The Cosmic Origins Spectrograph

James C. Green

Center for Astrophysics and Space Astronomy
University of Colorado, Boulder, CO 80309

Abstract

The Cosmic Origins Spectrograph (COS) is a new instrument for the Hubble Space Telescope that will be installed during servicing mission 4, currently scheduled for July 2003. The primary science objectives of the mission are the study of the origins of large scale structure in the universe, the formation, and evolution of galaxies, the origin of stellar and planetary systems and the cold interstellar medium. As such, COS has been designed for the highest possible sensitivity on point sources, while maintaining moderate ($\lambda/\Delta\lambda = 20{,}000$) spectral resolution. In this paper, the instrument design and predicted performance is summarized, as well as summary of the instrument flight and prototype component performance to date.
Keywords: ultraviolet, spectrograph, HST, space

1. Introduction

The Cosmic Origins Spectrograph (COS) has been selected as a replacement instrument for the Hubble Space Telescope. Installation is scheduled for summer 2003, replacing COSTAR, which at that time will be unnecessary. COS is a high throughput ultraviolet spectrometer operating from 1150 - 3200 Å with a spectral resolution of 20,000 or better. Low dispersion modes are also available for the observation of extremely faint objects.

The overriding design consideration for COS was to maximize the instrument sensitivity to faint point sources. While an instrument with such capabilities benefits many scientific endeavors, the primary science objective of the proposing science team is to perform studies of numerous faint extragalactic objects. These objectives are outlined below, and are detailed in Morse, *et al*, 1998[1].

The Lyα forest: In recent years, the observation of absorption systems along the line of sight towards distant quasars has led to a new level of understanding about the nature of the universe on large scales. The universe has transformed from a smooth medium at the time of the formation of the cosmic microwave background to the highly clustered environment in which we live. Recent studies have indicated that the distribution of baryonic matter as a function of redshift is best traced through the Lyα clouds, and not the luminous matter. In fact, the majority of the baryons may well be contained in the Lyα clouds and not in galaxies. For this reason, tracing their morphology, physical and chemical conditions provides enormous insight into the history of the universe. COS will study the Lyα forest at low redshifts (the majority of the historical age of the universe) though absorption lines studies using distant quasars as the fundamental sources.

