiles.

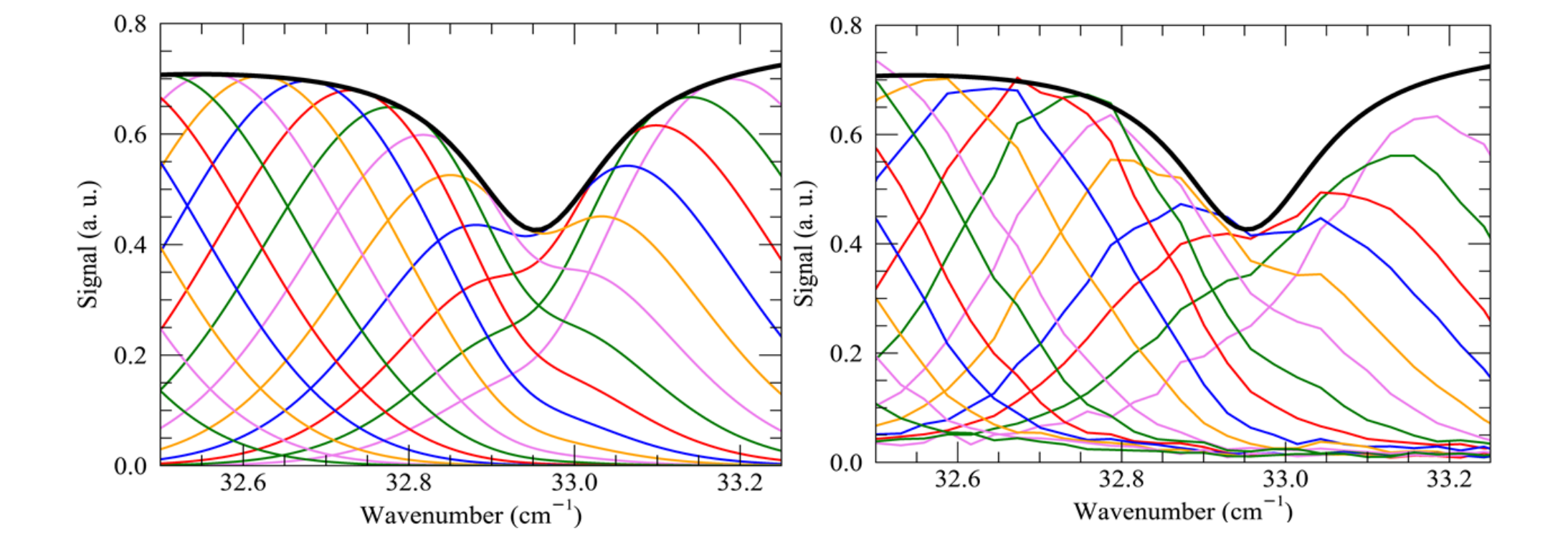

Figure 4: The plot on the left shows theoretical simulations generated using the theoretical resolving power of the grating as a function of center wavelength. The plot on the right shows measured spectra at several grating positions. The black curve is the transmission of a $\approx$1200 K blackbody through 50 cm of atmosphere at 10% relative humidity.

CONCLUSIONS

The new grating enclosure provided by Blue Sky Spectroscopy Inc. will allow us to study the efficiency of the grating. An epoxy-carborundum paste will be spread over the inside of the enclosure to decrease emissivity and increase absorptivity of the inner surfaces and reduce stray light reaching our detector. In future work, we will use the grating in series with the FTS to resolve artificial astronomical spectra which are similar to what would be observed by SPICA SAFARI.

References

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