New Techniques for the Next Far Ultraviolet Spectroscopic Mission

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The Far Ultraviolet Spectroscopic Explorer (FUSE) has been a great success, and has addressed many critical scientific questions (Moos, et al, 2000). However, it has also highlighted the need for even more powerful instrumentation in the 900-1200 Å regime. In particular, significantly increased effective area will permit the pursuit of additional scientific programs currently impractical or impossible with FUSE. It is unlikely that FUSE will last more than a few more years. Nor is it likely that any large scale UV-optical follow-on to HST (such as SUVO) will include the 900-1200 Å bandpass. However, FUSE remains well oversubscribed and continues to perform excellent science. Therefore, a MIDEX class mission in the next 4-6 years that could significantly improve on the FUSE capabilities would be a powerful scientific tool that would be of great utility to the astronomical community. It would open up new scientific programs if it can improve on the sensitivity of FUSE by an order of magnitude.

We have identified a powerful technique for efficient, high-resolution spectroscopy in the FUV (and possibly the EUV) that may provide exactly what is needed for such a mission To achieve a factor of 10 improvement in effective area, we propose using a large (meter class), low-cost, grazing incidence metal optics. This would produced in a manner similar to the EUVE mirrors (Green, et al, 1986), using diamond turning to create the optical figure followed by uncontrolled polishing to achieve a high quality surface. This process will introduce significant figure errors that will degrade the image quality. However, if a holographic grating is employed, *which has utilized the actual telescope in the recording geometry,* all wavefront errors will be automatically corrected in the end-to-end spectrometer, and high quality spectroscopy will be possible with low quality (and low-cost) optics. In this way a MIDEX class FUSE can be proposed with 10 times the effective area of the current instrument.

THE NEED FOR HIGHER FUV PERFORMANCE

The original vision for FUSE incorporated a large, grazing incidence telescope which provided significant effective area and performance into Extreme Ultraviolet (EUV). However, this approach was abandoned due to the prohibitive cost of procuring a 1-meter class, 1 arc second quality grazing incidence telescope. The normal incidence approach used in FUSE was an optimization within cost that resulted in significantly less overall throughput than the original, grazing incidence concept. With this loss of effective area came a loss of the faintest targets that FUSE hoped to examine, essentially the extra-galactic targets, and with this, the tracing of D/H over cosmic evolution out to $z \sim 0.2$. (For $z \geq 0.2$, Lyβ and Lyγ shift into the HST band, and HST and/or SUVO can study these transitions. It is very difficult to get D/H off of strong Lyα absorbers without exquisite signal-to-noise due to the wings of the strong Lyα line, which is unrealistic for any extragalactic targets without Hubble class effective area, such as on COS (Green, 2001).)

In addition, a future mission should provide higher spectral resolution and higher potential signal-to-noise than the current FUSE, to allow a detailed study of the components of hot gas, particularly OVI gas, which is inaccessible to any other wavelength band. A mission concept for such a FUSE successor could include the following:

A 1.5 meter class, moderate quality, diamond turned grazing incidence metal telescope. The likely design is a Hettrick-Bowyer Type II (diverging Gregorian analogue; Hettrick and Bowyer, 1984). Such a design was originally considered in the FUSE Phase A study. Such a telescope allows the full instrument length to be employed in the spectrograph throw length (increasing dispersion for the same line density) and enabling high-resolution without requiring line densities beyond our fabrication technology or small resolution elements (driving detector performance). However, a prime focus (with a short focal length) is formed so that a slit can be employed and target-acquisition slit-jaw-monitors can be included.

Holographic gratings that correct the aberration of the mount, and any wavefront error in the telescope, by utilizing the as-built flight telescope in the recording setup. The net optical performance of the telescope/grating pair will exceed that of the telescope alone, in the same way that correctors added to Hubble allow imaging performance beyond that achievable wiht the telescope alone.

Small format, moderate spatial resolution (50μm) microchannel plate detectors. By designing sufficient dispersion into the optical design, high spectral resolution can be achieved, even with large detector resols. Since a spectral resolution element covers many MCP pores, flat field effects are greatly reduced. The differential non-linearity in FUSE limits the achievable signal-to-noise. By sampling many microchannel pores in each spectral resolution element, much higher signal-to-noise can be obtained. In addition, producing readout systems to support a resolution of 50μm are much simpler, cheaper, and more robust than state-of-the-art read out systems. High quantum efficiency would be independently obtained by using state-of-the-art photocathodes.

