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CAL/004

Standard Astronomical Sources for ST
Volume I:

Report of the: 'OPTICAL CALIBRATION TARGET WORKING GROUP'

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"The Calibration Working Groups have been charged by the Science Verification Working Group to seek a consensus among the Investigation Definition Teams and Astrometry calibration specialists, the Space Telescope Science Institute and outside experts on the selection of astronomical calibration standards for the Scientific Instruments and Fine Guidance Sensors."

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Abstract

The Hubble Space Telescope has capabilities for direct imaging, photometry, spectrophotometry, polarimetry and astrometry. The combined instruments cover the wavelength range from approximately Ly-α to slightly longward of one micron. In the present report, we discuss the standard stars to be observed for photometric and spectrophotometric calibration in the optical wavelength region for all the ST Scientific Instruments, including the Fine Guidance Sensors.

I. Introduction

Just like for ground-based observations, ST will require calibration targets with well-defined properties like magnitudes and fluxes to achieve and maintain a proper standardization. The major goal is to choose the minimum set of standard stars which serves all calibration requirements, thereby minimizing ST-observing time 'wasted' on standards. This goal specifically includes cross-calibration of the various scientific instruments. In trying to meet these goals we have tried to take advantage of published and ongoing work in the area of calibration and standardization and to be sensitive to present and future needs of ground-based observers, for example by providing tie-ins to established ground-based systems.

One of the major complications to be faced in developing a system-wide concept for the calibration of ST is that standardization tends to be an area of astronomy on which it is hard to find unanimous opinions. Different ideas, approaches, as well as different sets of standard stars can be employed by individual researchers even when working on similar problems. The parallel existence of many such different 'systems' is generally scientifically justified and in particular can represent different ways of coping with limitations dictated by instrumentation and atmosphere.

All of the scientific instruments on ST are sensitive to optical light, except for the HRS. For the five scientific instruments that require calibration targets longward of 3200 Å, the linearity checks and sensitivity calibrations are of prime importance. Linearity is an essential characteristic of a good scientific instrument, ranking below only repeatability in importance. As a minimum, in-flight observations can be used to verify and place error bars on the laboratory linearity corrections. To the extent that different scientific instruments can observe the same stars in a linearity sequence or to the extent that the ground-based intensities can be reliably transformed to a science instrument bandpass, adjustments to the expected linearity corrections may be possible, if required.

The sensitivity calibration can be thought of in two complimentary ways. First, the absolute calibration is the relation between the instrumental output and the absolute flux of the source (i.e. the input). Second, the instrumental output can be related to traditional photometric systems, such as Johnson-Cousins UBVRI, via photometric transforms or can be used to establish a photometric system in its own right. For spectrographs or narrow band filters the absolute calibration can be done precisely, in principle. For broad band filters, both the interpretation of the absolute calibration and the photometric transformation depend on the color of the source. These comments on filter photometry calibration apply equally well to the cases where the result is in physical units (F) or magnitudes (m), since they are mathematically equivalent in the equation

$$m = -2.5 \log F + K.$$

In other words, any magnitude (regardless of how the zero point was established) may be equally well specified as an absolute effective flux as long as the value of K is known. A relative flux scale calibration is determined by setting K arbitrarily. A calibration on a specific photometric system with an indeterminate value of K can be achieved by observing standard stars for that system over a range in color so that appropriate photometric transformation coefficients can be derived. The transformation coefficients may be derived more precisely if relative spectrophotometry is available. In this purely photometric approach, the value of F in the magnitude equation is replaced by the response in counts per second (or some other signal measure), so that considerations of the physical flux are bypassed. If an absolute calibration is desired, the value of K must be determined by, e.g., observing spectrophotometric standards and applying the methods of synthetic photometry. An added benefit of a synthetic photometry approach is often a better understanding of the actual spectral bandpass, and even offers the possibility of tracking changes in filter bandpasses that are expected due to cumulative radiation damage.

A trend analysis of prime importance is the long and short term sensitivity change, i.e. the overall repeatability of each scientific instrument. Efforts to model changes in the shape of a filter bandpass are a lower priority part of this problem. No discussion of trend analysis is included in this document, because the required targets are a subset of those needed to do the calibration in the first place.

II. Choice of Photometric and Spectrophotometric 'Systems'

We discuss here the systems which will be used as a basis for reporting all ST observations. Cross calibration between the Scientific Instruments will be a high priority. Cross calibration is complicated by the wide range of observing modes available. The High Speed Photometer does not have spectroscopic facilities whereas the Faint Object Spectrograph and the High Resolution Spectrograph are dedicated spectrophotometric instruments. Both the WFPC and the FOC have (low resolution) spectrophotometric facilities in addition to the standard imaging modes.

II.1) Ultraviolet Photometry and Spectrophotometry

All of the Scientific Instruments on ST, except for the FGS, are capable of observing in the ultraviolet longward of 1200 Å. The ultraviolet fluxes of all ST-instruments will in principle be on the same absolute scale as the International Ultraviolet Explorer (Bohlin et al. 1984). There is some evidence (e.g. Slovak et al. 1983) that the long wavelength end of the IUE-scale fails to connect in a continuous manner to the short wavelength tail of most ground-based spectrophotometric absolute calibrations by approximately 5 to 10%. We must try to resolve any discrepancy for calibration purpose so that we can take advantage of the much higher accuracies which will be achievable with ST. Pre-launch efforts to investigate absolute calibrations in the 2800-4000 Å wavelength region are being undertaken (see Section V.6).

II.2) Optical Spectrophotometry

Frequently quoted sets of 'faint' spectrophotometric reference data are by Oke (1974) at Caltech and by Stone (1974 and 1977) at Lick (see also Hayes 1970). Oke has noted that his observations were never intended to be used for calibration purposes, but were adopted by the astronomical community for lack of better data. Recently, more accurate sets of spectrophotometric standard stars have been proposed by Oke and Gunn (1983), i.e., the 'AB79' system. Southern standards have been set up by Stone and Baldwin (1983) and Baldwin and Stone (1984).

The exact relationships between the Caltech (or 'AB79') and Lick 'systems' is not very well known. In principle, both systems are traceable to the Oke and Schild (1970) and Hayes and Latham (1975) calibrations of Alpha Lyrae. In the wavelength region of the higher Balmer lines as well as in the far red (Taylor 1979, 1984) the differences between the two systems could nevertheless amount to as much 5 or 10%.

Oke is currently collecting data on approximately 8 cool DC white dwarfs, 1 sdF, and some hot blue stars (e.g. sdOs) in order to set up new ground-based and future ST spectrophotometric standards. These new standards will be defined relative to the AB79 system, but will have the advantage of being observed at a higher spectral resolution. The new DC white dwarfs and sdF standards will have particular advantages for ground-based work because they not only exhibit almost featureless continuua, but they are faint enough ($V = 14.9 - 16.2$ mag) so as not to saturate 2D photon-counting spectrographic detectors now in use on many of the large telescopes. Because of these properties these standards will eventually develop a long history of use on ground-based telescopes. The brighter blue standards will become primary calibration targets for ST since many of them are also (IUE) UV spectrophotometric ST standards. They will be used for absolute sensitivity calibrations (and linearity and flat fielding with the FOS and the FOC long-slit mode) on all instruments. The new standards will be observed using the double spectrograph. The wavelength range will be 3200 - 10,000 Å. The spectral resolution will be 4 Å/pixel with a FWHM of 8 Å from 3200 - 5200 Å and 6 Å/pixel with a FWHM of 12 Å from 5200 - 10,000 Å. The internal accuracy will be 1% from 4000 - 8000 Å and 2 % outside that range except between 8900 - 9700 Å when water vapor absorption is high. The accuracy relative to the cool subdwarf standards which define the AB79 system will also be 1% from 4000 - 8000 Å and 2% outside that range except between 8900 - 9700 Å when water vapor absorption is high.

II.3) Optical Photometry

Optical photometry is commonly reported in the language of magnitudes. As noted earlier, with the proper calibration a measured magnitude can be converted to an effective flux at an effective wavelength. ST calibrations will allow observers to report their results in the language of magnitudes or effective fluxes. When reporting results in magnitudes it must be possible to transform ST instrumental magnitudes to traditional magnitude systems so that the extensive scientific work which is reported in the language of traditional magnitude systems can be easily utilized. For the purposes of deriving transformations between systems and deriving sensitivities for any particular ST filter-detector passbands relative spectrophotometry of adopted photometric standards is desireable. At present we have no firm commitments to obtain relative spectrophotometry for such programs, but several observers have expressed interest.

II.3.a) UBVRI [Johnson; Kron-Cousins]

Magnitudes and color indices are commonly given on the Johnson-Cousins UBVRI system (Johnson and Morgan 1953; Kron et al. 1953; Cousins 1976). [In this paper, the Kron-Cousins R and J bandpasses will be used throughout without further suffixes.] These passbands are partially determined by detectors whose spectral response is not matched by instruments aboard ST (i.e. HSP, WFPC and FOC). Therefore, it must be possible to transform magnitudes obtained with some of the ST instrumental passbands to Johnson-Cousins UBVRI. The basis of the transformations will be the Johnson-Cousins UBVRI magnitudes of Landolt (1973 and 1983) in 4 Selected Areas. These standards will be supplemented with some of Landolt's blue equatorial stars.

