# The Cosmic Origins Spectrograph: A Hubble Replacement Instrument for the 2002 Reservicing Mission

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**Abstract**

The Cosmic Origins Spectrograph is a new instrument for the Hubble Space Telescope that will be installed in 2002. It is designed for high throughput, medium resolution spectroscopy of point sources, allowing the efficient observation of numerous faint extragalactic and galactic ultraviolet sources. 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, and the origin of stellar and planetary systems and the cold interstellar medium.
**Keywords**: ultraviolet, spectrograph, HST, space

## 1. Introduction

The Cosmic Origins Spectrograph (COS) has recently been selected as a replacement instrument for the Hubble Space Telescope. Installation is scheduled for late 2002, replacing COSTAR, which at that time will be unnecessary. COS is a high throughput ultraviolet spectrometer operating from 1150 - 3000 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 many scientific endeavors are benefited by an instrument with such capabilities, 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*, in this volume. In addition, COS is a low-risk, low-cost instrument utilizing significant design and existing hardware heritage. Elements form the Goddard High Resolution Spectrograph (GHRS), the Space Telescope Imaging Spectrograph (STIS), and the Far Ultraviolet Spectroscopic Explorer[1] (FUSE) have all been employed to produce an instrument which provides large improvements in performance over existing ultraviolet spectrographs while presenting minimal technical risk

## 2. The COS Concept

The principle design constraint behind the COS concept is simultaneously maximizing both effective area and wavelength coverage in a 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 a 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. In this way COS achieves better than an order of magnitude improvement in sensitivity over existing and planned ultraviolet spectrographs. Not from the application of new technology, but from a design philosophy that uses a different optimization and operational paradigm. The resulting instrument is COS.

COS is not envisioned as a replacement for the existing ultraviolet spectrographs that would be operating in 2002. 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) will 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**

| Mode Designation | Simultaneous Bandpass Å | Channel Detector | Spectral Resolution | Peak Effective Area ($cm^2$) | Notes |
|---|---|---|---|---|---|
| G130M | 1150 - 1450 | FUV DDL | ≥ 20,000 | 2500 | |
| G160M | 1405 - 1775 | FUV DDL | ≥ 20,000 | 1500 | |
| G140L | 1230 - 2050 | FUV DDL | ≥ 2500 | 2200 | |
| G190M | 150 Å within 1750 - 2300 | NUV MAMA | ≥ 20,000 | 800 | produces 3 X 50 Å stripes |
| G260M | 150 Å within 2300 - 3000 | NUV MAMA | ≥ 20,000 | 800 | produces 3 X 50 Å stripes; includes short λ cutoff to eliminate order confusion |
| G230L | 1000 Å within 1750 - 3000 | NUV MAMA | ≥ 1000 | 800 | |
| G130MB | 150 Å within 1150 - 1800 | NUV MAMA | ≥ 20,000 | 500 | FUV back up mode |

The FUV channel is supported by a double delay line detector[2] (DDL), 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 allows COS to obtain a large bandpass in the FUV without using an echelle format. The NUV channel uses a STIS flight spare MAMA which is completely built and flight qualified. A large format DDL 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 DDL size.

## 3. Science Objectives

The science objectives of the COS science team are focused on a few specific areas, and these have driven the design of the system. While it is assumed that COS will be employed for numerous types of astrophysical observations, the discussion here will be limited to those that drove the optical design. As stated earlier, a much more detailed discussion of the instrument's science goals is presented in Morse *et al*, this volume.

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. 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. While 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.

COS will make significant contributions on the following areas of study:

The HeII Gunn-Peterson Effect: The epoch of the recombination of HeII creates a redshift dependent opacity from the strong HeII Ly$\alpha$ line at 304 Å. For redshifts where He is fully ionized, this strong absorption line does not exist. An overlapping continuum of HeII at large continuous redshifts creates an absorption edge known as the Gunn-Peterson effect[3]. Because this 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 allow an 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 hours, 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.

The Origin of Large Scale Structure: The distribution of non-luminous baryonic matter in the early universe can be a powerful probe of the initial state of clustering and the evolution of structure in the universe, which is currently a matter of debate. COS will have the power to map out the distribution of clouds of gas in the universe and determine their spatial distribution. This is an excellent example of why a survey of many lines of sight is required to perform the science investigation.