A schematic representation of the instrument concept is presented in Figure 1.

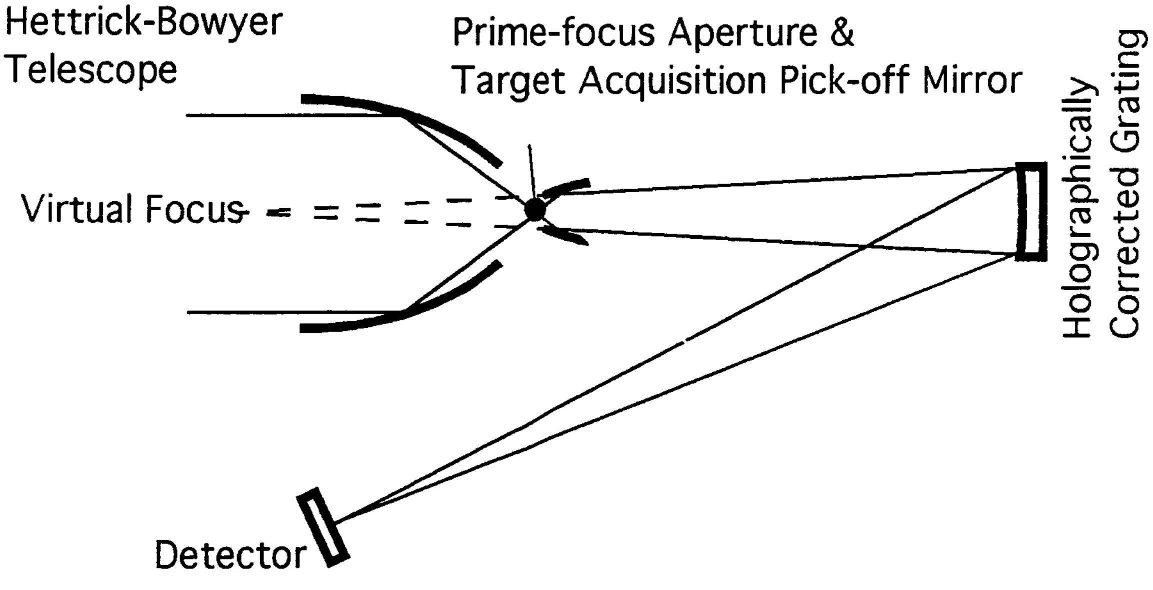


Figure 1: A schematic representation of the MIDEX concept. An H-B Type II grazing incidence telescope collects the light from the target. A slit at prime focus is used for target acquisition and rejection of diffuse emission. The H-B Type II forms a virtual focus which allows the full payload length to be used for the spectrograph dispersion. Additional, permanently mounted off-axis gratings provide multiple observing modes (not shown).

By incorporating these design elements, we believe that a scientifically compelling, technically robust and programmatically sound MIDEX proposal can be developed. The effective area of such a system can be simply estimated:

λ (Å)	Mirror ϕ (m)	Geom area (cm^2)	Aperture filling factor	Graz Inc reflec (surf 1)	Graz Inc reflec (surf 2)	Grat groove eff	Grat refl.	Det QE	Net effective area (cm^2)	FUSE Effective Area (cm^2)
950	1.2	11,310	.75	.8	.8	.55	.3	.45	403	19
1032	1.2	11,310	.75	.8	.8	.55	.6	.45	805	55
1150	1.2	11,310	.75	.8	.8	.50	.6	.4	650	41

Table 1: Effective area of a possible Far Ultraviolet mission. The grating efficiency numbers assume a blazed, holographic grating and are consistent with current COS results. Detector QE numbers assume CsI and are also consistent with COS results.