The HSP will observe the Landolt standards and therefore transformations between ST HSP BVR and Johnson-Cousins UBVRI can be done directly. However, it will only indirectly be possible to transform ST WFPC UBVRI observations to the standard Johnson-Cousins UBVRI system. The primary WFPC photometric calibration targets will be rich fields on the outskirts of globular clusters. The fields will contain Population II stars spanning a range of colours. The rich fields and the Selected Areas of Landolt will be observed by Baum and collaborators with a CCD detector having replica WFPC filters. These data will establish transformations between standard Johnson-Cousins UBVRI and the WFPC ground-based replica system. No attempt will be made to obtain photoelectric Johnson-Cousins observations in the rich fields due to possible problems with crowding. (Note that there are also WFPC filters roughly approximating some of the Thuan-Gunn (1976) passbands.) Calibration of FOC UBV filters will be accomplished either by observing Landolt's bright UBVRI standards with attenuation filters or by observing faint sequences which are yet to be identified with certainty.

II.3.b) uvbyβ [Strömgren]

Filters approximating the complete Strömgren passbands will be available with FOC, but not with HSP or WFPC. HSP does include imitation Strömgren u and v filters. It must be possible to transform FOC or HSP Strömgren magnitudes to standard Strömgren magnitudes. Since faint Strömgren standards do not exist, it is probably unrealistic to hope to calibrate the ST FOC Strömgren system filters without the use of neutral density filters. At this date there are no plans to obtain faint Strömgren standards, but efforts along these lines would be encouraged. A worthwhile (simple) project is to obtain

Strömgren four-colour data in Landolt's Selected Areas since these objects will be visited by ST rather frequently and have a good history of non-variability. At present, there are observers who have expressed an interest in undertaking such a task, but there are no firm commitments. Landolt is planning to extend UBVRI photometry in his Selected Areas to fainter magnitudes. Any effort to obtain Strömgren data of Landolt stars should include these faint standards. If data of fainter standards were available, FOC could then avoid using <u>all</u> of the neutral density filters to derive its calibration. David Crawford (private communication) has noted that additional intermediate (F and G type) stars would be helpful as the Strömgren system is most powerful for that spectral range. Thus, once an effort to obtain Strömgren data is initiated, the inclusion of more F and G type stars should be considered.

II.3.c) Non-standard filters

Every filter on ST is non-standard in some sense since standard Johnson-Cousins and Strömgren passbands are only approximated by ST filter-detector passbands. Grady (1984a) has described some useful algorithms for setting the zero point of the magnitude scale and the derivation of absolute effective fluxes. Regardless of the actual technique adopted, in order to derive the absolute calibration of a particular ST filter-detector passband independent of laboratory calibration data, standards spanning a range of colours and having spectrophotometry must be observed. The UV and optical spectrophotometric standards will be used. The Landolt standards can also be used for the HSP filters and rich fields on the outskirts of globular clusters can also be used for the WFPC filters providing relative spectrophotometry for these photometric standards is available. A combination of objects will be used in any case for cross-calibration purposes. Note that a subset of the WFPC flight filters will be supported by ground-based observation in the rich fields with a CCD and replica WFPC filters. The standards which will define the FOC photometric system are still unclear, but may include secondary spectrophotometric standard set up with the FOS.

III. Summary of the calibration tasks requiring optical targets

III.1) Fine Guidance Sensors (FGS)

The Fine Guidance Sensors have an approximate S20 sensitivity ranging from ~4500 to 7300 Å with an effective wavelength slightly longward of the Johnson V-band. Their nominal brightness range is from the 9th magnitude (which also corresponds to the bright cut-off limit of the Guide Star Selection System project) to approximately 14.5 at the faint end. No photometric calibration requirements for the FGSs have been proposed by the ST Astrometry Team, but reasonable tasks would presumably include a linearity-check, a count-to-magnitude conversion determination including a first-order colour correction (aiming for a 1% photometric conversion accuracy) as well as a determination of the signal-to-noise ratio as a function of magnitude. Neutral density filters for attenuation of up to four magnitudes are available. Laboratory measurements of the attenuation factors should suffice initially but an on-orbit calibration is desirable.

In principle, the calibration information defined above should be obtained for all three FGSs. But as the differences in throughput and responsivity will probably be sufficiently small as well as accurately known from laboratory measurements, the requirements can be somewhat relaxed. As a minimum initial calibration at least one star must be observed using all three of the FGSs.

III.2) High Speed Photometer (HSP)

The High Speed Photometer filter set consists of both standard and non-standard filters. The B, V and R filters from the Johnson-Cousins system are represented as are the Strömgren u and v filters. Colour transformations to the standard Johnson-Cousins BVR system and Strömgren uv system for these filters must be determined. In addition, HSP can observe through any of 21 ultraviolet filters centered between 1200 and 2800 Å and one centered at 5400 Å. These filters do not attempt to mimic any existing photometric system and their calibration is therefore less constrained. A total of five detectors are available, but only three of these require photometric calibration. (The remaining two being used in the so-called 'occultation' and 'polarimetry'-modes. The complete polarimetry calibration is discussed by Stockman et al. 1984.) The exact distribution of the filters over the three photometric Image Dissector Tubes is redundant in the sense that the same filter is usually duplicated on two different tubes. Besides avoiding a single point failure, this scheme allows simultaneous star and sky measurements using two different tubes.

HSP covers the largest dynamic range of all the instruments on ST as it can observe stars as bright as magnitude zero or one. These bright stars will be observed in the so called analog mode whereas the standard digital (pulse-counting) mode will typically be used for stars fainter than magnitude 6 or 7. HSP should be capable of obtaining useful data out to at least as faint as the 24th magnitude.

III.2.a) Linearity

Laboratory tests demonstrate that the digital mode is highly linear over the expected range of its use, i.e. for counting rates less than 2.5×10^5 counts per second, which corresponds to V = 8 and a 1% dead time correction. The linearity of the analog mode has also been verified in the lab for currents corresponding to stars in the V = 5 to 10 range. Thus, the main interest in linearity verification of the digital mode for flight lies in the range of V = 3 to 13, which allows a factor of 100, or 5 mag, on either side of the expected point of 1% non-linearity correction. The linearity of the analog mode should be checked in-flight over the full range of use from V = 0 to 10, with the expectation that any possible non-linearities due to space charge should appear at the brighter end of the range where lab tests have not been performed. To rigorously check the linearity, the precision of the ground-based data should be significantly better than one hundredth of a magnitude. Relative spectrophotometry of the stars is required in order to derive the most accurate ground-based to instrumental magnitude transformation.

An additional lower priority calibration task will be to check the linearity out to V = 17. This will definitely be done in the laboratory. An additional, on-orbit, effort to confirm such pre-launch data is desirable. Note that the data-quality required is approximately 0.01 mag or better. Such an accuracy becomes hard to achieve for stars fainter than the 17th or 18th magnitude using single channel photometers, even on large ground-based telescopes, as the sky-background becomes prohibitive. Since the linearity of photon counting detectors is good at low count-rates, HSP can safely extrapolate from the 17th magnitude to its faint limit.

Algorithms to analyze the linearity data are discussed by Grady (1984b). At least one star per magnitude interval is required.

III.2.b) Analog to Digital Conversion

Data on any object observed in both the digital and analog modes can be used to derive the analog to digital sensitivity ratio. Thus, obtaining the linearity data will allow the analog to digital conversion to be calibrated, except for the possibility that the analog to digital conversion ratio may be a function of wavelength. This possibility would be expected if a significant fraction of the detected photons produce two photo-electrons that are counted as only one pulse, while producing twice the analog current. To measure the level of significance of this possible effect, the two extreme filters on each detector should be used to get two more sets of simultaneous analog and digital data for comparison with the analog to digital ratio deduced from the third filter used in section III.2.b. The most appropriate target is in the range of 8 to 9 mag to minimize the digital linearity correction. The target should be a hot star with a smooth continuum over the bandpass so that no ambiguity will arise in the effective wavelength of the filter.

III.2.c) Sensitivity

Standard star observations will be used to derive instrumental magnitudes (relative to some zero point) and absolute effective fluxes. Transformations to the standard BVR Johnson-Cousins system and uv Strömgren system will be derived. In order to derive the most accurate effective fluxes and transformations, relative spectrophotometry is required. Standard star sequences should span a range of colours and have visual magnitudes in the range of 11-15. Algorithms to be used to derive instrumental magnitudes, effective fluxes and photometric transformations are presented in Grady (1984a).

