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Faint Object Spectrograph (FOS) early performance

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ABSTRACT

The Faint Object Spectrograph (FOS) instrument aboard the Hubble Space Telescope (HST) provides astronomers a moderate spectral resolution, low light level, analytical instrument sensitive throughout the wavelength region from below 120 nm to beyond 800 nm. The on-orbit performance of the HST + FOS instrument is described and illustrated with examples of initial scientific results.

The severe spherical aberration resulting from the misfiguring of the HST primary mirror strongly impacts the combined HST + FOS performance. The effects of the spherical aberration upon isolated point sources and in complex fields such as the nuclei of galaxies are analyzed.

Substantial effort has gone into studying possible means for eliminating the effects of spherical aberration. Concepts include using image enhancement software to extract maximum spatial and spectral information from the existing data as well as several options to repair or compensate the HST's optical performance. In particular, it may be possible to install corrective optics into the HST which will eliminate the spherical aberration for the FOS (and some of the other instruments). A brief description of the more promising ideas and calculations of the expected improvements in performance are provided.

1.0 INTRODUCTION

1.1 Overview of the FOS instrument

The FOS has been designed to provide low to moderate resolution spectroscopy of the faintest possible astronomical sources throughout the range from the far-UV($\lesssim$115 nm) to the near-IR($\gtrsim$800 nm). Previous publications[1,2,3,4] have described the design of the FOS and its anticipated performance based on ground-based calibrations. We can now compare these expectations to actual performance as revealed in just under one year of operation on orbit.

In its primary observing mode, the FOS provides spectroscopy with a resolution R = λ/Δλ ≈ 1300 over the wavelength range from 115 to over 800 nm. The lower limit is rather sharply set by absorption in the MgF_2 faceplate of the "blue" Digicon detector, and the upper limit arises from the gradual falloff in sensitivity of the S-20 photocathode of the "red" Digicon detector. Low resolution spectroscopy with R ≈ 200 are also possible over most of this wavelength range. A selectable set of apertures allows observations of regions of the sky varying in size from 0.1 arcseconds to 4.3 arcseconds on a side. A variety of aperture shapes -- square pairs, as well as individual circular, rectangular, and occulting-bar apertures -- allows the user to best select the portion of an image for spectral analysis to carry out the chosen scientific objectives of each observation.

In addition to its basic spectroscopic mode, the FOS allows several specialized modes of operation. A polarization analyzer can be commanded into the beam to measure linear and circular polarization as a function of wavelength, although the analyzer is optimized for UV linear polarization measurements[2]. Rapid-readout, time-resolved (phase-binned), and time-tagged modes allow the astronomer to search for periodic or aperiodic variability of targets as a function of wavelength. Finally, a nondispersed mode allows crude imaging, which is primarily used for target acquisition.

1.2 Typical FOS science programs

Astronomers will use the FOS to observe targets as near as our own Solar System and as remote as quasistellar objects (QSOs) near the edge of the observable universe. To illustrate the capabilities of the FOS for carrying out scientific observations, we discuss below a few of the programs planned by the FOS science team members.

The astrophysical interests of the FOS science team lie primarily in the broad area of extragalactic astrophysics. The team's observing programs include spectroscopy of QSOs, the nuclear regions of both active and normal galaxies, peculiar features such as knots and jetlike structures, supernovae, and planetary nebulae. In general, the science team's is both to understand the physics underlying the phenomena being observed, which are often dramatically energetic and even violent, and to use observations of objects throughout a large volume of space to seek to understand the chemical and structural evolution of the observable universe.

The most remote observable individual entities are the quasistellar objects. It is widely believed that these extremely luminous objects are powered by black holes devouring thousands of stellar masses each year. Our scientific interest in QSOs includes the desire to understand the physical processes which occur in what must be the most extremely violent regions of the universe, and to use our ability to observe such bright beacons at tremendous distances in order to probe the chemistry of the early universe and analyze the distribution of matter along the lines of sight to these objects. [Observations of distant targets automatically involves looking back toward the early universe due to the finite speed of light.]

Galaxies contain most of the visible matter in the universe. While not as bright as QSOs, galaxies can be observed to distances of several billion light-years. Some galaxies are observed to be undergoing extremely violent activity in their nuclei. Most theorists invoke the presence of black holes with masses up to millions of times that of the sun in order to explain the energy source for the quantities of radiated energy we observe. A specific high-priority goal of the FOS science team is to search for evidence of black holes in the nuclei of nearby galaxies and in (more remote) active galactic nuclei. Such studies require high spatial resolution imagery and spectroscopy of the nuclear regions of galaxies to best probe for evidence of massive black holes.