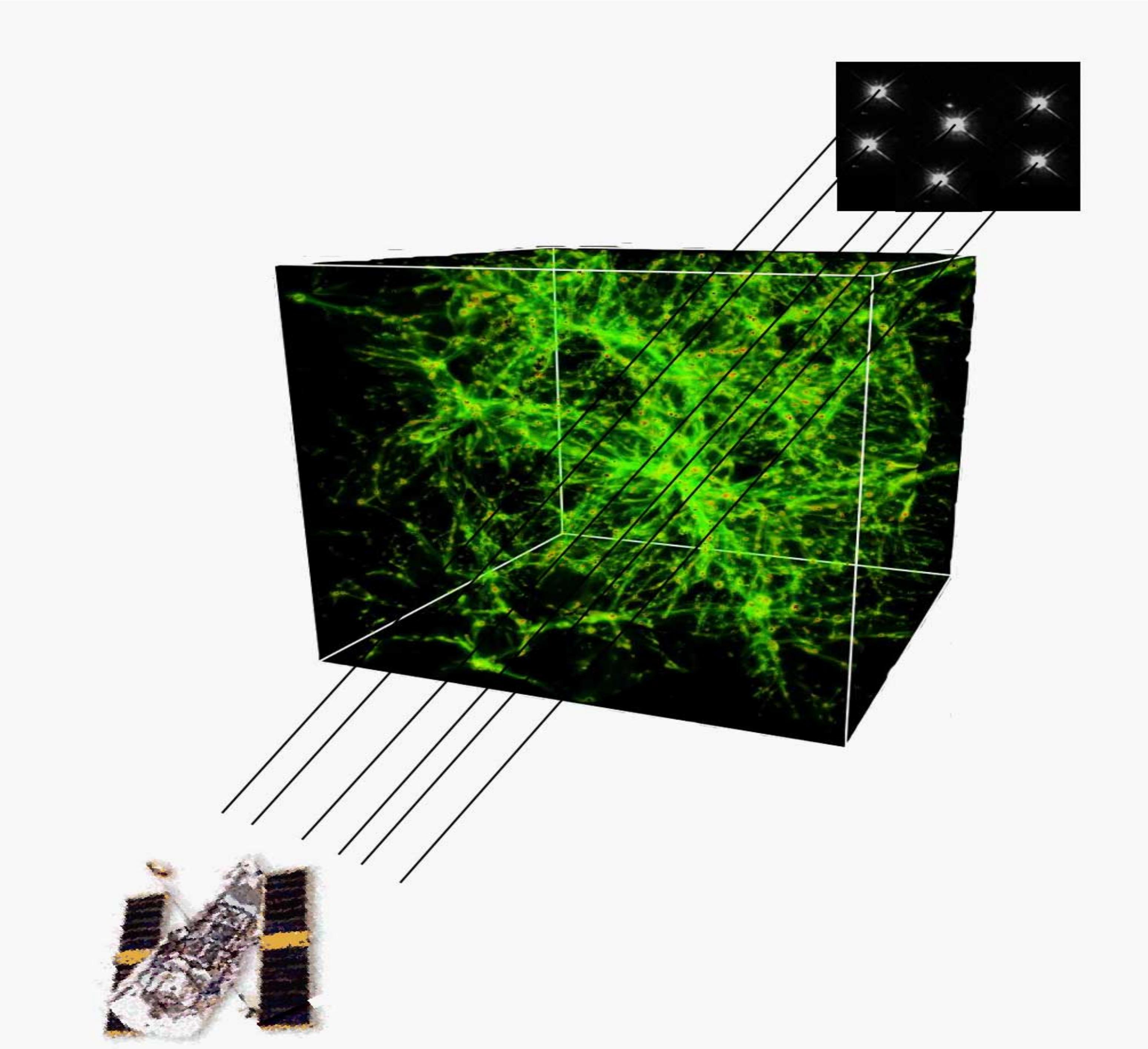

Figure 1: A representation of COS observing a series of distant quasars and probing the distribution of matter in the universe: the cosmic web. The web-like structure is a simulation a matter clustering on cosmological scales. Where the filaments cross is where galaxies can form. (Cosmic web simulation from Cen and Ostriker, 1999[2].)

Unfortunately, the most useful diagnostic observations are difficult to obtain, because the most interesting lines have their rest wavelength in the vacuum ultraviolet (at high enough redshifts, these can be observed in the optical, but then a whole epoch of history is missed) and the sources are very faint. Current instrumentation can make limited observations; the large integration times required for even the brightest objects means that only a few lines of sight can hoped to be probed with our current ultraviolet capabilities. While these few lines of sight have given new insight, only a thorough examination of many (perhaps 100) lines of sight can actually fill in the gaps in our knowledge. To efficiently perform such a survey requires an instrument with a large effective area, and a broad simultaneous bandpass. Since one does not know, *a priori*, the redshift of the intervening absorbing material toward a distant object, one has to cover the entire bandpass in order to observe all of the potential contributing components. This is why COS has been driven to large effective areas with large bandpasses and has been optimized for the observation of point sources.

The HeII Gunn-Peterson Effect: The epoch of the recombination of HeII creates a redshift dependent opacity from the strong HeII Lyα line at 304 Å. For redshifts where He is fully ionized (HeIII), this strong absorption line does not exist. A smooth distribution of HeII at large continuous redshifts creates continuously overlapping absorption lines, which manifest themselves as a continuum depression and absorption edge known as the Gunn-Peterson effect[3]. The absorption edge indicates the initiation of the epoch of He ionization. If the ancient intergalactic medium is not uniformly ionized, the discrete absorbers can be seen as individual absorption lines. Because the HeII 304 Å line can only be detected at redshifts greater than 2.78 (to move the 304 Å line into the COS bandpass) all potential targets are extremely faint. COS will enable the observation of numerous targets of this sort.

Big Bang Nucleosynthesis: The resolution of COS is sufficient to isolate deuterium (D) from hydrogen in the absorbing clouds and measure the ratio of D/H as a function of redshift. Since the primordial value of D/H is a powerful constraint on the physical conditions in the universe in its formative minutes, measuring D/H in pristine environments is of great interest. Additionally, we can detect features from elements heavier than helium in the distant intergalactic medium and determine what level of stellar reprocessing, and hence, stellar activity, has occurred in the young universe.

In addition, COS will study the halos of distant galaxies, heavily reddened regions of our own galaxy, and faint ultraviolet emissions from objects on our own solar system.