III.3) Wide Field and Planetary Camera (WFPC)

The WFPC utilizes a mosaic of four CCDs in both the PC and WFC modes; they are coated with coronene which down-converts ultraviolet light into the visible giving WFPC a response in the range 1200-11000 Å. Twelve filter wheels, which can be used in combination, allow the use of the five filters approximating UBVRI, three polarizers, three gratings as well as 37 non-standard filters. A circular attenuating spot 1.4 arcsec in diameter appears in one of the CCDs in each camera and provides an attenuation of a factor of a thousand (or 7.5 magnitudes). The minimum performance specifications of WFPC suggest that it will have a large enough dynamic range to make useful observations of stars ranging from V=9 mag to V=28.5 mag. Linearity is expected to be better than approximately 0.5% over the full dynamic range, and for high signal levels the relative photometric accuracy within a frame may approach 1% for isolated stars and 0.25% for diffuse sources covering a large number of pixels. Exposure times, as set by the mechanical shutter, are uncertain by about 1 msec. The absolute photometric accuracy is limited by this fact for exposures of $\lesssim$300-500 msec, or at V $\lesssim$ 14 mag in the WFC-mode through the CaF_2-filter. The field of view of the Wide Field Camera mode is 158 by 158 arcsec whereas the Planetary mode covers 68 by 68 arcsec.

III.3.a) Linearity

Any non-linearity in the WFPC should be a function of signal-level rather than signal-rate, thus exposures of different duration can be used to check for non-linearity. Note that on-board Tungsten flood lamps will not provide a means of making a linearity calibration for the case of 'broad' illumination since the lamp's temporal stability will not be adequate. Departures from linearity will occur when the maximum count per pixel is approached (this corresponds to approximately 30,000 electrons), but varies somewhat from one CCD to another, causing charge transfer along the columns. Observations of a faint standard rich star field (with no objects brighter than magnitude 15 and containing several objects in the 15-17 magnitude range) can be made to check the linearity. (These results may differ from the case of broad illumination and so diffuse objects should also be used.) WFPC Science Verification plans suggest taking observations through U and V filters in both cameras and comparing the results to previous ground-based photoelectric and/or CCD-observations. Observations designed to test geometric stability and calibrate the PSF can also be used to check linearity, especially if the data have been obtained for a large range of exposure times. This is desirable since it will allow additional absolute sensitivity checks during the linearity calibration. The technique employed to do these calibrations will have to be carefully planned since laboratory tests show that the detector sensitivity depends on its recent history.

III.3.b) Sensitivity

i) Photometric Modes

Photometric calibration (and colour transformations to standard Johnson-Cousins UBVRI) of the UBVRI filters as well as zero-point determinations for some of the other filters must be established. In the WFC an unreddened B0 star having V=11.7 would yield 20,000 electrons in the central pixel through the V-filter in about half a second. The corresponding exposure times for the U, B, R and I filters would be 2.0, 1.8, 0.6 and 1.0 seconds, respectively.

Standard rich star fields will be the calibration targets. These fields will have ground-based photometry done with filters closely resembling some WFPC filters. The fields should contain objects spanning a range of colours and have V magnitudes fainter than 12-14. Relative spectrophotometry of the targets (especially the blue ones) is desirable. Standards will also include UV-optical spectrophotometric standards.

ii) Spectral Modes

There are three gratings available on the WFPC: the ultraviolet, cross-dispersed, grating/prism combination covering λλ1280-2000 in the second order and λλ1600-3200 in the first order, the blue grating covering λλ3300-6400 in the first order as well as a red grating covering λλ5700-11000 also in the first order. Ground-based and IUE spectrophotometry of standard stars will be used to derive the absolute sensitivity calibration. In the WF camera mode, an unreddened B0 star observed with the blue grating will give up to 20,000 electrons per pixel in an 0.5 sec exposure for V=9.0. With the red grating, this requires an object with V=8.0. Due to the different dispersions, objects need to be 1.2 mag brighter in the PC mode to reach the same exposure level. The ideal spectrophotometric standards would have both optical and UV spectrophotometry and have visual magnitudes in the range from 9 to 11 mag. The UV calibration is described in the UV Standard Target report (Bohlin et al. 1984).

III.3.c) Point Spread Function

The point spread function will be determined at various effective wavelengths for targets in the 9-11 magnitude range. Ideally, speckle interferometry should be available for the targets as insurance that they are single point sources. Otherwise, no special targets are planned or required.

III.4) Faint Object Camera (FOC)

In-flight calibration of linearity, absolute sensitivity and point spread function (PSF) are required for the FOC f/48, f/96 and f/288 direct imaging modes, the f/48 and f/96 objective prism modes and the f/48 long-slit spectrographic mode. As the onset of non-linearity for flat field illumination is expected to occur at count rates as low as 0.3 to 0.6 counts sec^{-1} $pixel^{-1}$, the complete calibration (without employing attenuation filters) should preferably be accomplished with very faint standards. Once the point-spread function behaviour is well understood, it might be possible to observe brighter stars by ignoring the saturated core of the image, but it is the view of the Investigation Definition Team that this technique should not be relied on for primary calibration tasks.

The filters available in the direct imaging mode include both standard and non-standard filters. Colour transformations in the photometric calibrations for the standard filters will be derived. In the f/48 mode Johnson UB filters are available and in the f/96 (and f/288) mode Johnson UBV and Strömgren uvbyβ filters are available. Only in the f/96 (and f/288) mode is it possible to use neutral density filters (note that the f/288 mode is achieved by inserting a compact Cassegrain assembly in the f/96 optical path and that therefore the same filter wheels are available in the f/96 and f/288 modes). There are five neutral density filters in the f/96 relay (with attenuations of 8, 6, 4, 2 and 1 magnitudes) and due to their distribution over the two wheels, 1 to 9 magnitudes of attenuation can be used in combination with the standard filters; but only one magnitude of attenuation is available in the objective prism mode.

III.4.a.) Linearity

In addition to a linearity test provided by uniform illumination of the detector with the on-board LEDs, point source and external source linearity checks will have to be made. Laboratory tests of the FOC have shown that there are significant linearity differences between point-source and flat field illumination. When uniformly illuminated a rate of 0.6 counts/sec/pixel can be achieved with the f/96 detector, and slightly lower with the f/48 detector. At this level some saturation is already present (~10%). However for point source (laboratory pin hole) illumination count rates as high as ~5–6 counts/sec/pixel are achieved. There are also variations of the linearity from pixel-to-pixel. Thus the non-linearity is extremely difficult to calibrate out to any degree of accuracy. Photometry will have to be carried out at count rates where the detector is linear--it is the purpose of the in-orbit point-source and flat-field linearity studies to establish the optimum operating count rate.

During SV, point source linearity checks will be made using one standard rich star field in the 16 bit f/96 mode. The rich field will be observed using the 8, 6, 4 and 2 mag ND filters and without a neutral density filter using 2 colour filters (N190 at 1900 Å and N470 at 4700 Å; this last filter mimicks the Strömgren "b"-band). Useful count rates are expected to be in the range of 0.05 - 1.0 counts sec^{-1} $pixel^{-1}$. For an unreddened, unattenuated B0 star having U - V = -1.3, this corresponds to V in the range of 20.8 to 23.7 mag for the N190 filter and V in the range of 21.7 to 24.9 mag for the N470 filter (these are nominal performance values; minimal performance values are estimated to be 0.6 mag brighter by Anderegg). The SV calibration plans call for a linearity check using three extended sources (e.g. galaxies or

HII-regions) using the N470 filter in the f/96 16 bit pixel mode. The sources will be observed both with and without an appropriate attenuators. Count-rates between 0.05 and 0.5 can be obtained using an unattenuated ('B0- type') source with U in the range of 13.9 to 16.4 mag arcsec^{-2} (minimal performance values are 1.2 mag brighter).

III.4.b) Spectral Flat Field

Pixel to pixel sensitivity variations for the f/48 long-slit mode will be found from the flux calibration standards. Note that this requires that the spectral resolution of the standard star data match the actual FOC resolution characteristics or that the standard have smooth, featureless continuua. Standards should be ~15-16 mag.

III.4.c) Sensitivity

i) Photometric Modes

In the f/96 mode the photometric calibration (including colour transformations) of the UBV and uvbyβ standard filters is possible with relatively bright standards since neutral density filters of up to 9 magnitudes are available. A count rate of 0.3 counts sec^{-1} pixel^{-1} corresponds to an unattenuated star with V=23.8 mag (nominal performance) or V=23.2 (minimal performance). The Science Verification plan calls for the calibration of UBV and uvbyβ using two standard rich fields with possible attenuators. A reference calibration of non-standard filters in the f/96 mode can also be obtained using neutral density filters and relatively bright standards (e.g. spectrophotometric standards). The Science Verification plan does not presently call for a zero-point calibration for the magnitude systems of all non-standard filters, but this should eventually be done.

In the f/48 mode, no neutral density filters are available and therefore faint standard rich fields having objects with V fainter than 23.2 to 23.8 are desirable. It may be necessary to wait for complementary work with WFPC, HSP or the f/96 mode of FOC on a rich field so that secondary standards can be set up.