A supernova, the explosion of entire an star, shines briefly with the intensity of an entire galaxy. Although supernovae are extremely interesting phenomena in themselves, the FOS team's primary interest in them is to use them as calibratable light sources which can be observed over a wide range of distances in order to attempt to measure the Hubble constant H_0, which relates distance to recessional velocity, and the deceleration parameter q_0, which quantifies the degree to which the gravity of all the matter in the universe both slows down the Hubble expansion and curves space-time. This program is extremely challenging, requiring both excellent spatial resolution and sensitivity to extremely faint sources.

The FOS can, of course, be used to observe targets within our own galaxy. One example of such galactic astronomy programs is the attempt to use the angular resolution of the HST and the spectroscopic capability of the FOS to recover a nova in the globular cluster M14.

2.0 FOS ON-ORBIT PERFORMANCE

A quick summary of the FOS on-orbit performance is that it is performing almost exactly as planned. However, operation of the instrument has revealed a couple of quirks and one region of less-than-anticipated sensitivity. By far the major deviation from expected performance arises not from the FOS itself, but from the impact of the spherical aberration in the HST optical system.

2.1 Sensitivity

Figures 2.1-1 and 2.1-2 illustrate, for the red and blue channels respectively, the sensitivities for the FOS + HST derived from on-orbit observations of standard stars compared to the values anticipated prior to launch. The immediately obvious difference is a nearly wavelength independent reduction in sensitivity by about 30%. This corresponds extremely well to the loss of sensitivity calculated to occur in the FOS 4.3 arcsecond square aperture for the HST point spread function produced by the spherically aberrated optical system.

From 150 nm to beyond 800 nm, the sensitivity of the FOS itself is exactly as anticipated.

A closer look at the short wavelength sensitivity measurements, as shown in Figure 2.1-3, reveals a lower than anticipated sensitivity in the region shortward of 150 nm. The reduced efficiency is equally present in both the low-dispersion and high-dispersion gratings. Measurements by other instruments on the HST prove that the loss of efficiency does not arise within the HST, so that the reduced response must arise within the FOS. Our as yet limited understanding of the causes for this reduced far-UV response is described in Section 2.4.3.

2.2 Background

Instrumental background on orbit has been remarkably consistent with expectations based on computations performed in 1977. The dominant source of background is high-energy particle-induced Cerenkov radiation in the faceplates of the Digicon detectors. For both the red and blue Digicons, the Cerenkov radiation produces about 0.010 count/second/pixel background when the HST is outside the South Atlantic Anomaly. This matches exactly our prelaunch expectations.

To reduce the background count rates further when observing faint targets, the FOS onboard software is designed to reject Cerenkov light bursts by using the 512 channels of each Digicon as their own anticoincidence detectors. After each short integration cycle (typically 100 to 500 msec long), the sum of the counts from any number (often all) of the pixels is compared to a software limit. If the sum exceeds this limit, the data are rejected as a burst-noise event. Modeling and experience on the ground lead us to anticipate that, for faint object observations, the effective background rate can be reduced to 0.002 or 0.003 counts/second/pixel. The on-orbit observations to confirm this have not yet been performed, however.

2.3 Resolution

The spectral resolution produced by the FOS for short exposures is completely as expected. Longer exposures require extra processing of the data to remove the effects of deflections in the Digicon detectors due to variations in the earth's magnetic field; this is discussed in more detail in Section 2.4.2. With this extra data analysis effort, the FOS is capable of returning spectra with spectral resolution fully meeting our design goals.

Spherical aberration presents the astronomer with an unpleasant tradeoff between achieving maximum efficiency or retaining full spectral resolution. The aberrated point spread function of the HST contains only about 15% of the light in the inner core region with the rest of the energy spread out over a diameter around 4 arcseconds. Thus, using the FOS small apertures, which preserves the full spectral resolution of the instrument, results in loss of most of the light, which simply falls outside the entrance aperture. Conversely, selecting a larger entrance aperture to collect more light from the HST, decreases the spectral resolution.