THE OPTICAL TECHNIQUE

The correction of wavefront errors by holography is a well established practice. In principle, a hologram can be formed between two point sources (or using collimated light, the equivalent of an infinitely distant source) onto any arbitrary surface. The resulting grating will diffract light from one of the source to the others with perfect wavefront control, if it is utilized at the wavelength of the recording. In this way, high resolution, single wavelength optics can be made from "garbage can lids". Such optics have been successfully produced, for example, Andersen and Knize, 1998. See figure 2. The principle is simple.

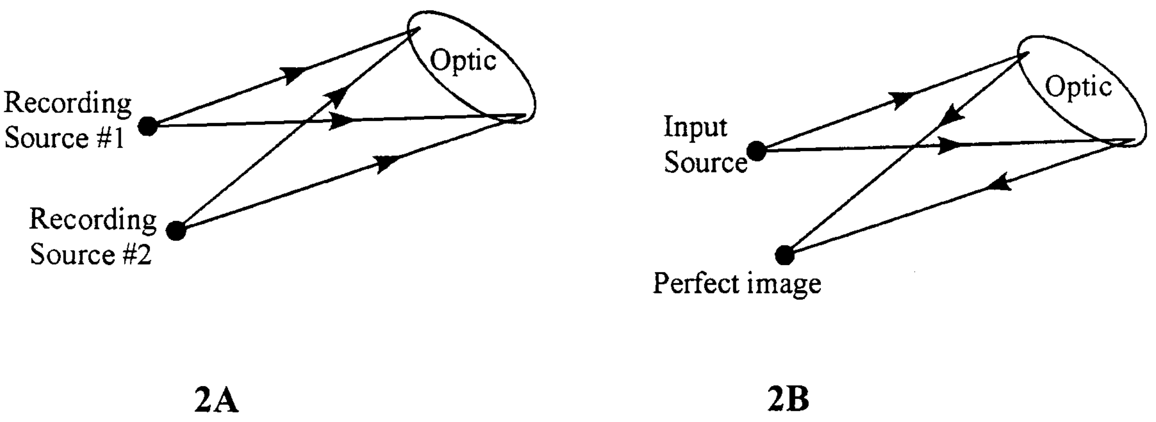
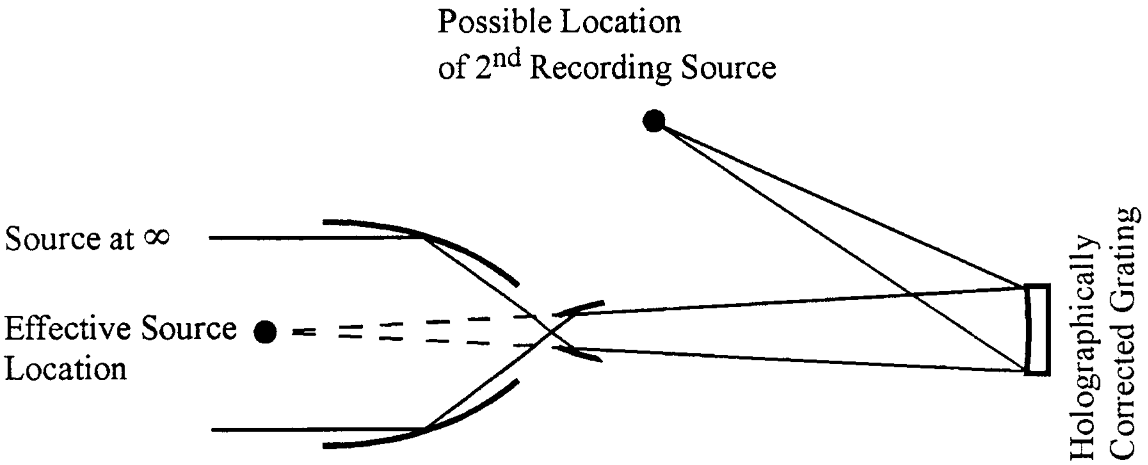


Figure 2:
2A: Make a hologram using an optic with an arbitrary figure..
2B: When utilized in the same geometry and at the same wavelength, the wavefront of the input beam preserved.