The f/288 mode is primarily intended for use in the ultraviolet and its calibration should be covered by the Ultraviolet Target Working Group.

ii) Spectral Modes

There are 2 objective prisms in the f/96 mode, 2 objective prisms in the f/48 mode and a long-slit spectrographic mode at f/48. The long-slit mode can be used with a cross-disperser so that the 1st, 2nd and 3rd orders can be observed simultaneously. The objective prism in the f/96 mode can be used in combination with the one magnitude neutral density filter. The Science Verification plans call for the objective prism photometric response to be calibrated using UV-optical standard sources. This work must be done in conjunction with establishing wavelength/dispersion calibration as outlined in Wavelength Calibration Target report (Ford, Hobbs and York 1984). UV-standards fainter than B=15.5 will not be available by launch and so it may be best to adopt sources used in the linearity check of FOS as standards. The f/48 spectrographic mode can be calibrated using B=15.5 mag hot stars for which both International Ultraviolet Explorer as well as ground-based spectrophotometry exists between 1200-6000 Å. The Science Verification plans call for the observation of two standards. The bright limit for the prism modes is strongly wavelength dependent and the exact characteristics are unknown at this time.

III.4.d) Point Spread Function

The PSF must be derived in the f/96 and f/288 modes. Observations will be made at $\lambda\lambda$1200, 1520, 1900, 2780, 5007 using the N120, N152, N190, N278 and I501 filters. It may be necessary to use ND filters.

III.5) Faint Object Spectrograph (FOS)

The Faint Object Spectrograph provides spectrophotometric data at a resolution of about 1200 over the wavelength range of $\lambda\lambda$1150-8500 through the use of two Digicon detectors and a set of six gratings. Two additional lower resolution gratings provide spectra from $\lambda\lambda$1150-2200 and $\lambda\lambda$2500-7000 with R=200. A prism is available for the wavelength range $\lambda\lambda$2500-7000 Å with a resolution which varies from R=400 at 2500 Å to R=25 at 7000 Å. The Faint Object Spectrograph is expected to generate useful data for objects as faint as the 22nd magnitude at the highest resolution, about two magnitudes fainter for the intermediate resolution and down to about 26th magnitude for the prism spectra. On the bright side, the Digicon detectors are count rate limited. The so-called paired pulse correction is in excess of 1% for count rates above approximately ten thousand counts sec^{-1} $diode^{-1}$. Visual standard stars are needed for four on-orbit calibrations of the FOS.

III.5.a) Scattered Light

The Faint Object Spectrograph is inherently susceptible to unwanted light since it is a single pass spectrograph employing blazed, concave, gratings and is sensitive over a wide spectral passband. The on orbit measurements of scattered light will be performed using red (late G or K-type giants) with known optical and ultraviolet fluxes. Suitable visual magnitudes are in the range of 6 to 8.

III.5.b) Linearity

Since optical spectrophotometry is more precise than the UV IUE data, optical standards will provide the FOS check on the linearity corrections derived before launch. The appropriate magnitude range is V=7 to 16 mag.

III.5.c) Spectral Flat Field

Featureless stellar spectra of white dwarfs are needed to confirm the spectral flat field corrections derived from laboratory spectra of continuum lamps. Spectral features begin to be detectable @ 0.1% of the continuum, or for an equivalent width of 0.005 Å at 6000 Å.

III.5.d) Absolute Sensitivity

Stars with visual magnitudes in the range of 10 to 14 mag are ideal for absolute spectrophotometric calibration. In order to properly understand any steep sensitivity changes with respect to the FOS resolution of R=1200, the resolution of the standard visual spectrophotometry should be better than R ~ 400. Featureless spectra are preferred to avoid small scale bumps in the sensitivity curves that are caused by dividing two spectra that have not been precisely degraded to the same resolution. The accuracy of the wavelength scale of the standard spectrophotometry should be better than one tenth the resolution of the R = 1200 FOS modes, eg. 0.5 Å at 6000 Å.

IV. Assignment of standard stars to specific calibration tasks

IV.1) Fine Guidance Sensors

The technically most straightforward approach is to observe two subsets of Landolt's equatorial UBVRI-standards (Landolt 1973, Landolt 1983 and Table 1). One subset should cover a range in (V-R) colour at a constant brightness level (say V-magnitude of about 10th) whereas the second set should cover at least the magnitude range given in Section II.1 (9-14.5 mag) with a possible extension on the faint end to establish the actual on-orbit brightness limit. The stars in this second set should have approximately the same (V-R) colours. (The two subsets defined this way can be thought of as being 'orthogonal' in the colour versus brightness plane.)

Such an approach would require a considerable amount of ST observing time and it is worthwhile to think of ways to obtain the required information in a 'cheaper' fashion. We suggest using the FGS-counts obtained on the guide stars to be selected for the (HSP) observations of the standard stars in Table 1. These standards lie in Selected Areas which are similar in extent to the field of view of ST; therefore, there is a good chance that guide stars for these photometric standards can be selected which are already photometric standards themselves.

If this approach were to be adopted, selecting guide stars for the photometric standards in Table 1 should be done as soon as possible. This selection should try to maximize the number of guide-stars for which photometric data are already available. Because of this unusual constraint as well as due to the urgency of this project, it appears desirable to do the selection by hand. Large scale photographs of the selected areas are available. The sample of chosen guide star should then be studied to check for sufficient range in colour as well as in brightness (and their degree of 'orthogonality'). The faint extensions needed to establish the signal-to-noise ratio as a function of magnitude (say 6 stars ranging between V=14.5 and V=17) would also be selected within the Selected Areas. Photometric measurements on guide stars for which no photometric data are available should then be urgently commissioned on a as-needed basis.

An additional advantage of this approach would be that the photometric standards will be revisited on a regular basis so that trend-analysis information on the FGSs would automatically become available, with some complications due to roll constraints. The neutral density filters can be calibrated on any of the brighter ($V \simeq 9$ mag) stars in the Selected Areas. Alternately, photometric data for stars bright enough to require these attenuators should be available in the literature allowing for a, a posteriori, calibration as needed.

The S-curve calibration, required for the FGSs, can use (a set of) guide stars within the Selected Areas.

IV.2) High Speed Photometer

IV.2.a) Linearity

There are several possible approaches under consideration. The use of existing Landolt (1973 and 1983) sequences which are faint extensions of other work (e.g. from 1953) would be one possibility. FOS linearity standards may also be useful assuming that standard star quality observations of these stars are obtained by Landolt. However, since the starting point of performing the linearity check is having highly accurate relative magnitudes (approaching 0.001 mag), a better data base might be obtained from other sources. Standards to check the linearity from V = 0 to V = 13 should be selected from existing data bases. (e.g. from the Geneva system or from Strömgren and Perry (1965), Crawford and Barnes (1970), Crawford, Barnes and Golson (1971), Crawford, Barnes and Hill (1977) and Olsen (1983)). Observations of bright standards with a filter having a narrow range of color are best suited to a linearity check (see Section V.8). To further check the linearity of the digital mode, high precision photometric data down to V ≈ 17 are required. The Selected Areas in Table 1 are being studied by Landolt and expanded in order to obtain faint sequences with a limited range in color. In order to do high accuracy transformations between a ST HSP instrumental passband and the ground based instrumental passband, accurate relative spectrophotometry will be required. We currently have no commitment to obtain relative spectrophotometry of linearity standards.

IV.2.b) Analog to Digital Conversion

A sequence of 5-10 standards from V = 10 to 5 will be required to calibrate the analog to digital conversion (for this conversion exact magnitudes need not be known). However, since data in this magnitude interval will also be used to check the linearity, targets used to derive the analog to digital conversion will be taken from the linearity standards.

IV.2.c) Sensitivity

We will use the photometric standard stars in the four equatorial Selected Areas in Table 1 to obtain the magnitude and colour transformations of the standard HSP Johnson-Cousins BVR and Strömgren uv filters. In these four regions there are 29 standards having V = 11.21 to 15.67 and B - V = -0.28 to 2.00. These standards should be supplemented with some of Landolt's equatorial blue standards listed in Table 4. Observations in a single Selected Area should suffice for an initial calibration as well as for stability checks during the orbital life-time. Also, according to Bless (private communication) only ~3 of the red stars in a region may have to be observed. Ideally, the full calibration should be based on observations of all stars in all four Selected Areas plus additional blue stars. A small amount of additional UBVRI photometry must be obtained by Landolt in these regions. Strömgren uv data of these standards should also be obtained, but we have no firm commitments to obtain this data at the present time. The HSP non-standard filters should be calibrated with respect to some reference point by using some of Landolt's standards (Tables 1 and 4), but primarily with objects which are both UV and optical spectrophotometric standards (Table 2) which have a range of colour. This would be one step towards ensuring a proper cross-calibration between the various scientific instruments. An effective way to achieve this would be to have some of the standards in the Selected Areas (i.e. Table 1) be adopted as UV and optical spectrophotometric standards (i.e. added to the Bohlin et al. list and Table 2) or to make sure that some of the standards in Table 4 have optical photometric, optical spectrophotometric and UV spectrophotometric data available. Thus, a complete set of data (including uvbyβ) should also exist for some of the objects presented in Table 4. We are continuing our efforts to arrange this.