How to select the best mix of efficiency and spectral resolution is not always intuitively obvious. To achieve a given spectral resolution, one might either use the (small) aperture which produces the needed resolution but suffers reduced efficiency, or one may select a larger aperture to collect more photons and attempt to recover the needed spectral resolution by image deconvolution techniques. Our preliminary models of typical observations indicate that it is usually best to use the small aperture to obtain the spectral resolution directly even though fewer photons are collected by the spectrograph. One of the examples of FOS science discussed in Section 3.1 illustrate these tradeoffs.

2.4 Anomalies

The FOS instrument is basically performing flawlessly with the exception of three anomalies. Two of these, a microprocessor reset susceptibility and a less than ideal magnetic shielding of the Digicons, are fairly minor. The former has already been fixed, as discussed in Section 2.4.1. The second can be ameliorated by software and eventually completely compensated, as described in Section 2.4.2. The third, the loss of far-UV sensitivity, is by far the most serious defect in the instrument, and is further described in Section 2.4.3.

2.4.1 Microprocessor reset

[INSERT J FITCH SECTION HERE]

2.4.2 Magnetic shielding

[J FITCH SECTION DESCRIBING ENGINEERING ASPECTS]

The deflection of the photoelectrons caused by penetration of varying magnetic fields into the Digicon detectors create motions of the images and spectra recorded by the detectors. These apparent motions may produce three potentially deleterious effects. Motions during target acquisition imagery might cause inaccurate centering onto a target. Motions along the direction of dispersion during spectroscopic observations slightly reduce the spectral resolution during long exposures. Motions perpendicular to the direction of dispersion during spectroscopic observations induce variations in efficiency which compromise spectrophotometric accuracy.

Magnetically-produced motions of an image on the Digicon diode array during target acquisition cannot be distinguished by the FOS from target motions resulting from repointing of the HST. Long exposures to acquire faint targets may result in positional errors. The full range of motion produced by worst-case variation of the earth's magnetic field might produce errors as large as 0.3 arcseconds in the red detector and as large as 0.1 arcseconds in the blue detector. Although typical errors in target acquisition are much smaller than worst-case, it is prudent to include a peak-up centering of targets in the aperture which will be used for observations if miscentering of the target will strongly affect the science results.

Motions along the direction of dispersion during spectroscopic observations slightly reduce the spectral resolution by effectively streaking the spectrum along itself. Normal readouts of FOS exposures are frequent enough (typically, every 2 minutes) so that little loss of spectral resolution occurs during one incremental accumulation time. The integrated spectrum from the entire exposure will typically have diminished spectral resolution due to the shifts of the spectrum from magnetic field variations. The full spectral resolution can be fully recovered by separately shifting each spectrum from each short readout by an amount which can be calculated from a model of the earth's magnetic field, the pointing and roll angle of the HST, and the geometry of the FOS detectors with respect to the HST. Needless to say, this is tedious enough that we plan to eliminate the problem as soon as possible by using our deflection coils to actively null out the effects of variations in the earth's magnetic field.

Motions of the electrons perpendicular to the dispersion direction may result in varying amounts of the signal falling off the ends of the diode arrays. Because the spectra are not perfectly aligned along the length of the diode array, and because imperfections in the electric and magnetic fields within the Digicons produce some image distortion (C-distortion and S-distortion primarily), image shifts can produce variations in count rates which are pixel dependent. For spectra, such variations will produce low-frequency spectrophotometric errors. The effect is worse when larger apertures are used, since less motion is needed to cause loss of light over the ends of the diodes. Active control of the deflection coils will eliminate this problem completely.

2.4.3 Far-UV Response

Might errors in the ground-based calibration account for the discrepancy in the FOS far-UV sensitivity described in Section 2.1? In view of the difficulty of performing absolute photometric calibrations in the far-UV, an error in the original ground-based calibrations cannot be dismissed out of hand. However, comparison of the FOS and the Goddard High Resolution Spectrograph (GHRS) measurements on standard stars indicate a true decrease in FOS efficiency below 150 nm larger than what would be expected from the difference in Digicon faceplate materials and photocathode types. We have identified two plausible explanations for the reduced far-UV efficiency.

One possibility is that the photocathode of the blue Digicon has accumulated a thin layer of a hydrocarbon contaminant, which can produce absorption in the far-UV region. Because the photocathodes are cooled by heat pipes connected to a radiator, contaminant sources might collect preferentially on the Digicon windows. However, the far-UV sensitivity appears not to have varied either on orbit nor during the last few years prior to launch. The stability prior to launch is not fully conclusive, as it is based on measurements with the FOS internal spectral calibration lamps, which are not photometric standards. Still, a change in spectral calibration lamp output exactly offsetting real changes in the FOS far-UV response seems a bit contrived.

