SPACE TELESCOPE SCIENCE INSTITUTE

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1990 July 18

Dear Colleague:

I am writing to bring you up to date on the status of the Hubble Space Telescope mission. As you are undoubtedly aware, the HST was launched aboard the space shuttle *Discovery* on April 24 and successfully deployed on the next day. Since then, the Orbital Verification process has been underway, and to date all of the Scientific Instruments appear to be operating nominally.

Unfortunately, a serious and long-term problem with HST's imaging performance has been identified over the past several weeks. This letter and the enclosed materials are intended to inform you of the nature of this problem as fully as is possible at present, and to discuss the impact on current and future scientific programs.

The following materials are enclosed:

1. A letter to the astronomical community from the NASA Project Scientist for HST, Dr. Albert Boggess, which describes the optical problem—spherical aberration—in broad terms.

2. A joint statement from the HST Science Working Group and the HST Users Committee, which discusses the impact of the imaging quality upon the performance of the Scientific Instruments, and contains recommendations to NASA regarding current and future HST programs.

3. A more detailed report, prepared by the Science Programs Division at STScI, on the imaging capabilities.

As you will see from these materials, HST will not be able to achieve its full goals for imaging performance in the near future. In particular, most scientific programs involving visual and high-resolution ultraviolet imaging with the Wide Field and Planetary Camera and the Faint Object Camera will be affected severely.

However, HST retains many of its spectroscopic, photometric, and astrometric capabilities. We are confident that HST will be used 100% of the time to produce exciting, forefront scientific results in these areas during the coming months and years. Moreover, it appears that a limited but important class of imaging programs can be accomplished with HST by employing image-reconstruction techniques to achieve nearly diffraction-limited performance.

A longer-term, complete solution of the problem appears feasible, through inclusion of corrective optics in the second-generation instruments that are already under development for future installation in HST.

We are currently undertaking an evaluation of the status of the approved General Observer and Guaranteed Time Observer programs. Within the next month, we will be communicating directly with Principal Investigators for accepted Cycle 1 GO projects and asking them to provide detailed assessments of the impact of the imaging performance upon their programs.

You will be kept fully informed as we develop responses to this new challenge, through special mailings, the STScI *Newsletter* (the next issue of which will be distributed in August), and our Electronic Information Service (see the March 1990 *Newsletter* for details). We have not yet set a deadline for submission of Cycle 2 proposals; as stated previously, the deadline will be no earlier than November 15, 1990.

We appreciate your continued interest in, and support of, the HST mission.

Sincerely,

Riccardo Giacconi
Director
and

H. S. Stockman
Deputy Director

July 3, 1990

Dear Colleague:

As you have no doubt heard from the press, the Hubble Space Telescope has serious optical problems. Since the media do not always communicate the technical details with full accuracy, I would like to inform the astronomical community about just what is wrong and what its consequences are likely to be.

Tests in orbit have shown that the Optical Telescope Assembly has about half a wave (r.m.s.) of spherical aberration. If this error were entirely due to the shape of the primary (which is only an assumption) it would correspond to a mirror curvature that is too shallow, with a total center-to-edge error of about two microns. Consequently the images will not achieve their anticipated quality. At a compromise focus, star images have cores whose full width at half maximum is 65 to 70 milliarcsec. Although this core size is within specification, it contains only about 15 percent of the light. The remainder of the energy is in a faint halo that spreads over an arc second or more.

The HST Science Working Group and the newly-formed HST Users Committee met on June 27/28 to consider the implications of this situation, which is obviously a major setback. The two groups concluded that HST never-the-less has capabilities that far exceed and complement those available on the ground and that its program should go forward vigorously, emphasizing the unique and valuable science that can be done with the telescope in its present condition. The Working Group and Users Committee drafted a short report to NASA summarizing their position, and that report is attached for your information.

The cause and exact nature of the spherical aberration is still being analyzed. At present we do not know whether the error is in the primary mirror or the secondary or distributed in some way between them. Although there are force actuators on the back of the primary, they were designed to remove small amounts of coma and astigmatism. The correction needed now is a relatively large motion in a direction in which the mirror blank is quite stiff, and the actuators are not strong enough to do that job. Consequently, the aberration does not appear to be curable in orbit and the existing instruments will suffer degraded performance - more or less, depending on the particular instrument. A quick assessment of these performances is contained in the accompanying report. On the other hand, we now believe that the Advanced Scientific Instruments which are already planned and scheduled for in-orbit installation can be fully compensated for the aberration, so that two and a half or three years from now we can expect the WF/PC-II to provide the sharp imaging that we had intended to achieve in the present WF/PC.