Note that filters change in passband and effective wavelength in the orbital environment (e.g. OAO-2) and therefore relative spectrophotometry over an appropriate range of colours is needed to monitor and analyse these changes. Efforts should therefore be made to have relative spectrophotometry available for all HSP standards. This data would be indirectly used for the calibrations, (e.g. for developing accurate colour transformations). We currently have no firm commitment to obtain this relative spectrophotometry, but we do have several good possibilities. Such data would reside in a "reference" calibration data base.

IV.3) Wide Field Planetary Camera

IV.3.a) Linearity

Faint fields and diffuse sources (section II.3.a) must be found to study WFPC linearity. Since calibrated targets are not required, these "standards" can be taken from the literature.

IV.3.b) Sensitivity

Photometric calibration of the WFPC UBVRI filters will be obtained by observing the rich fields in Table 3. These standard star fields contain several stars of 14th to 17th magnitude within 1 x 1 arcminute, i.e., within the f/30 WFPC field-of-view to be desirable for WFPC calibration. These fields also include at least one unreddened B star (sometimes two) as well as some relatively red stars. There are no stars brighter than about 12th magnitude within 2 arcminutes of the center (i.e., within the f/12.9 WFPC field-of-view), and there is not an excessively crowded background of faint stars or nebulosity. Taken together, these were rather restrictive requirements, but candidate fields were located in the outskirts of six of the nearest metal-poor globular clusters and in one old open cluster. We recommend that first priority be given to NGC 5139 (Omega Centauri) and second priority be given to NGC 6752. NGC 6752 is a WFPC polarization calibration target. Data in these two fields is essential, but it would also be nice to have a northern field. As a third priority the northern field NGC 2419 should be adopted (this is also a WFPC polarization calibration target).

Photometry of both the standard rich fields and Landolt selected area standards will be obtained by Baum and collaborators with a CCD and WFPC replica filters. WFPC prism modes and non-standard filters will be calibrated using objects which are both optical and UV absolute spectrophotometric standards (Table 2). However, absolute optical and UV spectrophotometry (the latter of which is only possible with FOS or the FOS long-slit) of at least the blue stars in the rich cluster fields is worthwhile for use as backup standards for calibrating the prism modes and non-standard filters. Spectrophotometric standards in WFPC rich standard fields could also be used for cross-calibration purposes, if necessary. We note again that relative spectrophotometry of all WFPC photometric standards would be valuable to have in a reference calibration data base in order to help derive colour transformations to standard Johnson-Cousins UBVRI and to monitor and analyse changes in WFPC filter passbands and effective wavelengths which occur in the orbital environment. We presently have no commitment to obtain relative spectrophotometry in these fields.

IV.3.c) Point Spread Function

Point spread function data at various wavelengths will be acquired naturally during the linearity and sensitivity calibrations (e.g. when observing spectrophotometric standards with the non-standard filters).

IV.4) Faint Object Camera

IV.4.a) Linearity

If linearity tests are to be done independently from those of Section IV.4.c), a faint rich field as well as a diffuse source will be selected from existing data.

IV.4.b) Spectral Flat Field

Calibration of the pixel to pixel sensitivity variations in the f/48 long-slit will be derived by observing stars from the list of UV and optical spectrophotometric flux standards (Table 2).

IV.4.c) Sensitivity

A straightforward way of calibrating the FOC UBV filters of the f/96 mode would be to adopt Landolt's Selected areas in Table 1 and utilize ND filters. However very large values of attenuation (up to 9 mag) may have to be used and so this approach is not considered satisfactory as the principal calibration mode. Landolt is planning to extend his UBVRI work to fainter sequences in the Selected areas and this will be helpful to the FOC calibration, thereby allowing observation with smaller attenuation.

Calibration of the f/96 mode FOC Strömgren filters using standards in the Selected areas will first require the calibration of these standards on the Strömgren system. Presently we have no firm commitment for obtaining these data, but several observers have been contacted.

The most desirable approach to calibrating the photometric filters would be to observe a number of faint standard stars, having a range of colour, within a single FOC field of view, using a rich field. This approach minimises the observing time and is being used by the WFPC IDT. However, that camera's field of view is larger than the FOC's field of view and can observe much brighter stars before saturation occurs, so it is unlikely that the WFPC rich fields (Table 3) will be of use to the FOC. Also, the nearby globular clusters do not have sufficient intrinsic ranges in colour at the brightness levels relevant for FOC.

In the context of the rich-field approach, it does appear that recent ground-based CCD studies of globular clusters in combination with sophisticated data analysis software designed to work in crowded fields is capable of yielding B, V photometry (and possibly U) of very faint stars in fields compatible with the FOC's field of view. The best example, to date, is undoubtedly the study by Hesser and Harris (1984 personal communication) of fields in 47 Tuc (NGC 104) which yield accurate B, V photometry for stars at least as faint as 23 and which have a colour range of ~1.5 magnitudes (B-V). Note that this range in colour in this particular field is exceptional as it is due to a combination of red stars from the 47 Tuc population with blue halo population stars from the Small Magellanic Cloud.

Work by the FOC IDT is underway to study the data of Hesser and Harris in detail to identify suitable rich fields on the scale of the FOC field of view. Other suitable faint fields may become available before launch, for example, from Landolt's work on faint sequences in the selected areas. Additional potential calibration fields might be derived from Kron's photographic work in the north galactic pole which has yielded ~15 blue stars in the 21-22 mag range; Kron and Koo are searching for red stars within ~10 arcsec of these blue objects. In addition, the WFPC IDT is planning to do

WFPC science that may yield faint standards in the Magellanic Clouds, using globular cluster fields. Ground-based CCD work of such fields to determine their usefulness as calibrators for the FOC are being planned.

The FOC IDT proposes to calibrate its f/96 UBV filters using several rich fields--the prime candidate being 47 Tuc--without the use of ND filters. In addition, the faintest of Landolt's standards will be observed through ND filters to provide an independent check on the calibration. If needed, the WFPC standards could also be observed--again through ND filters--to cross-calibrate FOC and WFPC filters. However, the WFPC standards are not expected to be as accurate or as reliable as those of Landolt.

The f/48 UBV filters may also be calibrated using fields such as 47 Tuc if faint enough standards are available. If not then they will have to be calibrated using standards generated from the f/96 chain or other ST scientific instruments.

The FOC Strömgren filters present a major problem; there are no known ground-based standards faint enough for their calibration. The scale of the problem is that existing standards are ~6-7 mag, i.e. ~15 magnitudes brighter than the FOC bright limit! On the other hand, there is little scientific interest in their use--as judged by the FOC IDT science programme (which was opened to the ESA community). One programme that does aim to use these filters has stated that it will set up ground-based Strömgren standards (Jakobsen and Gustafsson 1984, personal communication). Clearly the impetus to calibrate these filters will have to be driven by any scientific use.

Calibration of the non-standard filters can be accomplished using objects which are both optical and UV spectrophotometric standards (Tables 2 and 4) and ND filters. At a later time objects that have been observed with FOS could be used without ND filters.

Calibration of the spectral modes of FOC will rely on FOS data for the f/48 prism modes and optical and UV spectrophotometric standards for the f/96 prism modes and the f/48 long-slit spectrographic mode (see Table 2).

IV.4.d) Point Spread Function

R136a, b and c in 30 Doradus is mentioned in FOC SV plans as a possible PSF target.

IV.5) Faint Object Spectrograph

IV.5.a) Scattered Light

As discussed by Bohlin et al. (1984) late type stars in the 5-7 mag. range will allow studies of scattered light as a function of wavelength. For example, using the Bohlin et al. technique optical spectrophotometry of HD 27836 and HD 186427 will allow us to quantify constraints on the amount of scattered light present. We still need to get a commitment to obtain spectrophotometry of these stars. ANS photometry is available for HD 27836. Other targets for which ANS photometry is available must still be investigated.

IV.5.b) Linearity

The standards in Table 2 range from V = 9.5 to 16.2 and thus can be used for the FOS linearity check. (Note that it is still somewhat desireable to have even fainter standards for the FOS linearity check.)

IV.5.c) Spectral Flat Fields

Targets for spectral flat fields can be taken from absolute sensitivity standards (Table 2) since these objects have featureless continuua.

IV.5.d) Sensitivity

Calibration of the optical absolute sensitivity of the FOS will be accomplished by observing the optical spectrophotometric standards presented in Table 2. Presently, this list consists of 6 DCs, 1 sdF and various hot blue stars (e.g. sdOs). In the future the DCs and sdF will undoubtedly become the primary spectrophotometric standards for use on large ground-based telescopes, while the hot blue stars will be the primary ST spectrophotometric standards since IUE data can be obtained only for these objects. An effort should also be made to make some spectrophotometric standards optical photometric standards for cross-calibration purposes.