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

## 4. 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 proposed COS only operated from 1150-1775 Å, and adhered to all of the design principles below. The NUV capability was added after selection. Due to he unavailability of a similar detector in the near UV (1750 - 3000 Å) the NUV modes do not offer as significant advantages in throughput and bandpass as does the FUV channel. However, the fundamental premises of the design are:

### 4.1 Minimum Reflections

Each reflection in the far ultraviolet costs about 20% of the total system throughput. While this is not nearly as costly as it is in instruments operating shortward of the $MgF_2$ reflection cutoff (such as FUSE) or particularly those that require grazing incidence reflections (such as EUVE), traditional spectroscopic designs employ numerous reflections, and the subsequent throughput losses. This is particularly true of HST designs that must correct the spherical aberration of the Hubble Optical Telescope Assembly (OTA). A standard approach is to reimage the light with a two bounce corrector system, place an aperture at this new focus, and then have a classic collimating-diffracting-reimaging system. This an result in five or more reflections, including two grating reflections in echelle systems. The net result is a significant reduction in overall system efficiency. The COS FUV channel uses a single optic to correct the spherical aberration, provide the spectral dispersion and reimage the light. The design is a modified Rowland Circle mount, employing a large, curved to 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 $4^{th}$ and $6^{th}$ order deformations to a spherical substrate. The rulings are applied holographically, and these correct the natural astigmatism of the Rowland mount. Please refer to figure 1 for a layout of the FUV channel.

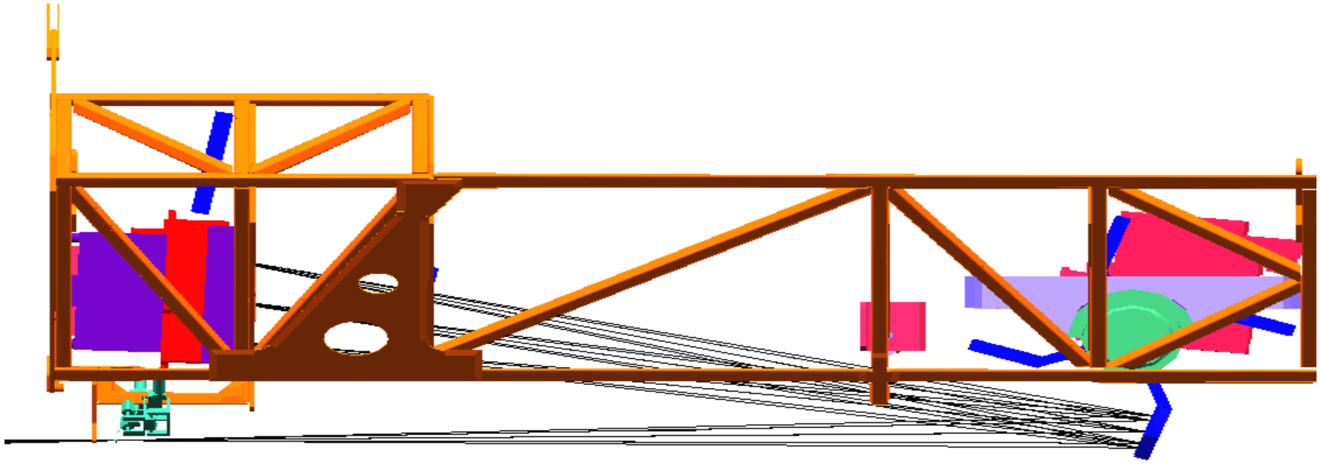

Figure 1: A layout of COS FUV Channel. The light path is represented by the thin lines. Light enters through the aperture at the lower left, and bounces off one of four possible optics on the selection mechanism in the lower right. Light is diffracted and reimaged onto the detector, shown on the left above the input aperture. In one exposure, 300 Å of coverage is provided at 20,000 resolution.