2. The COS Concept

The principle design constraint behind the COS concept is simultaneously maximizing both effective area and wavelength coverage in an ultraviolet spectrograph while providing a spectral resolution of at least 20,000. Both aspects are required for efficient observation of faint absorbing systems that appear at a variety of redshifts along a single line of sight. A conscious choice was made to optimize the performance for point source spectroscopy, even at the expense of diffuse source performance. In addition, it was decided early on that the instrument would support a minimum number of modes to reduce end-to-end system cost, not just in the instrument development, but in calibration, operations, and science support. It was felt that in order to achieve greater than a factor of ten improvement in effective area over existing ultraviolet spectrographs, it would be necessary to design an instrument which maximized one aspect of performance at the expense of observing versatility.

COS is not envisioned as a replacement for the existing ultraviolet spectrographs that would be operating in 2003. By having focused performance objectives, COS is able greatly exceed current and planned capabilities in select areas. For other observing scenarios, another instrument (notably STIS) may be the spectrograph of choice.

COS has two channels, the Far Ultraviolet (FUV) channel covering 1150-1775 Å, and the Near Ultraviolet (NUV) channel, covering 1750-3000 Å. The available modes of COS are listed in Table 1.

Table 1
COS Operational Modes

Channel	Operating Range (Å)	Simultaneous Bandpass (Å)	Spectral Resolution	Average Effective Area (cm^2)	Average Sensitivity (cnts/resol/ergs/ cm^2/s/Å)
G130M	1150-1450	1150-1450	20,000	2200	1.0×10^{13}
G160M	1405-1775	1405-1775	20,000	1200	7.0×10^{12}
G140L	1240-2300	1240-2300	2000	1000	3.5×10^{13}
G185M	1700-2100	3 x 28*	20,000	600	8.0×10^{12}
G225M	2000-2600	3 x 35*	20,000	650	8.0×10^{12}
G285M	2500-3200	3 x 41*	20,000	450	8.0×10^{12}
G230L	1700-3200	500	2000	500	9.0×10^{13}
TA1	1150-3200	1150-3200	Imaging	-----	---------

*The NUV mode of COS utilizes a modified Czerny-Turner design with three camera mirrors (see below). This results in three separate spectra, each of bandpass as listed above. The wavelength segments are not contiguous. By shifting the wavelength coverage of each exposure, full coverage of the stated operating range can be achieved with multiple exposures.

The FUV channel is supported by a cross delay line detector (XDL), similar, but not identical to that employed by the FUSE spectrograph, and supplied by the Dr. Oswald Siegmund of the University of California at Berkeley. The detector has dual curved microchannel plate systems, with a total active area of 170 mm by 10 mm. This large active area is essential to the COS concept as it allows COS to obtain a large bandpass in the FUV without using an echelle format. Both dispersion and cross dispersion coordinates are determined by time-delay anodes.

The NUV channel uses a STIS flight spare MAMA which is completely built and flight qualified. A large format XDL detector in the NUV range is not feasible because the nature of the required photocathode dictates a sealed tube detector, which is impractical for the XDL size.

3. Optical Design

COS is designed to provide the maximum possible performance for the lowest cost and risk. This philosophy permeates every aspect of the instrument, from the optical design to the technical implementation. The design philosophy is outlined below, followed by the specifics of the FUV design.

The COS FUV channel is a slitless spectrograph with a single optical element to provide refocusing, dispersion, and correction of the Hubble spherical aberration and correction of the inherent aberrations of a single element design. The design is a modified Rowland Circle mount, employing a large, curved detector to provide substantial simultaneous wavelength coverage. Because COS is designed to observe point sources, it is not necessary to correct the spherical aberration except at one particular off-axis position. For this reason, the aberration can be corrected with a single symmetric, aspheric optic, employing 4th and 6th order deformations to a spherical substrate. Essentially, by restricting the field of view top a few arc seconds, any out of focus optic is a reasonable pupil mapping. The rulings are applied holographically, and these correct the natural astigmatism of the Rowland mount. Please refer to figure 2 for a layout of the FUV channel.