V. Outline of pre-launch ground-based observational requirements

V.1) Complete UBVRI-photometry in the Selected Areas and obtain UBVRI-photometry of other Calibration Targets

and

V.2) Obtain uvbyβ photometry in the Selected Areas and obtain uvbyβ photometry for other Calibration Targets

The stars listed in Table 1 represent the UVBRI-system for the purpose of calibrating the photometric modes of the various Scientific Instruments on the Space Telescope. Landolt is undertaking this UBVRI calibration task. Most of these stars have been included for many years in Landolt's observing runs and show no signs of variability. Some further observations are needed to complete this program.

As these same stars will be used for the calibration of the uv HSP system and the FOC uvbyβ system (with ND), such observations also need to be collected. We have had communications with several of the astronomers associated with the uvbyβ system (Breger, Crawford, Olsen) and chances for finding somebody who might be interested in obtaining these data are good, especially as there is some interest in using these same stars for uvbyβ standardization purposes on large ground based telescopes. No firm committment in this area is available at this time.

The set of spectrophotometric standards in Table 2 will provide a primary frame of reference for the absolute flux calibration of all Space Telescope Scientific Instruments with wavelength coverage in the range 3200-10800 Å. Only the very best data will suffice for this purpose and one way to achieve quality-assurance is through redundancy. Therefore, we propose ground based observations of as many of these calibration targets as is possible through both UBVRI and uvbyβ filter sets. Such observations should preferably be obtained on a regular basis to check for possible variability. The results of such work will play an important role in synthetic photometry programs. We will be trying to have these targets added to Landolt's program and will recommend that they be part of any Strömgren filter program.

V.3) Obtain double spectrograph data for the primary spectrophotometric standards and obtain relative spectrophotometry of selected additional standards

The hot blue stars in Table 2 will form the primary reference for the spectrophotometric and photometric flux calibration for all Scientific Instruments on the Space Telescope over the wavelength region of 1200-12000 Å. Measurements for these stars with a spectral resolution varying between 400 - 800 will be obtained by Oke, using the 5-m at Palomar in combination with his double spectrograph. His data will provide the reference frame for many tasks (linearity, absolute sensitivity, flat fielding) and it is therefore important that his results become available to the community as soon as possible.

We note that obtaining high resolution ground-based data of the primary calibration targets is important because of the check it allows on the success of the flat-fielding procedure as applied to the ST-spectroscopic observations. In particular, if we have some detailed (high-resolution) spectrophotometry of the standards from ground-based work, flat-fielding of the data can be viewed as a check since absolute sensitivity can be found directly for each pixel. In addition, absolutely calibrated higher resolution observations permits synthetic photometry which will aid in developing color transformations between the ST photometric systems and other photometric systems now in use.

For the reasons outlined throughout the text, it is important to have relative spectrophotometry of selected additional standards: the Landolt standards (Table 1), FOS scattered light targets, WFPC rich field targets (Table 3). Some of this work may be carried out at CTIO, Lick Observatory and Steward Observatory, but we have no firm commitments.

V.4) Obtain CCD and single channel photometry in the Selected Areas and search for already existing faint sequences; Monitor potential (22^m) standards (for FOC) for variability

Landolt plans to extend sequences in his selected areas to 16-17 mag. This would be helpful to any FOC calibration relying on attenuation filters. Investigations of the suitability of existing faint sequences will continue. We have no commitments to monitor faint standards once they are identified, but note that the Kron 22^m blue stars (see IV.4.c) have been studied for many years and have good photometric histories.

V.5) Obtain CCD photometric in the selected globular clusters

Ground-based CCD observations with WFPC replica filters will be obtained in at least two of the globular cluster calibration fields of Table 3 by Baum and collaborators. Photometric data reductions in the rich fields will include many more stars than the few 14th to 17th-magnitude stars in the central arcminute. Stars within a 4-arcminute diameter circle should become standards so as to fill the f/12.9 WFPC field-of-view for any ST roll angle. Ideally stars fainter than 17th magnitude should be included.

Magnitudes and colors of the stars in these calibration fields will be tied to the existing Johnson-Cousins UBVRI sequences established by Landolt (1973, 1983) in four of the Kapteyn Selected Areas (Table 1). Actual observations in this program should include at least two of the Landolt sequences.

V.6) Study the wavelength region from 2800 to 4000 Å

Very little spectrophotometry has till now been done in the wavelength-region from ~3000 Å and the Balmer-discontinuity at ~3700 Å. No previous satellites have covered this range in a continuous manner. The longest wavelength listed for the OAO-2 spectrum scanners, for example, is 3580 Å (Code and Meade 1979; Meade and Code 1980). The TD1a ultraviolet scanner data only go out to 2540 Å (Jamar et al. 1976). The International Ultraviolet Explorer has some sensitivity out to approximately 3200 Å, but fluxes obtained by this satellite longward of 3080 Å suffer from increasing scatter due to a rapidly falling sensitivity function. The accuracy achievable though ground-based observations in this wavelength region is limited by the atmosphere. Extinction-coefficients rise sharply around 3700 Å and reach values in excess of one magnitude per airmass shortward of 3200 Å even at relatively high sites such as Cerro Tololo (Stone and Baldwin 1983).

We are planning programs to bridge this gap in our knowledge. A potentially fruitful approach is to obtain new long wavelength IUE data and to do archival research on high quality long wavelength IUE observations of hot stars (i.e. white dwarfs, see Finley et al. 1984). Ground based spectrophotometry is being obtained for some objects for which good IUE data longward of 3000 Å are available by Oke (Table 2) and Stone. The IUE data should be reprocessed or corrected to allow for the changes of sensitivity of IUE during its life in orbit, if necessary.

Note that in ground-based programs, wavelength coverage can be limited to the wavelength region of 3080 Å to approximately 4000 Å. As a supplement, standard stars to be used could also include a carefully considered mix of stars from Oke and Gunn (1983), Stone (1974 and 1977) Stone and Baldwin (1983) and Baldwin and Stone (1984). Any analysis could include a comparison with appropriate stellar models.

This study will allow the adjustment of the IUE and/or optical flux scale for mutual consistency.

V.7) Set the zero-point of the photometric magnitude scales and predict the absolute flux density for zero magnitude

The High Speed Photometer, the Faint Object Camera, the Wide Field Planetary camera and the Fine Guidance Sensors use a wide variety of photometric filters for which it is necessary to define a magnitude scale as it is expected that many of the scientific results from ST will be reported in the language of magnitudes and colours. Such magnitude scales should be defined in such a way that a plot of magnitude versus effective wavelength for a given object is physically 'reasonable' in terms of the implied energy distribution. This should be true even if the observations have been obtained with a mix of ST instruments. In many cases, data obtained through 'standard' filters will be treated as if the filter were 'non-standard'. A sensible zero-point has to be defined for all filters.

Generally speaking, the only way of setting a photometric zero-point is by pre-assigning a set of magnitudes (one for each filter under consideration) to one (or a number of), primary, standard star(s). The absolute calibration is traditionally assigned later by convoluting the best available estimates of the absolute flux distribution of the stars defining the zero-point with the then current information regarding the characteristics of the photometric passbands. In this scheme, the zero-point of the magnitude scale will be set once and for all, but the absolute flux-density for zero-magnitude is updated if improved fundamental flux-standards or better passband parameters become available. Indeed, the very purpose of defining a magnitude scale is to create a stable reference frame regardless of the then current knowledge of the absolute calibration.

If, as is the case for ST, it is important to have a good absolute calibration as well as a sensible magnitude system, the stars observed for these purposes should have both accurately known absolute fluxes as well as pre-assigned magnitudes. The most direct way of doing this is by assigning magnitudes for all photometric passbands on ST to (a subset of) the spectrophotometric standards of this paper (and the lists of Bohlin et al. for the ultraviolet) using synthetic photometric techniques.

After performing the convolution of the flux distribution with the photometric passband, a constant needs to be introduced for every filter. This can be done such that:

- a (hypothetical) A0-dwarf would have zero-colours, or

- a (hypothetical) star with constant flux per unit wavelength interval would have zero colours, or

- a (hypothetical) star with a spectrum resembling an infinite temperature black-body would have zero-colours, or

- other.

Given the large wavelength range covered by ST, none of the traditional methods are really satisfactory and some creative thinking is required.

V.8) Determine the relationship between the "Caltech" and the "Lick" spectrophotometric systems

To open up the data-base of spectrophotometric observations which are calibrated relative to the Lick-standards, to further the redundancy in the spectrophotometric calibration effort, and as a service to the community, we propose that observations be obtained of the standard stars in Table 2, as well as the AB79 standards of Oke and Gunn (1983), relative to the Lick-spectrophotometric system proposed by Stone (1974 and 1977) and also Stone and Baldwin (1983) and Baldwin and Stone (1984). Stone hopes to be able to carry out this work.

V.9) Determine or select linear sequences

To profit from the potential of the High Speed Photometer to produce photometric data with exceptionally high accuracy, a desirable task is to create some photometric sequences which can confirm the linearity. As mentioned in Section III.2, we require sequences of stars each with magnitudes ranging between at least 0-13 (down to 17 is desirable). The photometric passband used for this purpose is still to be selected. To minimize colour corrections, we suggest limiting the range in spectral type within each sample. To approach the desirable accuracy (<< 0.01 mag) over this large a dynamic range a special project would have to be initiated or else highly accurate existing photometry would have to be used in combination with synthetic photometry techniques.