In the far ultraviolet, recording lasers and the corresponding photoresists are not available to form the holograms at the wavelength of intended use. Therefore, an alternate recording wavelength laser is used in an different geometry to minimize the wavefront error at the desired wavelength of operation and the functional geometry. This technique is summarized in Noda, Namioka and Seya (1974) and has been used on FUSE and COS (Green, 2001). In these applications, the spectrographs were considered separate from the feeding optical systems, which were assumed to deliver a known wavefront. In the case of FUSE, this was assumed to be a perfect wavefront, in the case of COS, the known spherical aberration of the HST was included in the analysis and is partially corrected by the holographic pattern. In that application, the wavefront error was well understood, and could be included in any design. By extending this concept to correcting the arbitrary wavefront errors of the feeding telescope, we eliminate the need for fine figure control during the surface polishing. By including the as-built flight telescope in the recording, the hologram should correct the wavefront error of the feeding optic.

While this is known to work when the geometry and wavelengths are the same, further study is needed to demonstrate that it will work when employed in ultraviolet applications. In principal, the wavefront information should be embedded in the hologram, unless the recording wavelength does not sample a surface frequency domain that is relevant to the wavelength of use. In Figure 3, we show an example of such an application for the MIDEX concept.



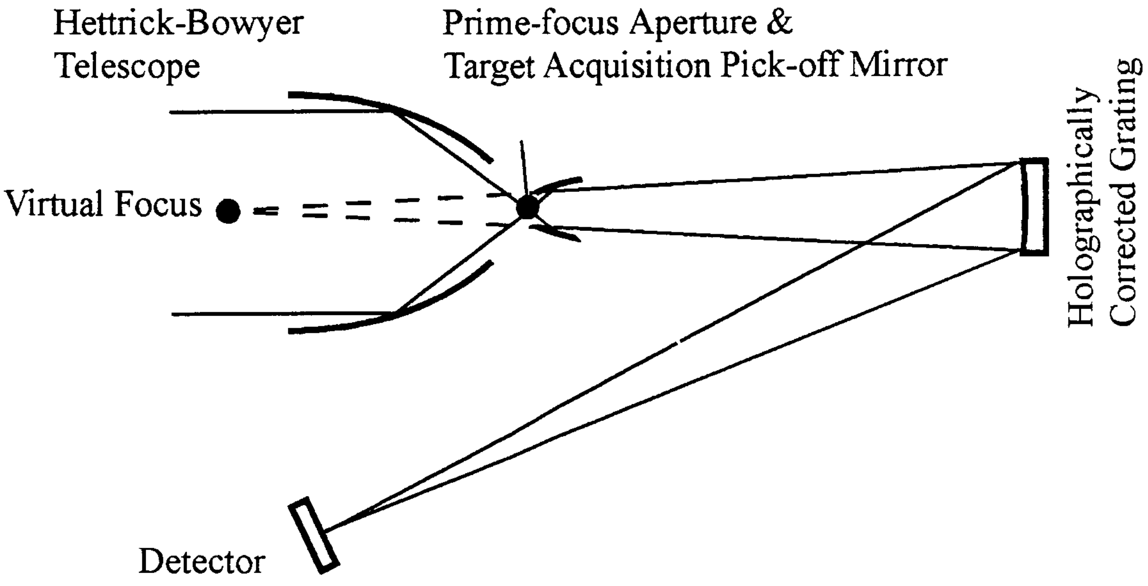


Figure 3: By recording the grating in a setup such as shown in the upper figure, with a properly chosen geometry and at a different wavelength, we expect that when utilized in the flight geometry (as in the lower figure) , the wavefront errors of the telescope will not be present in the spectrum. Therefore, small spot sizes and high resolution spectroscopy will be achievable even with a low quality telescope.

CONCLUSIONS

As is the case with most successful observatories, FUSE has whetted our appetites for even better performance in the Far Ultraviolet. We believe that a follow on mission, with greatly enhanced capabilities, would be a viable proposal in a future MIDEX opportunity. The original vision of FUSE, and much more, can be restored by using a low-cost, grazing incidence telescope. Since a grazing incidence optic is included, EUV instrumentation to follow on the success of EUVE could be incorporated. Since image correction is inherent in the holography, emission line imaging will be available, and long slit spectroscopy enabled. Different gratings, employed at, and recorded at, various off-axis positions, could enable different modes optimized for imaging, low dispersion, or limited bandpass, high resolution.

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