It is too early to state just what changes may be required in the HST observing program. The Project must thoroughly quantify the present performance of the observatory, and NASA and the Space Telescope Science Institute must reexamine their plans for observatory usage. In the meantime, I wanted you to read the facts as I know them. I encourage you to continue monitoring Ron Polidan's HST news reports on email and the ST Science Institute's reports for new information as it becomes available.

Albert Boggess
Project Scientist for HST

POSITION PAPER OF THE HST SCIENCE WORKING GROUP AND THE HST USERS COMMITTEE

JUNE 29, 1990

SUMMARY

Our groups met jointly on June 27 and 28, 1990, at the GSFC and received reports from key Project personnel about the status of the Hubble Space Telescope, with particular emphasis on the imaging performance. Although the program has clearly suffered a major setback due to telescope optics that are well below specification, we are convinced that the long-term prospects for completion of the science program are highly encouraging. Furthermore, a valuable subset of the scientific program can be executed with the telescope even in its present state, with the result that HST still has the potential to produce many key discoveries in the near future.

HST right now has capabilities that vastly exceed ground-based observatories. Most important are spectroscopy, photometry and imaging at ultraviolet wavelengths, none of which are possible at all from the ground. High resolution visible-light imaging on bright objects will also be possible, achieving to some degree the original fine details expected in HST pictures.

For the longer term, it appears highly probable that the full imaging capabilities of HST can be restored by straightforward modifications to the Second-Generation Scientific Instruments. These are already under development as Orbital Replacement Instruments (ORIs), to be installed in the observatory over the next several years. We recommend that the development of these ORIs be accelerated as much as possible. With determined effort, the WFPC-II camera could be installed in as little as 2 1/2 years, producing images that meet the original design goals.

THE OPTICAL CAPABILITY

We understand that there is approximately one-half wave rms spherical aberration error (2 micron center-to-edge surface error) in the OTA wavefront, leading to images that fail to meet the Level I 70% enclosed light specification by roughly a factor of 7. The observed image radius is 0.7", versus a specified radius of 0.1". For certain focal positions, the images possess sharp cores (~0.07" FWHM), so that at some level the high spatial resolving power of HST is preserved. However, these cores contain only ~15% of the light, the remaining light being dispersed over a wide halo comparable in size to ground-based images. A summary of what capabilities for science are allowed by these image properties and what can be done to recover the full Level I performance of the observatory is given below.

THE SCIENTIFIC CAPABILITIES

HST is an extremely versatile observatory with many modes of observation. Loss of image quality has damaged some of these, modes, but many remain wholly or largely intact. Temporarily being able to use only certain of these modes will not alter the fact that we will still be able to do forefront science 100% of the time, but the initial scientific emphasis will have to be different. The number of programs that can be done with the HST has always greatly exceeded the time available for their execution, and this remains true even with the telescope in its current state.

The near-term observing plan will now have to give greater emphasis to ultraviolet imaging (FOC), ultraviolet spectroscopy (FOS and GHRS), and ultraviolet photometry (HSP), plus the use of bright core images in visible light (WF/PC and FOC). These, plus the ongoing astrometry program (FGS), will easily occupy all the time available and will return scientific results of great interest and utility. The fulfillment of the original imaging programs will still be possible, but will largely have to be scheduled later.

These near-term programs are possible because HST, even in its present state, has unique capabilities that cannot be matched anywhere, either in space or on the ground. The core of the sharply focused image can yield sharp pictures for bright, high-contrast objects such as stars and galactic nuclei. The ultraviolet spectroscopic capability is still largely intact, although some trade-offs are now involved. Obtaining spectra at the planned spectral resolution and desired signal-to-noise will be possible, but the targets will have to be brighter, or the exposure times longer. Spectra of faint targets should also be possible, although with some loss of spectral purity. Fortunately, many programs of the HSP will not be impacted, and the astrometry capability of the FGS will apparently not be compromised at all. Realizing these capabilities will require some new effort; for example, it will be necessary to revise target acquisition methods for the small-aperture instruments and to develop image deconvolution algorithms far the cameras. However, these are not major tasks.