A possibility might be to use one of the UBVRI filters and results from Landolt, supplemented with brighter data from the older literature. However, it is not clear whether such, inhomogeneous, data could be transformed to one of the HSP filters with sufficient accuracy.

On the other hand uvbyβ system magnitudes and colours (indices) are routinely published (e.g. Olsen, 1983) to three significant places since rms errors for single observations on that system can be significantly less than 0.01 mag. The internal mean errors of the indices of standard stars are less than 0.001 mag (cf. Gronbech et al., 1976). This suggests that a literature search (preferably by a member of the Strömgren community) might be an acceptable low-cost alternative. Also, Rufener (private communication) has suggested using a set of ~50 stars brighter than 12 mag measured 215 times (on the average) on the Geneva system for which precisions are ~0.001 mag.

If new measurements were taken for this program, objects which will be used for FOS linearity in the 9-16 mag range should be candidates for the faint targets.

Thusfar, we have no proposals to undertake this type of work.

V.10) Determine accurate and complete red star flux distributions

Red stars will be used to determine scattered light levels in spectrophotometric modes and possibly so-called red leaks in photometric modes. Precise requirements for such calibration targets are not defined at this time, but K-giants are likely candidates (see discussion on two possible candidates in section IV.5.a). A problem with these stars is that their exact fluxes in the blue and ultraviolet are not very well known. A comparison of data from OAO-2, TD1a and ANS (Koornneef et al., 1982) shows large variations in the observed blue fluxes for these stars. The major cause for these apparent fluctuations is instrumental in the sense that scattered red light and/or red leaks through filters is a non-negligible component of the observed signal. Of the three satellites mentioned above, it appears that ANS has the smallest contribution of unwanted light. The scattered light contribution for the case of the International Ultraviolet Explorer is similarly uncertain. A recent contribution to this subject has been made by Kjaergaard et al. (1984).

Further studies of the detailed flux distributions of late type giants in the blue and ultraviolet would be helpful. The goal would be to generate a list of stars and associated energy distributions suitable for the measurement of scattered light and red leaks on all the Scientific Instruments on the Space Telescope. For spectral regions with an exceedingly depressed energy distribution, well documented estimates or upper limits would be acceptable.

Requirements for such a study include a thorough knowledge of previous ultraviolet satellites, models for late type stars and synthetic photometry.

Thus far, we have no proposals to undertake this type of work.

V.11) Obtain MK-spectral classification of selected standard stars

Many of the standard stars selected for ST-calibration purposes are faint enough so that MK-spectral types are not available from the literature. For a selected number of targets it would be desirable to have a reference calibration data base which contains spectral information. Apart from providing information on possible peculiarity, temperatures, abundances and luminosity, this data (together with the available photometry) will yield distances and reddening, and, with the aid of synthetic photometry, will allow more reliable colour transformations between different systems. Exactly which subset of the stars can gain from such information needs to be discussed, but the photometric standards of Table 1 are prime candidates.

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Table 1

UBVRI and uvbyβ Equatorial Standards

SA 95 RA $3^h 50^m$ NAME	V	B-V	SA 101 RA $10^h 00^m$ NAME	V	B-V
GD50	14.05	-0.28	GD108	13.56	-0.23
42	15.67	-0.25	207	12.41	+0.52
190	12.60	+0.27	330	13.76	+0.62
132	12.05	+0.44	429	13.51	+1.04
218	12.08	+0.71	327	13.43	+1.23
302	11.68	+0.84	431	13.70	+1.27
301	11.21	+1.29			
317	13.49	+1.30			
275	13.51	+1.73			
330	12.19	+2.00			

SA 107 RA $15^h 50^m$ NAME	V	B-V	SA 113 RA $21^h 40^m$ NAME	V	B-V
G153 41	13.41	-0.22	G93-48	12.74	-0.01
351	12.34	+0.56	260	12.44	+0.46
x 626?	13.38	+0.74	339	12.25	+0.58
456	12.94	+0.92	221	12.16	+1.00
x 626?	13.50	+0.96	241	14.44	+1.36
x 602	12.12	+0.97			
x 568	13.14	+1.10			
x 601	14.77	+1.41			

Giclas Lowell proper motion survey: The G # stars

Table 1

UBVRI and uvbyβ Equatorial Standards

SA 95, RA $3^h\ 50^m$

NAME	V	B-V
GD50	14.05	-0.28
42	15.67	-0.25
190	12.60	+0.27
132	12.05	+0.44
218	12.08	+0.71
302	11.68	+0.84
301	11.21	+1.29
317	13.49	+1.30
275	13.51	+1.73
330	12.19	+2.00

SA 101, RA $10^h\ 00^m$

NAME	V	B-V
GD108	13.56	-0.23
207	12.41	+0.52
330	13.76	+0.62
429	13.51	+1.04
327	13.43	+1.23
431	13.70	+1.27

SA 107, RA $15^h\ 50^m$

NAME	V	B-V
G153-41	13.43	-0.20
351	12.34	+0.55
627	13.34	+0.77
456	12.91	+0.92
626	13.47	+1.01
602	12.12	+0.99
568	13.04	+1.15
601	14.65	+1.40

SA 113, RA $21^h\ 40^m$

NAME	V	B-V
G93-48	12.74	-0.01
260	12.44	+0.46
339	12.25	+0.58
221	12.16	+1.00
241	14.44	+1.36

The G # stars: Giclas Lowell proper motion survey

Table 2

OPTICAL SPECTROPHOTOMETRIC STANDARDS
THE FOLLOWING STARS WILL DEFINE THE CALTECH SYSTEM:

Moderate Temperature Cool Subdwarfs or DCs

G158-100	sdF	0031-12	14.9	very good, in use
G193-74	DC	0749+53	15.8	good
G60-54	DC	1257+04	15.8	
G138-31	DC	1625+09	16.2	cool
G24-9	DC	2011+06	15.8	cool
LTT 9491	DC‡	2318-17	14.1	good
GD 248	DC	2323+15	15.1	no features, in use eclipsing binary

THE FOLLOWING STARS WILL BE OBSERVED ON THE CALTECH SYSTEM

Hot Blue Stars

Feige 11		0101+03	12.1	potential UV standard, UBVRI standard
HZ4	DA	0355+09	14.4	UV standard
G191B2B	DA	0505+52	11.8	UV standard
BD+75°325	sdO	0810+74	9.5	UV standard
PG0919+026		0919+02	13.3	potential UV standard, UBVRI standard
A+81°266	sdO	0921+81	12.1	UV standard
PG1035+001		1035+00	13.2	potential UV standard, UBVRI standard
Feige 34	sdO	1036+43	11.3	potential UV standard
HD93521	O9Vp	1048+37	7.0	UV standard
HZ21	DO1	1213+32	14.2	UV standard
Feige 66	sdO	1234+25	10.4	potential UV standard
Feige 67	sdO	1239+17	11.7	potential UV standard
HZ44	sdO	1322+36	11.7	UV standard
PG1323-086		1323-08	13.5	potential UV standard, UBVRI standard
Grw 70°5824	DA	1338+70	12.9	UV standard
GD190	DB3	1544+18	14.9	potential UV standard
BD+33°2642	B2IV	1551+32	10.8	UV standard
LDS749B	DB4	2132+00	14.7	potential UV standard
L930-80	DB4	2147-07	14.8	potential UV standard
BD+28°4211	Op	2151+28	10.5	UV standard
NGC7293	v. hot	2229-20	13.4	UV standard
Feige 110	sdO	2317-05	11.5	UV standard

‡According to J. Liebert, this object has been classified as DB4.

Table 3

Fields Selected for WFPC (and FOC)

1) 68"x 68" field in the southwest (11.5' W; 7.4'S) outskirts of ω Centauri (NGC 5139)
Coordinates: $13^h\ 24^m$ -47 ; Distance Modulus 13.9

Brightest Stars in this Field

V	B-V
14.6	0.8
16.6	1.0
14.7	0.0
14.8	-0.3
15.8	0.6
15.8	-0.2

2) A field in the northwest (10.6'; 17.5' N) outskirts of NGC 6752.‡
Coordinates: $19^h\ 07^m$ -60°
There are 2 blue stars within 1' x 1', the brightest being 15.0 mag.

‡NGC 6752 is also a WFPC polarimetric standard field.

3) It would be worthwhile if a 3rd field were added which was northern and a polarimetric calibration target. We suggest NGC 2419 with RA = 07 34.8 and DEC = + 39 00.

Other fields which could be valuable:

Cluster NGC#,M	Approx. Coordinates	Location of Candidate Field	Brightest Blue Star	Blue stars within 1'x1'
188*	00:42 +85	1.4'E, 4.4'N	16.3	1
288	00:50 -27	4.4'E, 1.7'N	16.0	2
6809,M55	19:37 -31	0.4'E, 5.0'N	14.9	2

*NGC 188 is the FGS astrometric calibration field.

