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The Hubble Space Telescope High Speed Photometer

G. W. Van Citters, Jr.

Division of Astronomical Sciences
National Science Foundation
Washington, D.C.

and the

HSP Investigation Definition Team*

*R. C. Bless (P. I.), J. F. Dolan, J. L. Elliot, E. L. Robinson, R. L. White

Short Title: Space Telescope High Speed Photometer

Abstract

The atmosphere of the Earth affects the performance of ground-based astronomical photometers in a variety of ways. Seeing, scintillation, scattered light, airglow, and changing extinction all act on various time scales and in different wavelength regions to make precise photometry from the ground a challenging task. In addition the ultraviolet region of the spectrum, important for the study of hot objects and energetic processes, is not available. The Hubble Space Telescope will provide the opportunity to perform precise astronomical photometry above the disturbing effects of the atmosphere. The High Speed Photometer is designed to provide the observatory with a stable, precise photometer with wide dynamic range, broad wavelength coverage, time resolution in the microsecond region, and polarimetric capability. In this paper we briefly examine the scientific requirements for the instrument, explore the unique design features of the photometer, and project the improvements to be expected over the performance of ground-based instruments.

I. Introduction

An aperture photometer based on one or more photomultipliers has been an indispensable part of the equipment complement of ground-based observatories for many years. The large number of photometric systems that have been devised and used successfully to determine such parameters as temperature, surface gravity, metallicity, interstellar reddening, etc., speak to the widespread understanding of the basic detector. The photomultiplier provides a large dynamic range with linear response, broad wavelength coverage with respectable detected quantum efficiency, high time resolution, low intrinsic noise, and an extensive literature that documents both its power and limitations.

In fact in many spectral and time domains the limitations on the precision of astronomical photometry stem not from the basic detector but from the influence of the Earth's atmosphere. Variable extinction, seeing, scintillation, airglow, and scattered light all limit the performance of photometry from the ground. The effects have been extensively treated [e.g. Young, 1974], so will not be dealt with in any detail here. Some of the problems are amenable to variations in basic photometer design, such as the two-channel approach [e.g. Nather, 1972; Grauer and Bond, 1981] which can combat transparency variations and slowly varying sky brightness. The advent of area detectors in the form of charge coupled devices allows optimization of signal to noise ratio through synthetic aperture techniques and simultaneous sky background measurement [Nather, 1972]. However the photometric performance of CCDs has not yet been demonstrated to be equal to that of the well understood photomultiplier.

With a conventional photometer and considerable care the internal precision of measurements from the ground for bright (m_V = 8) stars can approach 0.001 magnitude [e.g. Kurtz and Martinez, 1987] for time scales from tens of seconds to a few hours. At higher frequencies, scintillation noise becomes increasingly important (see [Fuentes, et al., 1987] for a recent study in the near IR), and long term atmospheric variations and instrumental instabilities make longer period phenomena difficult to investigate. No technique can provide access to the ultraviolet wavelengths from the ground.

Launch of the Hubble Space Telescope will provide a platform from which to perform photometry above the disturbing effects of the atmosphere. The High Speed Photometer Investigation Definition Team set out to design an instrument that would take advantage of this environment, both the lack of atmosphere and the relatively stable ambient conditions, to perform precise photometry over a wide range of time scales. The instrument was to be based on the photomultiplier, both because of its demonstrated performance in space applications and the long history of use in ground-based photometry. In Section II we examine some of the scientific programs and the resulting instrumental requirements. We then look at the optical design and electronics in Section III, pointing out some of the unique features of the Space Telescope instrument in comparison to its ground-based predecessors. Finally, Section IV provides a brief description of the operation of the photometer and some projections of its performance.

II. Scientific Program and Instrumental Requirements

The scientific interests of the co-investigators are varied, running from cataclysmic variables to planetary science. The study of variable compact objects such as white dwarfs, neutron stars and black holes forms an important part of our program. The characteristic time scales of variations in these objects (from seconds or minutes for white dwarfs down to milliseconds or less for neutron stars and black holes) occur in a regime where the atmosphere mimics or masks features in the intrinsic light curve. The flux maxima of these objects are at ultraviolet wavelengths inaccessible from the ground. In addition these objects are intrinsically faint, and the amplitude of the variations is frequently small, hence reduction of the sky background is an important goal.