An alternate possibility is that the loss is occurring at the aluminum grazing-incidence mirror, which is used to deflect (nearly on-axis) light away from the walls of the FOS to allow adequate room for placement of the filter-grating wheel mechanism. This mirror was measured in 1980 and found to produce acceptable reflectivity throughout the broad wavelength range of the FOS. Based on measurements of its reflectivity (at the same angle of incidence as in the FOS) versus wavelength, we estimated that the mirror had grown an oxide approximately 40A thick. The diminished UV response of the FOS could be explained if this oxide has roughly doubled in thickness during the decade from our measurements to launch of the HST.

At present, we do not know which explanation is correct. Repeated on-orbit calibrations to monitor FOS photometric stability are planned. Any changes in UV sensitivity would favor hydrocarbon contamination as the likely cause of reduced far-UV response. It may be possible to use the FOS polarization analyzer, which outputs two beams linearly polarized in orthogonal directions, to estimate the oxide thickness on the grazing mirror from wavelength-dependent differences in reflection for the two polarization states. The measurements to do this are quite straightforward. The calculations, incorporating the correct geometry of the FOS polarizer and optical surfaces, will not be simple and have not yet been done.

3.0 Early FOS science results

Following the discovery of spherical aberration, the HST Program decided to carry out an Early Release Observation (ERO) and Science Assessment Observation (SAO) program using each of the instruments to determine what science programs could reasonably still be accomplished. The first such observation with the FOS occurred on 28 October 1990, and other ERO and SAO programs with the FOS have continued through February 1991. The scientific results of these programs are being published elsewhere. Below we discuss some of the operational implications of the information obtained from the ERO and SAO programs.

During the 4 month period from 28 October 1990 to 28 February 1991, the FOS obtained spectra of four QSOs, two Seyfert galaxy nuclei, and a nova candidate in a globular cluster. From these observations, it is clear that high-quality spectroscopic science can be accomplished with the FOS despite the problems caused by spherical aberration. In nearly all cases, however, longer exposure times will be necessary, and some scientific programs will not be feasible without somehow correcting the effects of the aberration.

3.1 Quasistellar objects

The first scientific target of the FOS (excluding calibration stars) was the moderately faint (visual magnitude V ≈ 17) high-redshift (z = 2.148) quasistellar object UM 675. The FOS science team also observed the nearby (z = 0.078) quasistellar object CSO 251 and the distant (z = 2.62) quasistellar object CSO 38, both moderate apparent luminosity objects with V ≈ 16. In January 1991, John Bahcall and FOS scientists made extensive observations of the nearby (z = 0.158) bright (V ≈ 13) quasistellar object 3C 273 through several different FOS entrance apertures.

Spectroscopy of isolated pointlike objects is the type of science observation with the FOS which is least impacted by the effects of spherical aberration. For sufficiently bright targets that instrumental or sky backgrounds are not dominant, the effect of spherical aberration is simply to force on the astronomer the obligation to accept some mixture of increased exposure times and decreased spectral resolution, as discussed in Section 2.3. The QSOs observed with the FOS all meet the criterion that sky and instrumental background noise are much less than the signal.

The observations of 3C 273 most directly address the tradeoff between signal intensity and spectral resolution. Figure 3.1-1 illustrates the extreme of maximizing signal at the expense of resolution. This spectrum was taken through the 4.3 arcsecond square aperture normally used for target acquisition. The spectrum in Figure 3.1-2, taken through the 0.3 arcsecond diameter circular aperture, contains substantially more spectral information but collects signal at about one quarter the rate of the previous configuration. The spectrum shown in Figure 3.1-3 was taken through a slit aperture 0.25 arcseconds wide in the dispersion direction. The length of the observed region in the cross-dispersion direction is set not by the aperture but by the height of the diodes, which correspond to 1.4 arcseconds on the sky. This aperture retains the spectral information of the 0.3 arcsecond diameter aperture, but collects signal about 50% faster.