Note: A recent CCD-study of 47 Tuc by Hesser and Harris (1984) shows that this galactic globular cluster is severely 'contaminated' by faint (and relatively blue) stars associated with the Small Magellanic Cloud. Further study might be indicated to decide whether such a field has potential for FOC calibration purposes.

References:

KPNO list of potential Calibration Fields (Lindsey Davis)

Memo by Bill Baum and Tobias Kreidl dated December 29, 1983

Table 4

Further Stars of Special Interest

NAME	RA	DEC	V	B-V	SOURCE
Feige 11	1 03	+ 4 06	12.06	-0.25	Landolt, 1973
Feige 16	1 53	- 6 54	12.41	-0.02	"
Feige 22	2 29	+ 5 10	12.79	-0.05	"
Feige 24	2 34	+ 3 38	12.42	-0.21	" (4-day binary)
GD 71	5 51	+15 53	13.04	-0.24	"
Rubin 149	7 23	- 0 30	13.86	-0.11	Rubin et al., 1974
Rubin 152	7 29	- 2 04	13.01	-0.18	"
194 287	9 20	+ 2 51	13.33	-0.27	Landolt (unpublished)
G 192 66	10 32	-11 34	13.00	-0.16	Landolt, 1973
206 166	10 36	- 0 02	13.20	-0.36	Landolt (unpublished)
G 163 27	10 56	- 7 23	14.33	+0.30	Landolt, 1973
G 163 50	11 07	- 5 01	13.06	+0.03	"
G 163 51	11 07	- 5 05	12.53	+1.51	"
235 57	13 25	- 8 44	13.51	-0.16	Landolt (unpublished)
G 21 15	18 26	+ 4 03	13.91	+0.08	Landolt, 1973
Mark A	20 43	-10 46	13.27	-0.20	Landolt (unpublished)
GD 246	23 11	+10 39	13.10	-0.32	Landolt, 1973
Feige 108	23 15	- 1 59	12.97	-0.23	"

Distribution:

Albrecht, R.	ST-ECF
Adelman, S.J.	U.S.A.
Andersen, J.	Denmark
Bahcall, J.	Princeton
Bahcall, N.	STScI
Baldwin, J.	CTIO
Ball, D.	STScI/CSC
Barnes, T.G.	McDonald
Batten, A.H.	Canada
Baum, W.A.	Lowell
Baumert, J.	STScI/CSC
Benvenuti, P.	ST-ECF
Bessel, M.	Mt. Stromlo
Blades, J.C.	FOC-IDT
Bless, R.C.	HSP-IDT
Boeshaar, G.	STScI
Boggess, A.	GSFC/STP-G
Bohlin, R.C.	STScI
Boksenberg, A.	RGO
Bozyan, E.P.	Austin
Brandt, J.	HRS-IDT
Breger, M.	Vienna
Brown, R.C.	MSFC/STP
Burrows, C.	STScI
Buser, R.	Basel
Cannon, R.	Edinburgh
Capriotti, E.R.	Ohio
Cayrel de Strobel, G.	Mendon
Chaffe, F.	MMT
Chincarini, G.L.	Oklahoma/ESO
Chipman, E.	STScI/CSC
Christian, C.	CFHT
Code, A.D.	Wisconsin
Cohen, R.	FOS-UCSD
Conti, P.S.	JILA
Cox, C.	STScI
Crane, P.	ESO
Crawford, D.L.	KPNO
Courvoisier, Th.	ST-ECF
Danielson, G. E.	Caltech
Davis, L.	KPNO
Dolan, J.F.	HSP-IDT
Downs, R.	FOS-ARC
Doxsey, R.	STScI
Dupree, A.K.	CfA
Ebbets, D.	STScI
Ewald, S.P.	STScI
Faber, S.M.	Lick
Faraggiana, R.	Italy
Fastie, W.	JHU
Fernie, J.D.	DDO
Finley, D.	Berkeley
Ford, H.C.	STScI
Fosbury, B.	ST-ECF
Fracassini, M.	Italy
Freedman, W.	Mt Wilson
Fresneau, A.	STScI
Garrison, R.F.	Canada
Gerbaldi, M.	France
Giacconi, R.	STScI
Gieseking, F.	Germany F.R.
Glushneva, I.N.	U.S.S.R.
Goldberg, A.	GSFC/STP-G
Graham, J.A.	DTM
Gray, D. F.	Ontario
Griffin, R.F.	U.K./Cambridge
Griffiths, R.	STScI
Groth, E.	DOT
Gunn, J. E.	Princeton
Gustafsson, B.	Uppsala
Hack, M.	Italy
Hall, D.S.	Hawaii
Hanes, D.	Ontario
Harris, E.E.	McMaster
Harms, R.	FOS-IDT
Hartig, G.	STScI
Hauck, B.	Lausanne
Hayes, D.S.	KPNO
Heap, S.	HRS-IDT
Heck, A.	Strasbourg
Hemenway, P.	FGS-IDT
Hesser, J.M.	DAO
Hoag, A.	Lowell
Hoessel, J.	STScI
Holm, A.	STScI/CSC
Houziaux, L.	Belgium
Humphreys, R.	Minnesota
Illingworth, G.	STScI
Jaffe, W.	STScI
Jakobsen, P.	FOC-IDT
Jaschek, C.	Strasbourg
Jefferys, W.	FGS-IDT
Jenkner, H.	STScI
Kalinowski, K.	GSFC
Keenan, P.C.	Perkins
Kelsall, T.	WFPC-IDT
Kemper, E.	STScI/CSC
King, I.R.	Berkeley
Koo, D.	STScI
Koornneef, J.	STScI
Krelowski, J.	Poland
Kron, R.	Chicago
Labhardt, L.	Basel
Landolt, A.	Baton Rouge
Lasker, B.	STScI
Latham, D.	CfA
Leckrone, D.	GSFC/STP-G
Liebert, J.W.	Steward
Lindler, D.	STScI
Lub, J.	Leiden
Lupie, O.	STScI/CSC
Lynga, G.	Sweden
Macchetto, F.	STScI
MacKay, C.	Cambridge
Madore, B.	Caltech/DDO
Malagnini, M.L.	Italy
Mantegazza, L.	Italy
Maran, S.P.	HRS-IDT
Margon, B.	FOS-IDT
McElroy, D.	STScI/CSC
Milkey, R.	STScI
Morguleff, N.	France
Morossi, C.	Trieste
Morton, D.C.	AAT
Mould, J.	Caltech
Neckel, H.	Germany F.R.
Nordstrom, B.	Copenhagen
Oblak, E.	Besancon
Oegerle, W.	STScI
Oke, J.B.	Caltech
Olsen, E.H.	Copenhagen
Osmer, P.	CTIO
Papoular, R.	France
Paresce, F.	STScI
Pascu, D.	U.S.A.
Pasinetti, L.E.	Italy/Milano
Pastori, L.	Italy
Pelizzari, M.	STScI/CSC
Pence, W.	STScI
Penny, A.	RGO
Perry, P.	CSC
Philip, A.G.D.	New York
Phillips, M.	CTIO
Piirola, V	Helsinki
Quintana, H.	Chile
Rakos, K. D.	Vienna
Rees, M.	Cambridge
Roman, N.G.	ORI
Rossi, L.	Frascati
Rountree-Lesh, J.	U.S.A.
Rufener, F.	Geneva
Russell, J.	STScI
Sandage, A.R.	Mt Wilson
Sargent, W.	Caltech
Schiffer, F.	STScI/CSC
Schild, R.	CfA
Schmidt, E.	Nebraska
Schreier, E.	STScI
Schroeder, D.	TELSCI/Beloit
Seggewiss, W.	Germany F.R.
Seitzer, P.	KPNO/CTIO
Sherill, T.J.	Lockheed
Simko, M.	STScI/CSC
Sinnerstad U.E.	Sweden
Smith, H.J.	McDonald
Spite, M.	France
Stetson, P.	DAO
Stockman, H.S.	STScI
Stone, R.	Lick
Strittmatter, P.	Steward
Stryker, L.L.	DTM/CIW
Sturch, C.	STScI/CSC
Tapia, S.	Steward
Taylor, B.	Brigham Young
Tinbergen, J.	Roden/NL
Turnshek, D.	STScI
Tyson, J.A.	Bell Labs
van Citters, W.	HSP-IDT
van der Hucht, K.A.	Netherlands
Van't Veer, C.	France
Viotti, R.	Italy
Walker, A.	Cape Town
Walker, G.	Vancouver
Wamsteker, W.	IUE/Madrid
Wesselink, A.J.	Bethany
Wesselius, P.R.	Groningen
Westphal, J.A.	WFPC-IDT
White, N.M.	Lowell
White, R.	STScI
Wilkening, L.	LPL
Wills, R.	ESTEC
Wisniewski, W.	LPL
Woltjer, L.	ESO
Wu, C-C	STScI/CSC