Another class of compact object, the central stars of planetary nebulae, provides a different observational challenge and an interesting scientific opportunity. Evolutionary models [Schonberner, 1981] suggest that the luminosity decrease of the central star as it joins the white dwarf cooling sequence should amount to 5×10^{-4} magnitude per year. With access to the ultraviolet and with a very precise, stable photometer such a decrease might be directly measurable on a time scale of several years. The value of such a measurement to the theory of advanced stages of stellar evolution is apparent. Techniques such as those used on the ground to achieve 0.001 magnitude precision, when applied in space, may be capable of such performance. The HSP, normally thought of as making observations on millisecond timescales, may contribute information on the cooling time of central stars, measured in hundreds of thousands of years.

We also plan to use occultations of stars by the planets and their associated moons and ring systems to probe planetary atmospheres and ring composition and dynamics. These observations will be carried out in the visual and red regions in addition to the ultraviolet. Again important structure occurs in the occultation light curves with frequencies of 1 Hz and higher. The increase in signal to noise afforded by the lack of scintillation, scattered light and smaller apertures will allow many more occultations to be observed than can be from the ground. Even with the limitations inherent in ground-based observations, this technique has added much to our understanding of the solar system. Observations from Space Telescope should provide very detailed information on ring structure, composition and origin and the best temperature profiles available for the planetary atmospheres.

To provide the observational capabilities for the programs mentioned above and to provide an overall photometric capability for the General Observer on the Hubble Space Telescope, the design characteristics of the HSP are:

Time Resolution:	10 microseconds, pulse counting 4 millisecond, current mode
Apertures:	0.4, 1.0 arcsec for normal observations 10.0 arcsec for acquisition
Wavelength Range:	1200 - 7500 Ångstroms, 23 filters
Polarimetry:	4 ultraviolet filters
Sensitivity:	S/N = 10 for 24^m star in B band in 2000 sec
Accuracy:	Systematic errors < 0.1% from $m_V=0$ to $m_V=20$

III. Instrument Design

Optics

The desire to provide the versatility inherent in the characteristics presented above and yet to provide a simple, stable and reliable instrument on orbit resulted in a rather unconventional design. Four image dissectors and one conventional photomultiplier provide linear, well understood detectors. The dissectors are ITT 4012RP Vidissectors, two with CsTe photocathodes on MgF_2 faceplates (sensitive from 1200 to 3000 Ångstroms) and two with bialkali cathodes on quartz faceplates (sensitive from 1800 to 7000 Ångstroms. Each dissector, its voltage divider, deflection and focus coils are contained in a double magnetic shield within the housing. The photomultiplier is a Hamamatsu R666S with a GaAs photocathode. Three of the image dissectors, the two CsTe and one of the bialkali tubes, are used for photometry. The second bialkali dissector is used for polarimetry, and the photomultiplier along with the bialkali photometry dissector are used for occultation observations.

Figure 1 shows the arrangement of the detectors and optics in the HSP. For photometry, light from the Space Telescope enters the HSP through one of three holes in its forward bulkhead. Since the focal plane of the HST is shared by five instruments with the Wide Field/Planetary Camera on-axis, these entrance holes are of necessity all centered on an arc about 8 arc minutes off-axis. The beam from the telescope first encounters the filter-aperture tube. Each tube contains thirteen filters mounted in two rows 36mm ahead of the ST focal plane. At this location the converging beam from the ST is 1.5mm in diameter. This placement of the filters provides insensitivity to small pointing and guiding errors in the event of filter nonuniformities, pin holes or the development of color centers on-orbit. The superb tracking capability of the HST (0.007 arc sec RMS) allows this departure from conventional filter placement. Behind the filters and in the focal plane of the telescope are the field apertures. These 50 apertures are arranged in rows directly behind the filter strips. Figure 2 shows a typical arrangement, in this case for the bialkali dissector filter assembly. The aperture choices are 0.4 and 1.0 arcsec diameters. Each tube also has one 10 arcsec diameter aperture available for target acquisition.

The choice of filter and aperture for a given observation is thus made by pointing the HST so the object of interest falls on the correct filter/aperture pair. After passing through this pair the light is brought to a focus on the dissector cathode by a relay mirror - a 60 mm off-axis ellipsoid located some 800mm behind the HST focal plane. This relay arrangement actually images a complete filter/aperture set on each dissector cathode allowing a greater number of detectors to access the focal plane, providing about 0.25 arc sec diameter images on the photocathodes. Again the tracking capability of the telescope allows this approach rather than a conventional Fabry lens. Within the dissector the photoelectrons are magnetically focussed and deflected such that the image of the desired filter/aperture pair is directed through the 180 micron (1 arc sec on sky) dissector aperture, and thence to the 12 stage multiplier section of the tube. Thus with no moving parts 27 different filter/aperture combinations are available for each photometry detector.