Most encouraging of all, it should be possible ultimately to realize the full capability of the HST through the use of the Second-Generation Scientific Instruments (SIs). The WF/PC-II instrument that is currently planned for flight some 3 years after launch has an optical design that will permit complete correction of the errors in the OTA. The other two new Scientific Instruments, both already in development, will also be able to correct simply for the limitations of the telescope optics. The NICMOS instrument will extend the wavelength range of the HST and open up a new window to infra-red observations. The STIS instrument will expand the spectroscopic power of the HST by at least an order of magnitude beyond the goals for the first generation of spectrographs. Completion of all three of the Second-Generation Instruments is now clearly more urgent than ever.

CONCLUSIONS AND RECOMMENDATIONS

While some of the important scientific goals of the Hubble Space Telescope are currently not achievable because of the spherical aberration in the telescope optics, other unique scientific goals do remain viable, and HST therefore still has the potential to produce many important discoveries during its first years of operation. The original goals for the 15-year mission of the HST continue to be achievable. We therefore recommend that all necessary actions be taken to insure that HST will operate as productively as possible in the short-term, and that activities directed at restoring full capability over the long-term be pursued vigorously. In the short term, this means that on-going HST operations must be fully supported and that the telescope and instrument performance evaluations and analyses must be continued. We also need to adjust to the larger images by developing new target acquisition techniques and by modifying various other capabilities as indicated by the results of ongoing studies.

For the longer term, it is clear that the full imaging capabilities of HST can be restored by suitable modifications to the Second-Generation Scientific Instruments, which are planned as Orbital Replacement Instruments (ORIs), to be installed in the observatory over the next several years. We recommend that the development of these ORIs be accelerated. Finally, we recommend that the first Maintenance and Refurbishment Mission, which will install the WF/PC-II in place of the original WF/PC, be directed to proceed as expeditiously as possible, with the goal of being completed in less than 2 1/2 years rather than the planned 3-year schedule.

By way of conclusion, we would like to emphasize that an enormous number of technically difficult challenges involved in the design of HST have been successfully met. These include the basic smoothness of the optics, the high degree of accuracy required from the Pointing Control System, and the proper functioning of a suite of complex scientific instruments, to name only a few. In comparison to the huge investment already made in HST, the effort involved in correcting the optical aberrations is fairly small. In comparison to the planned 15-year lifetime of HST, the few-year delay until delivery of WFPC-II is also small. With this perspective in mind, we feel it is important to keep our eyes on the long-term future and work diligently to realize the full potential of the observatory, which is still a fully viable goal.

For the HST Science Working Group
Albert Boggess

For the HST Users Committee
Arthur Davidsen

HST'S IMAGING PERFORMANCE—A PRELIMINARY REPORT

As discussed in the enclosed documents, a serious problem with HST's imaging quality has been identified in the past several weeks. The following report describes the nature of this problem as it is presently understood and its potential impact on current and future HST users. The article was compiled in the Science Programs Division at STScI from a variety of reports available to us through July 16, 1990.

The Problem

Evaluation of WF/PC and FOC images together with WFS data has shown that the HST optics suffer from approximately 0.5 wavelengths of spherical aberration. In simple terms, light from the inner and outer edges of the primary mirror cannot be brought to the same focal plane; instead, light from the outer edge is focussed about 4 cm behind light from the inner edge. The geometric circle of least confusion has a diameter of $1''.5$.

The aberration has been demonstrated over the past few weeks by several tests, including a series of WF/PC images taken over a wide range of focus settings of the secondary mirror. Images taken with all 8 CCDs (through several different filters) in the WF/PC, and with the FOC, all agree in showing the problem. Images of the Kelsall dots within the WF/PC are sharp, indicating that the problem is external to the camera. Computer simulations of the images agree extremely well both qualitatively and quantitatively with the observations, when the above amount of spherical aberration is assumed.

It is believed that the faulty optical surface lies on the primary mirror. (If it were on the secondary mirror, FGS transfer-function scans would be exhibiting very little S-curve modulation, due to the presence of about 0.5 waves of off-axis coma.)

The primary mirror has a set of 24 actuators that can apply forces to its back side in order to make small adjustments to the mirror figure; however, these are not optimally placed for removal of spherical aberration, and it currently appears that less than 10% of the aberration could be removed with the actuators. The secondary mirror's figure cannot be adjusted, but the mirror can be translated and tilted, as well as moved toward or away from the primary. Again, however, these adjustments will be insufficient to remove the aberrations.