For this object, which exhibits narrow absorption lines (mostly from gas in our own galaxy), the spectra with greater spectral resolution are clearly superior to the spectrum through the 4.3 arcsecond aperture. Even with 2 to 4 times more signal per unit exposure time, deconvolution techniques will not restore the spectrum of Figure 3.1-1 to the information content of the other two spectra. In most respects, the slit spectrum of Figure 3.1-3 is fully as good as the small aperture spectrum of Figure 3.1-2, and can be obtained with a shorter exposure. Note, however, that where sky background is not negligible due to geocoronal Lyman α emission at $\lambda = 1216$ Å, the smaller aperture produces better results.

The three spectra do indicate a change in the likely usage of the various FOS apertures. With good point spread functions, we expected to use primarily the 0.3 arcsecond circular and 0.25 arcsecond square apertures, with the slit aperture relegated to use only in specialized observations. For observations of not too faint isolated objects, the slit aperture is likely to be the aperture of choice for nearly all spectroscopy with the FOS until the spherical aberration is compensated.

3.2 Active galactic nuclei

Studies of the nuclear regions of active (or normal) galactic nuclei are intrinsically far more difficult to study than isolated pointlike objects, particularly in the presence of spherical aberration. The aberrated point spread function means that, for these observations, not only will the intended signal in the aperture be reduced but also that unwanted light from adjacent regions will be thrown into the aperture, thus greatly increasing the effective sky noise background.

The two ERO/SAO programs of the nuclei of (Seyfert type) active galactic nuclei began with imaging of the regions of interest using either the Faint Object Camera (FOC) or the Wide Field/Planetary Camera (WF/PC) on the HST. From these images, we selected the regions for obtaining FOS spectra. This procedure was identical to what had always been planned before we learned of spherical aberration. The images showed that, for Seyfert nuclei, sometimes the central cores resolve into separate features as in NGC 1068, and others do not as in NGC 1566.

For objects such as NGC 1068 which contain resolved structures on subarcsecond scales, the spreading of the light from spherical aberration clearly is going to complicate the analysis of spectroscopic data. Figures 3.2-1 and 3.2-2 illustrate the complexity. Figure 3.2-1 shows the intensity of the Hβ spectral region in the nucleus of NGC 1068 observed through the 0.3 arcsecond diameter aperture. Figure 3.2-2 depicts a model fit to the observed spectrum, illustrating that several regions of disparate velocity dispersion and mean velocity. It is likely that these differing profiles correspond to the resolved structures seen in the images, but because the present HST point spread function mixes light from several nearby clumps into any spectrum, disentangling the true situation will require taking multiple spectra and deriving the true spectrum for each resolved emission feature as a system of linear equations. Our initial results indicate that interesting information from cores of galaxies can be obtained even in the presence of spherical aberration, but factors of 10 or so increases in total exposure times will probably be required compared to studies with an ideal HST.

3.3 Globular cluster M14

The attempt to recover a nova in the globular cluster M14 further illustrates the difficulties caused by spherical aberration. The images of M14, obtained with the FOC, produced what Bruce Margon could describe without overstatement as the most spectacular images of a globular cluster ever seen by the human race. These beautiful images[5] show how the sharp central core of the HST point spread function meets its design goals for resolving individual bright pointlike sources. The candidate star for the nova resolved into a half dozen images within a 0.5 arcsecond region. The spherical aberration guarantees that spectra of individual objects in this region are impossible to obtain, since significant amounts of light from several of them will invariably be mixed into any entrance aperture no matter how small. As of late February, we have obtained a spectrum which includes several of these candidate objects, but have not been able to identify the nova.

4.0 Impact of HST spherical aberration

As the sample programs above make clear, the presence of spherical aberration in the HST strongly impacts spectroscopic science investigations. For moderately bright, well isolated point sources, the effect is some combination of increased exposure time and decreased spectral resolution. For closely spaced pointlike objects or continuum sources, the impact is far more severe. The spatial mixing results in severe degradation of signal-to-noise ratios, reduced spatial information, and major increases in required exposure times.

For other programs, the effect is yet more severe: they simply cannot be done. The loss in collected light means that the faintest objects simply become unobservable. Similarly, programs which require studying faint structures near bright sources, such as galaxies which may surround QSOs, are simply impossible; the halo of the point spread function from the bright object simply overwhelms the faint structures of interest. Spatial mixing degrades the signal-to-noise ratio for all studies of extended objects; for faint targets such as supernovae in distant galaxies, this loss of information is likely to prove fatal to many scientific investigations.