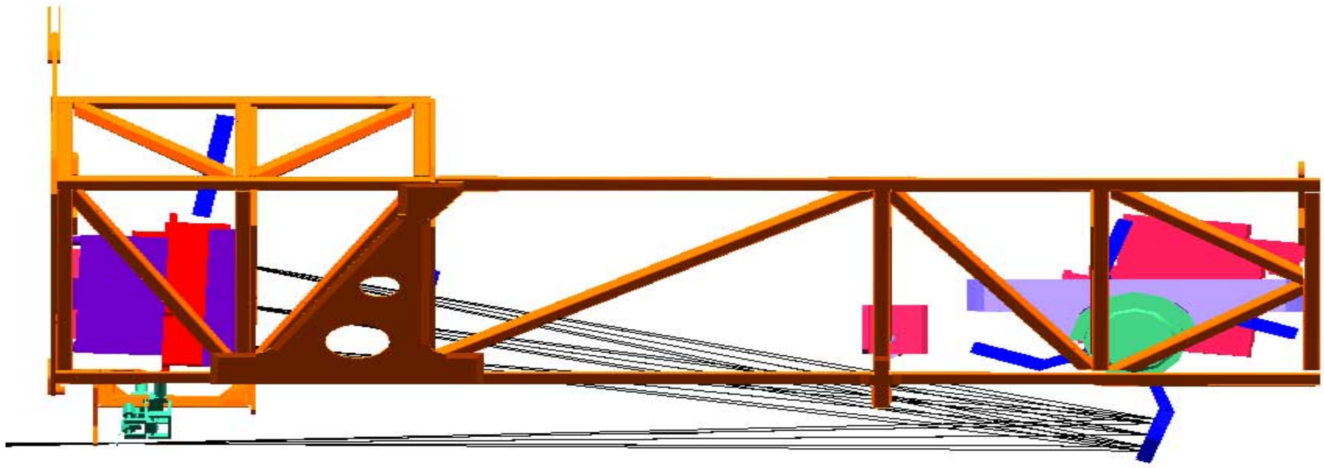

Figure 2: A layout of COS FUV Channel. The light path is represented by the thin lines. Light enters through the aperture at the lower left, and bounces off one of four possible optics on the selection mechanism in the lower right. Light is diffracted and reimaged onto the detector, shown on the left above the input aperture. In one exposure, 300 Å of coverage is provided at 20,000 resolution.

.

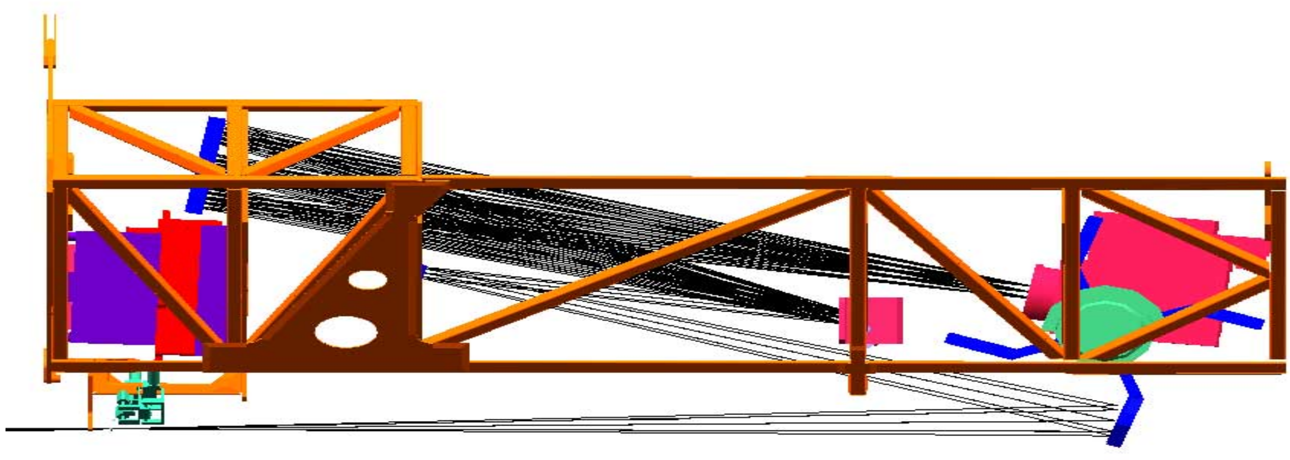

Figure 3: A layout of the COS NUV channel. Light again enters from the same aperture, and is reimaged and corrected by the NUV first optic (lower right). Light is then collimated with a small optic, and reflected to the selected flat, uniform groove density grating which can be tilted to access the desired wavelength range. Three camera optics (upper left) then reimage three stripes onto the MAMA detector (far right).

COS is a slitless spectrograph. 100% of the light collected by the HST OTA is transmitted to the COS spectrograph. A second, bright object aperture can be placed in the beam for the observation of targets that would normally be too bright for the detector systems. This aperture has a neutral density filter in place with a nominal transmission of 1%.