The HST Point-Spread Function

Figure 1 gives a pictorial representation of a stellar image obtained close to the best OTA focus setting with the PC and the F547M (5470 Å) filter. The size of the image core is close to the diffraction limit expected for HST (about $0''.1$ radius), but contains only about 15% of the energy. The core is surrounded by a halo that encircles most of the energy and extends out to a diameter of about $1''.5$. The remaining $\sim$30% of the light is scattered outside the halo by a combination of mirror microroughness and aperture obscurations into a characteristic "tendril" pattern.

The PSF is strongly focus- and wavelength-dependent, and it varies with field position in the WF/PC because of the camera's internal vignetting.

Figure 2 shows encircled-energy plots for stellar images obtained with the PC between June 10 and 24, taken over a range of near-optimum focus settings. As can be seen, 70% of the energy is contained within a radius of about $0''.7$. (For comparison, the Level I Requirement for the HST optical system was 70% encircled energy within $0''.10$.) The image size, therefore, is comparable to that achieved at the best ground-based facilities, although

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We appreciate your continued interest in, and support of, the HST mission.

Sincerely,

Riccardo Giacconi
Director
and

H. S. Stockman
Deputy Director

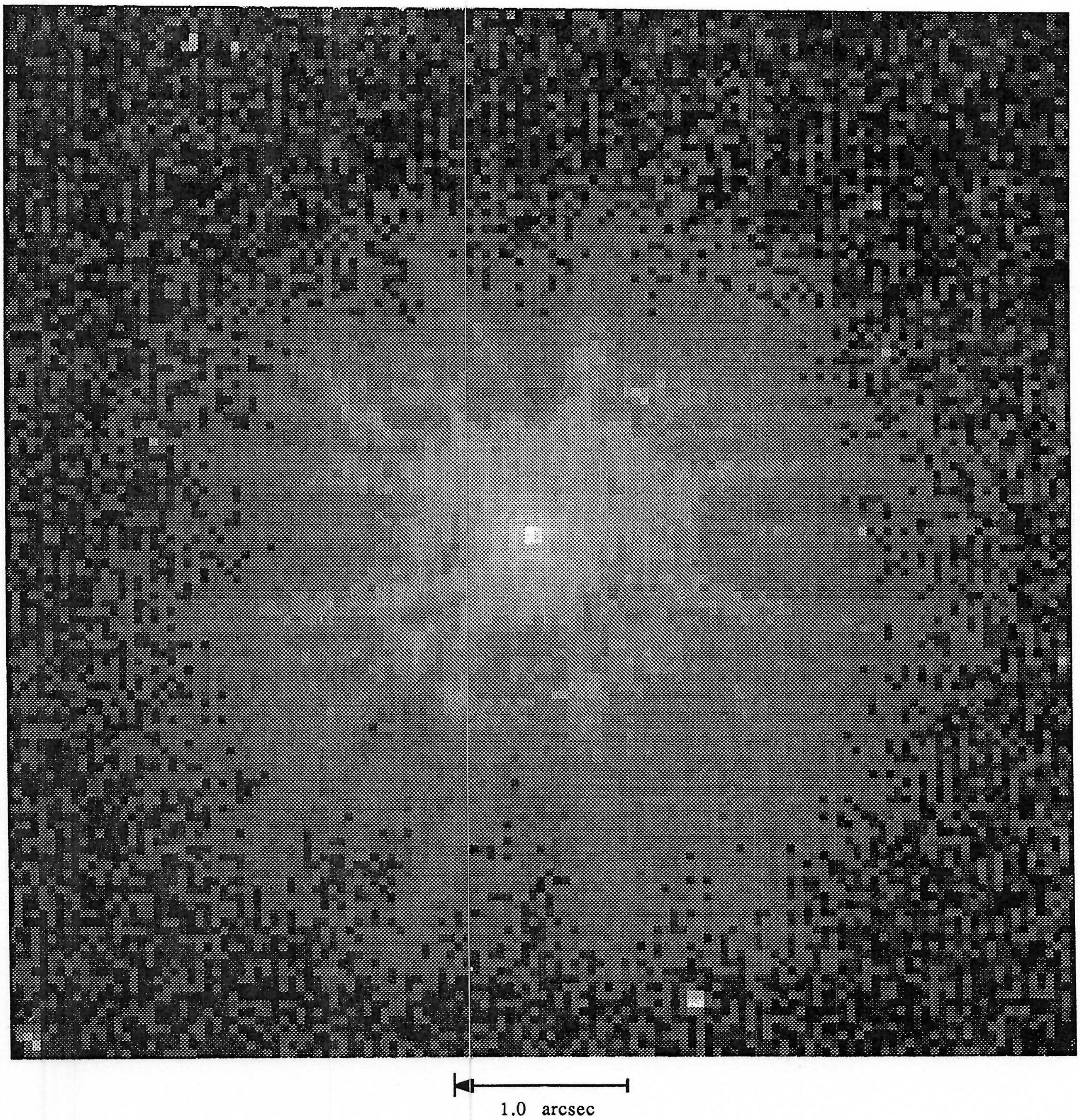

FIG. 1—Planetary camera stellar image through filter F547M.

the images do contain a sharp core that provides some information at nearly the diffraction limit.