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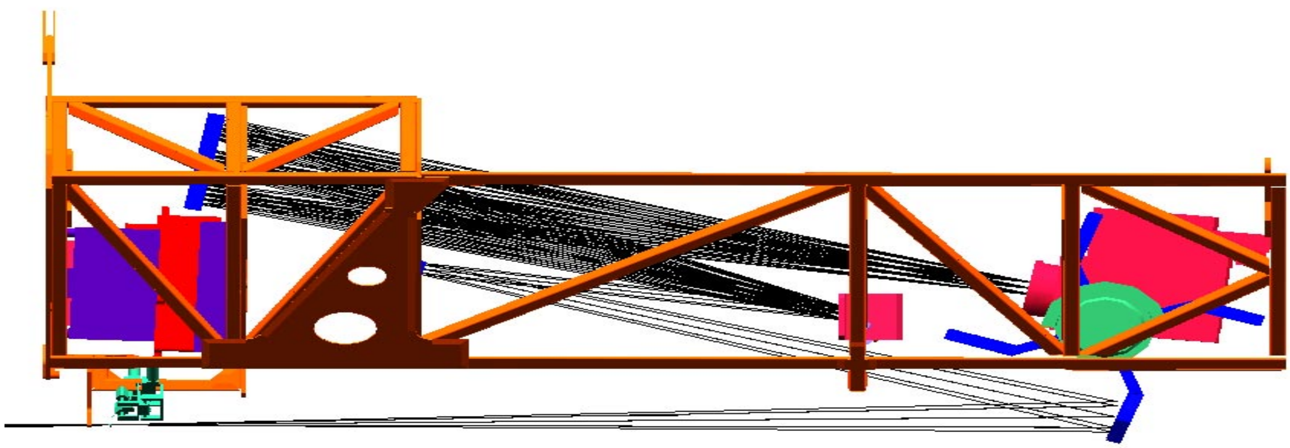

Figure 2: A layout of the COS NUV channel. Light again enters from the same aperture, and is reimaged and corrected by the NUV first optic (lower right). Light is then collimated with a small optic, and reflected to flat, uniform grating which can be tilted to access the desired wavelength range. Three camera optics (upper left) then reimage three 50 Å stripes onto the MAMA detector (far right).

In the NUV Channel (please refer to Figure 2) COS cannot adopt the straightforward design employed in the FUV. There are no large format detectors available in the NUV. Therefore, COS employs a modified Czerny-Turner approach. The use of multiple camera optics allows one to capture three independent segments of the diffracted spectrum, effectively tripling the simultaneous bandpass coverage of the instrument.

**4.2 No Slit Losses**

One of the primary areas where light is lost in standard spectrographic designs is at the slit, which is normally employed to ensure that the point spread function which feeds the spectrograph is sufficiently narrow to guarantee that the spectral resolution is adequate. However, the point spread function provided by the Hubble OTA is excellent, except for the presence of the correctable spherical aberration, and the pointing jitter is so small that it can be negligible to a spectrograph whose plate scale is appropriately matched to the known HST performance. For that reason, COS is designed as an essentially slitless spectrograph. The spectrograph re-images the sky, and not the slit. The primary slit is present only to reduce the contribution from diffuse sky emission and possible confusion form nearby point sources. For that reason, the star position within the slit affects the absolute (but not the relative) wavelength calibration of any observation. A straightforward technique has been developed to center the object in the aperture for those observations which require a high level of absolute wavelength knowledge. Two additional apertures will be available, a small aperture which will allow the observation of bright targets (intentionally introducing slit losses) and a wide aperture for the high sensitivity/low resolution observation of faint diffuse objects.

### 4.3 No Windows or Filters

In the FUV channel, the DDL detector is windowless. This means that the window transmission (typically only 60%) in other typical systems is not lost. There are no filters that can be inserted in the system. The NUV channel does have a windowed detector, however, the MAMA window for COS is known to not have any problems that would cause a high background on orbit.

### 4.4 Operational Simplicity

There are only seven spectroscopic modes that can be selected, and three apertures, which can be used in any mode. This greatly reduces the burden on operations and calibration support for the instrument, reducing total mission cost. While this simplicity means that certain types of observing scenarios cannot be implemented, this was the optimization choice made for COS. It was decided to excel in a particular subset of potential ultraviolet observing modes rather than be good in all modes.

### 4.5 Technical Heritage

COS has chosen to reuse many design elements form previous NASA missions, and even existing, flight qualified hardware. For example, the DDL detector is a knockoff of the existing FUSE DDL design. The NUV MAMA is an existing piece of STIS spare hardware. COS will reuse the GHRS optical bench and structure, and the electronics packages and interfaces will all be replicas of the STIS electronics. The optical fabrication techniques for the substrates use technologies proven from the STIS and COSTAR experiences, and the holographic recording techniques have been demonstrated on FUSE.

## 5. 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.

## 5. References

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