Both wavelength and flat field calibrations can be performed. The wavelength calibration is offset from the location of the science spectrum in the cross-dispersion direction. The flat field system (D_2 lamp) provides a defocused continuum (a pseudo-continuum shortward of 1600 Å) in the exact location of the science spectrum, and passing through the spectrograph, so that the f/#, wavelength, and angle of incidence are well approximated.

4. Design Specifics

The optical design parameters for the FUV channels are detailed in the table below. The COS slit is 90.49mm off-axis from the HST optical axis and 6414.4mm from the nominal HST secondary vertex (measured in projection along the HST optical axis). The surface of the optic is a sphere of the quoted radius deviated by an amount $\Delta z = a4r^4 + a6r^6$ where z is measured along the vertex normal. The quantities γ, δ, rc and rd are the standard positions of the recording sources as defined by Noda, Namioka and Seya[4].

Table 2
FUV Design Parameters

Channel Name	G130M	G160M	G140L
Vertex/Slit (z)	6414.4mm	6414.4mm	6414.4mm
Slit Off Axis	90.49mm	90.49mm	90.49mm
Slit/Grating	1626.57mm	1626.57mm	1626.57mm
α	20.1°	20.1°	7.40745°
β	8.6466°	8.6466°	-4.04595°
α-β	11.4534°	11.4534°	11.4534°
Grating/Detector	1541.25mm	1541.25mm	1541.25mm
Detector Normal /Central Ray	9.04664°	9.04664°	9.04664°
Groove density (l/mm)	3800.	3093.3	480.
radius	1652.mm	1652.mm	1613.87mm
a4	1.45789e-9	1.45789e-9	1.33939e-9
a6	-4.85338e-15	-4.85338e-15	1.48854e-13
γ	-71.0°	-62.5°	10.0°
δ	65.3512°	38.5004°	24.0722°
rc	-4813.92mm	-4363.6mm	3674.09mm
rd	5238.29mm	4180.27mm	3305.19mm
recording λ	4880 Å	4880 Å	4880 Å

The G130M and G160M gratings are ion etched to produce a triangular profile. Due to their low line density, the G140L gratings will have a laminar profile introduced through ion etching. A second set of G140L gratings will be produced, on a best effort basis, with a triangular profile. Should this triangular blaze attempt prove successful, the effective area of the G140L channel will increase by an average of 30%.

5. Component Performance

The G130M gratings have been produced and coated. The imaging, scatter and throughput performance f one of these is presented in Osterman, *et al*, in this volume[5]. They currently meet or exceed their requirements in all categories.

Prototype components have been produced for the COS FUV detector. Current anode designs are delivering better than 25 μm resolution (FWHM) over more than 80% of the active area. Detector quantum efficiency has been measured on a set of flight reject plates (the highest qulaity plate set *not* selected for flight production or flight spares) and their performance is summarized in the table below. These plates utilize a CsI photocathode.

Table 3
Prototype Microchannel Plate Detection Quantum Efficiency

Wavelength (Å)	DQE Requirement	DQE Measured
1152	44%	49%
1216	32%	35%
1278	------	35%
1335	25%	26%
1460	19%	22%
1560	17%	18%
1710	11%	12%

6. Conclusion

The Cosmic Origins Spectrograph will be, by a factor of nearly 20, the most sensitive ultraviolet spectrograph to have ever flown. Its enormous sensitivity will allow the pursuit of scientific investigations that were not previously possible. Some of these investigations have been outlined in this paper. However, the vast majority of observations will be conducted by the astronomical community at large, and only time will reveal what objectives these programs will have. The diagnostic capability of quantitative spectroscopy remains a most powerful tool for astrophysical investigation, and COS is the latest in a long tradition of ultraviolet spectrographs. Its power would not be possible without the aperture and performance of the Hubble Space Telescope, and the next generation of ultraviolet instrumentation will require a successor to Hubble that exceeds its performance.

7. References

1. Morse, J., *et al*, 1998, Proc SPIE, **3356**, 361

2. Cen, R., and Ostriker, J., 1999, ApJ, **514**, 1

3. Madau and A. Meiksin, “The He II Lyman-Alpha Opacity of the Universe,” Astrophysical Journal (letters), vol. 433, pp. L53 - L56

4. Noda, H., Namioka, T., and Seya, M, 1974, J. Opt. Soc. Amer., **64**, 1031

5. Osterman, S., Wilkinson, E., Green, J., and Redman, K, 2000, Proc SPIE, in press