Software has been developed at STScI that simulates the sensitivity and imaging performance of the HST and its Scientific Instruments. The software models all the major known effects on HST images, including the spherical aberration. Observers who have an interest in such detailed modeling are encouraged to contact the User Support Branch and also look for detailed information in the forthcoming *Newsletter*.

Planned Course of Action

In the immediate future, WF/PC, FOC, and WFS data will continue to be used to complete the alignment of the OTA optics. This will result in some improvement of the imaging performance through removal of the remaining focus, coma, and astigmatism errors.

It is possible that the primary-mirror actuators may be used to reduce the spherical aberration, although, as noted above, it is anticipated that only a small fraction of the aberration can be removed in this fashion.

Dr. Lennard Fisk, NASA Associate Administrator for Space Science and Applications, has convened a formal review board, chaired by Dr. Lew Allen (JPL), which is studying the OTA design and fabrication procedures in an attempt to identify the cause of the aberration.

Longer-Term Solutions

After final alignment of the optics, the OTA wave-front errors will be mapped in detail. The advanced Scientific Instruments that are now being developed could thus incorporate compensating optics which, it is currently anticipated, could completely remove the spherical aberration.

A shuttle mission to revisit HST had already been planned for 1993, and it is possible, for example, that the WF/PC II currently under development at JPL could be fitted with corrective optics and installed by that time. It is likewise anticipated that the STIS and NICMOS will be able to achieve nominal spectroscopic, imaging, and IR performance through addition of compensating optics.

Impact on the Scientific Instruments

The following paragraphs give preliminary assessments of the impact of the image quality on the scientific capabilities of the SIs. The Institute will prepare more detailed descriptions of the expected scientific performance of the SIs, as additional spacecraft data are obtained during the verification activities.

WF/PC. The impact is most severe on the WF/PC. At this point it appears that many programs that require the limiting capabilities of the WF/PC will not be able to achieve their scientific goals. However, as discussed above, the HST images do contain more information than typical ground-based telescopes, and moreover HST images are expected to be extremely stable. Thus it is possible that some WF/PC programs may remain viable, through use of image-deconvolution techniques. Significant increases in exposure time, however, will probably be required.

FOC. In visible light, the FOC will suffer the same problems as outlined for the WF/PC. For imaging in the ultraviolet region that does not require fully diffraction-limited performance, unique scientific programs remain possible; but, as for the WF/PC, increased exposure times may be required.