The reader is referred to the High Speed Photometer Instrument Handbook available from the Space Telescope Science Institute for a complete list of the various filters and their characteristics. Some filters are common to all three tubes to provide redundancy and to allow the tubes to be tied together photometrically. Other filters are similar to those flown on previous space missions, to filters used in ground-based systems and to filters in the Wide Field and Faint Object Cameras. For occultations, a beamsplitter passes red light to the photomultiplier through a normal Fabry lens arrangement with the blue light directed to an image dissector. Thus occultation measurements can be made simultaneously at 7500 and 3200 Ångstroms, or in a single bandpass through any of the other filter/aperture combinations.

The polarimetric dissector is located only 4 minutes off axis and the light proceeds directly to the cathode after passing through the focal plane filter/aperture assembly. Four ultraviolet filters are provided, each with four strips of 3M Polacoat rotated 45° from strip to strip. The apertures are 1.0 arc sec in diameter with two apertures for each filter/polarizer combination.

Electronics

A full description of the electronics is beyond the scope of this paper. We concentrate here on those aspects relevant to the performance of the instrument and its comparison to other ground-based instruments.

The high voltage power supplies are programmable in approximately four volt increments from 1500 to 2500 volts for each of the detectors. Preamplifiers, located near their respective detectors, provide a voltage gain of 7. The preamplifier output is received by pulse amplifier/discriminators with programmable threshold settings, allowing optimization of the signal-to-noise ratio for any high voltage setting. All of the detectors can be operated in either the pulse counting or current mode. In the pulse counting mode the integration times can be as short as 10 microseconds and are commandable in 1 microsecond steps up to about 16 seconds. Similarly each integration can be separated from the previous by a delay of from zero to 16 seconds. The pulse pair resolution of the amplifiers is about 50 nsec, enabling count rates of up to 2×10^5 Hz to be accommodated with dead time corrections of less than one percent. In the analog mode a current-to-voltage converter measures detector current over a range of 1 nA to 10 μA full scale in 5 gain settings. For each gain setting the amplifier output is digitized to 12 bits. The shortest observation times range from 4 milliseconds in the 1nA range to 0.4 milliseconds in the 10 μA range.

Initially the absolute time of observations will only be known to within 10 milliseconds, limited by the specifications on the HST spacecraft clock. However it is hoped that observations of "standard" sources such as the Crab Pulsar will allow better calibration of clock errors and substantially improved timing after some experience in orbit.

IV. Operations and Projected Performance

For objects with well known coordinates (or re-visits) the HST can be commanded to place the object in the desired filter/aperture combination. Acquisition of objects with less certain coordinates (or those in complex fields) begins by commanding the telescope to place the object in one of the 10 arcsec acquisition apertures. A 20x20 pixel scan is then carried out with the dissector to provide an acquisition image. On-board software can determine the centroid of the object (including logic to specify the n^{th} brightest object) and compute the offset necessary to place it in the aperture of choice. For more complex fields the acquisition image can be sent to the ground where the observer can determine the object location and then have software compute and uplink the necessary offset.

With multiple apertures associated with each filter, background ("sky") measurements can be easily interleaved with object measurements; the dissector is simply commanded to step between the object and a corresponding aperture on the same filter strip between integrations. However, since the telescope must be moved to change filters, multi-filter observations involve a delay of 30 (if the filters on the same dissector) to 60 (if the filters are on different dissectors) seconds between observations in different filters. To allow high time resolution measurements at widely separated wavelengths, three pairs of filters have been linked with beam-splitting prisms. These provide two pairs in the ultraviolet separated by approximately 1200 Ångstroms, and one pair on the bialkali tube that spans from below the atmospheric cutoff to 5500 Ångstroms. The filter pair for occultations can, of course, also be used for high time resolution observations.

Radiometric calibration of the HSP will be accomplished through observations of stars with known spectral energy distributions. Figure 3 has been adopted from the High Speed Photometer Instrument Handbook and gives estimated integration times necessary to reach a signal-to-noise ratio of 100 for a m_V=15 source as a function of source temperature for a subset of filters. The throughput of the entire HST-HSP system has been taken into account in this calculation.

Final figures on both systematic and random error sources will have to await on-orbit experience. However the photometer has been designed to minimize both types of error sources and hopefully both will contribute at a level less than 0.1% of the signal. Such performance will provide an excellent photometric capability for the Hubble

Space Telescope, both for the scientific programs of the Investigation Definition Team and for those of the many General Observers using the instrument for years after launch.