5.0 Compensating for spherical aberration

Because many of HST's highest priority research programs are made difficult or impossible by the presence of spherical aberration, the HST community has vigorously sought ways to ameliorate or correct the problem. Possible ways to restore the full capabilities of the HST range from minor improvements to radical replacement, near-term to turn-of-the-century, and nearly free to impracticably expensive solutions.

5.1 Range of approaches

In the short term, defined as before the next Shuttle mission to service HST, the only techniques to deal with the spherical aberration involve cleverness in observing strategy and in data analysis. The ERO/SAO programs were designed to improve our cleverness in observing strategy. The advice of experts in image deconvolution techniques from within and without the astronomical community has been sought to improve our cleverness at analyzing the HST data. While both optimized observing strategy and intelligent use of image restoration techniques will allow us to carry out much excellent science with a spherically-aberrated HST, they will not allow astronomers to perform some of the HST's highest priority scientific investigations for which it was built.

To conduct investigations making use of the full angular resolution and faint limiting magnitudes for which the HST was designed, we must correct or compensate the spherical aberration. Political and fiscal realities probably preclude actually correcting the optics of the HST (or replacing HST with a clone built around the backup primary mirror). However, optics to compensate individual instruments for the spherical aberration are both possible and planned.

The replacement Wide Field/Planetary Camera, known as WF/PC II, will incorporate corrective internal optics which will restore essentially the full design imaging capability of the original WF/PC with an ideal HST. The WF/PC II is to be installed into the HST on the first Shuttle servicing mission planned in late 1993 or early 1994. This will restore much of HST's intended imaging capability, but will leave the highest spatial resolution imaging of the FOC and all spectroscopic capabilities uncorrected for spherical aberration. Installation of the Space Telescope Imaging Spectrometer (STIS) with the second Shuttle mission to HST (planned for 1996 or 1997) will restore the full range of spectroscopic capability. No definite plans to obtain the ultimate spatial resolution in imagery through a compensated FOC exist currently.

5.2 Optical compensation hardware

The leisurely pace for restoring HST capabilities described above is unacceptable to many. This has led to attempts to define quicker solutions to restoring HST's design capabilities which make use of many of the current instruments already installed on the HST. The most promising approach identified to date is the Corrective Optics Space Telescope Axial Replacement (COSTAR). The idea is to fabricate a set of corrective optics for the FOC, FOS, and GHRS which fits into an axial instrument enclosure. On the first Shuttle servicing mission, both the COSTAR and the WF/PC II are to be installed, fully restoring the WF/PC imaging and the FOS and GHRS spectroscopic design capabilities, and restoring the FOC imaging capabilities over a portion of its field of view. Thus, by late 1993 or early 1994, the HST could be restored to nearly its full design capabilities.

Installation of the COSTAR can restore the angular resolution of the HST + FOS to its full design capability. The two extra mirrors in the COSTAR mean that the limiting magnitude would remain about one-half magnitude brighter than would have been the case had HST been fabricated properly. Still, this represents about two magnitudes improvement over the present situation for isolated pointlike objects and even greater gains for extended or complex source distributions. The only FOS capability not restored with the COSTAR is spectropolarimetry; the off-axis design necessary in COSTAR means that its mirrors should be removed from the beam for polarimetric observations, which thus would suffer as now from the effects of spherical aberration.

As of late February, when this paper is being written, NASA has not yet decided whether to baseline the COSTAR option. Its promise is the quick restoration of HST to nearly its full design capabilities. Its risk is the technical effort required in a demanding schedule. Of course, paying for its development is not a negligible issue.

5.3 Recovery of science capabilities

For the FOS, the COSTAR offers the means to recover virtually all of the instrument's scientific capabilities now seriously compromised by spherical aberration. For the small fields of view of the FOS, it is possible to completely compensate for HST's spherical aberration, so that the full angular resolution will allow scientists to search for black holes in the nuclei of normal and active galaxies, to use distant supernovae to measure the values for H_0 and q_0, and to determine the nature of the diffuse material surrounding quasistellar objects. These and similarly exciting investigations are the programs for which the HST was built at such great cost to the public. The promise of the COSTAR for enhancing FOS and other science programs is so great that the FOS science team unanimously urges NASA to proceed with the COSTAR effort at high priority, giving up the effort only if technical infeasibility, schedule slippage, or significant cost growth make its successful installation into HST on the first Shuttle servicing mission impossible.

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