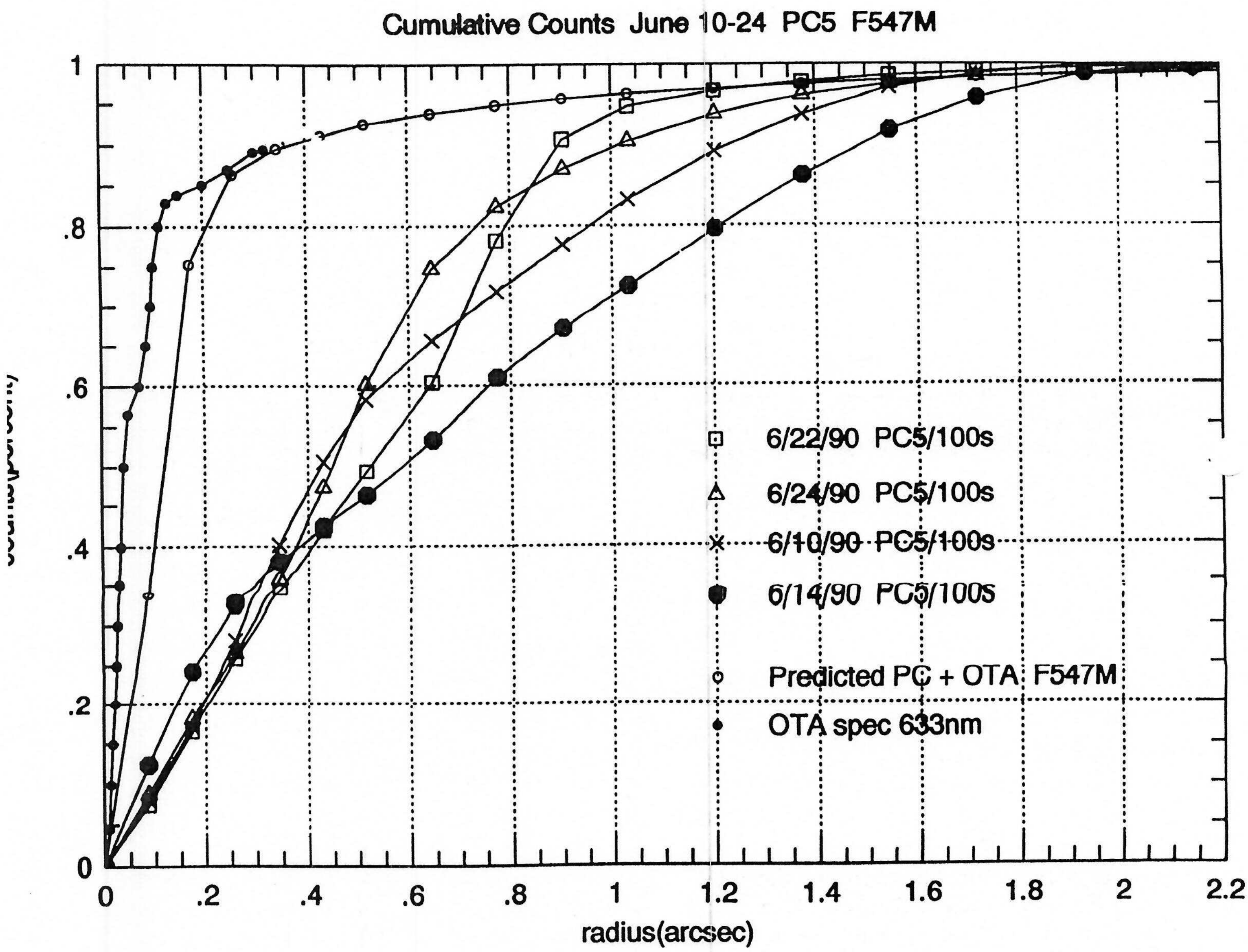

FIG. 2—Measured encircled energy for stellar images as a function of radius for Planetary Camera images taken at four focus settings. Also shown are the design specification for the OTA (at 6330 Å) and the predicted profile for the PC+OTA combination through the F547M filter. Diagram courtesy of the WF/PC IDT.

FOS. There will be a loss of throughput and spectral resolution, but much FOS science remains viable. Programs involving isolation of very crowded objects, however, are compromised, and FOS spectroscopy in the visible region can now probably be done as easily from the ground.

GHRS. The impact is similar to that on the FOS. The throughput of the $0''.25$ aperture is reduced by about a factor of 5 below that originally expected. The $2''.0$ aperture will have good throughput (reduced by about a factor of 2), but there will be some loss of spectral resolution (partially recoverable through deconvolution).

HSP. The HSP will suffer from reduced throughput and from noise due to guiding jitter, especially through its small aperture, but many programs remain viable.

FGS. Most astrometric programs remain viable.

Policies

No policy decisions in relation to accepted Cycle 1 GOs, GTOs, or Cycle 2 proposals have been taken at this writing. The STScI Director will consult widely with members of the scientific community before taking any action.

Further communications will appear in the STScI Electronic Information Service (see the March 1990 *Newsletter* for details) and in forthcoming issues of the STScI *Newsletter*.

—Compiled by Howard E. Bond (User Support Branch)
and Chris Burrows (Telescope and Instruments Branch)

Acronyms

CCD	Charge-Coupled Device
FGS	Fine Guidance Sensors
FOC	Faint Object Camera
FOS	Faint Object Spectrograph
GHRS	Goddard High Resolution Spectrograph
GO	General Observer
GTO	Guaranteed Time Observer
HSP	High Speed Photometer
HST	Hubble Space Telescope
JPL	Jet Propulsion Laboratory
NICMOS	Near Infrared Camera and Multi-Object Spectrograph
OTA	Optical Telescope Assembly
PC	Planetary Camera
PSF	Point-Spread Function
SI	Scientific Instrument
STIS	Space Telescope Imaging Spectrograph
WF/PC	Wide Field and Planetary Camera
WFS	Wave Front Sensor

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