Acknowledgements

In preparing this paper, the author has relied heavily on (and borrowed liberally from) material presented by Bless [1982], White [1985], and material in the observing proposals of members of the IDT. Their contributions are gratefully acknowledged.

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G. W. Van Citters, Jr. : Division of Astronomical Sciences, National Science Foundation, Washington, D. C. 20550

R. C. Bless : Washburn Observatory, University of Wisconsin, 475 N. Charter St., Madison, WI 53706

J. F. Dolan : NASA/Goddard Space Flight Center, Code 681, Greenbelt, MD 20771

J. L. Elliot : Dept. of Phys. & Earth and Planetary Sci., MIT, Bldg. 54-422A, Cambridge, MA 02139

E. L Robinson : Department of Astronomy, University of Texas at Austin, Austin, TX 78712

R. L. White : Space Telescope Science Institute, Homewood Campus, Baltimore, MD 21218

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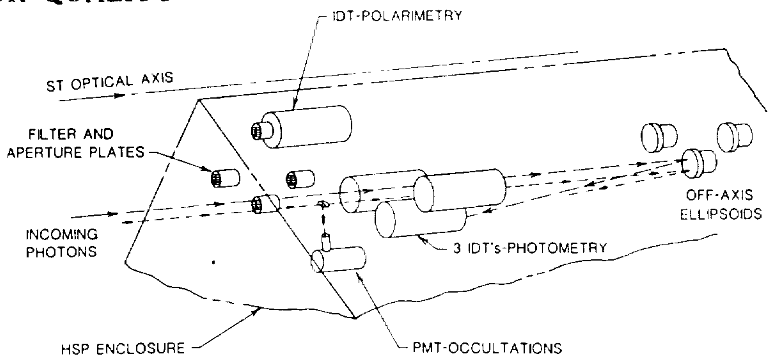

Figure 1. Schematic Diagram of HSP Optics and Detectors (Figure courtesy of Space Telescope Science Institute)

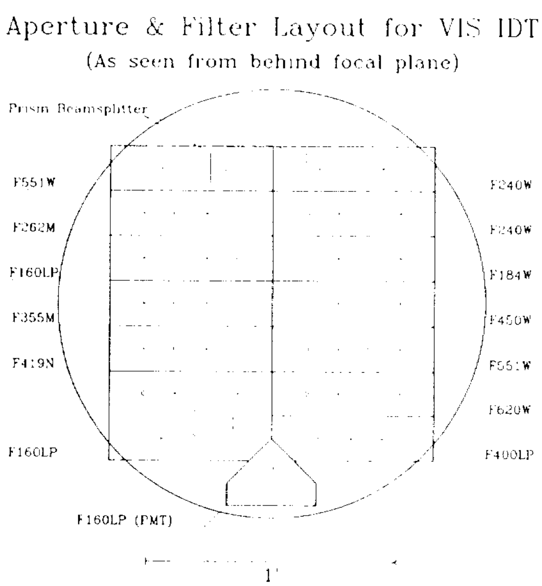

Figure 2. Visible Wavelength Image Dissector Apertures and Filters (Figure courtesy of Space Telescope Science Institute)

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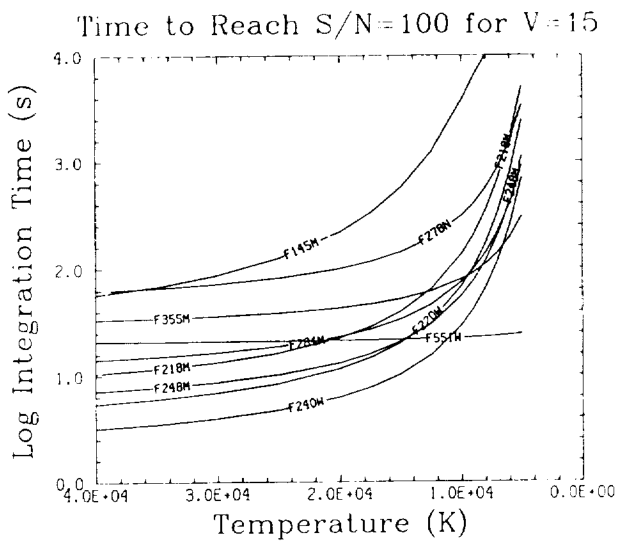

Figure 3. **Time to Reach V=15 with S/N=100 for various filters (Figure courtesy of Space Telescope Science Institute)**