X-610-64-188

TM X-55079

AN ULTRAVIOLET SPECTROPHOTOMETER FOR SATELLITE ASTRONOMY

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JULY 1964

NASA

GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

Presented at the ICO Conference on Photographic and Spectroscopic Optics, Tokyo, Japan, September 1 - 8, 1964

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ABSTRACT

An astronomical spectrophotometer is described which was designed for use on OSO-B, the second U.S. Orbiting Solar Observatory. The spectrophotometer is intended to analyze the ultraviolet emission from stars and nebulae. The entrance slit of the spectrophotometer defines the field at the primary focus of a 6-inch Gregorian reflecting telescope. The secondary serves as the collimator for a rotating 1200 lines/mm plane reflection grating. Diffracted light from the grating is collected by an off-axis parabaloid and focused through the exit slit to the photomultiplier. The signal from the photomultiplier is pulse-counted and fed into the magnetic tape storage of the space-craft. The instrument utilizes the spin of the gyroscopically-stabilized satellite to sweep the 1° x 0.4° field over the celestial sphere. Slow precession of the spin axis allows eventual coverage of the whole sky. Ten adjacent wavelength bands of 180 Å width between 1500 Å and 3300 Å are defined by succesive steps of the grating.

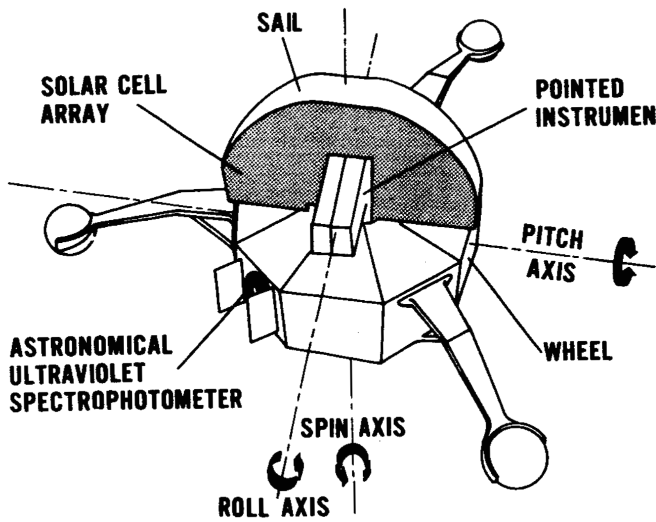
An input flux of 4×10^{-9} erg/sec. cm^2 Å or over results in a statistical error in the output of 2%, while a flux 8×10^{-11} erg/sec. cm^2 Å may be determined within 10% mean error. This sensitivity will permit useful observations of stars 5 stellar magnitudes fainter then the brightest ones. Details of the optical system and special requirements imposed upon it by characteristics of its special environment are reviewed.

INTRODUCTION

An astronomical spectrophotometer is described which is designed to gather comprehensive data on the ultraviolet radiation from the brighter stars and nebulae. The experiment is constructed for use in a wheel compartment aboard the Orbiting Solar Observatory B spacecraft. Precession of the satellite spin axis about the solar vector combined with the earth's movement with respect to the sun are utilized in obtaining nearly full sky coverage of both the northern and southern hempisphere. Spectral scanning is accomplished by the incremental movement of 1200 line/mm original plane reflection grating blazed for 2000A. Its spatial resolution of $1^\circ.00 \times 0^\circ.44$ is preserved by sequencing the spectrophotometer output to an azimuth sensor. Viewing of scattered solar irradiance from the Earths upper atmosphere necessitated the incorporation of an albedo sensing system into the experiment to minimize residual saturation effects in the spectrophotometer detector.

SPACECRAFT

The Orbiting Solar Observatory B as shown in Figure 1 consists of a pointed experiment compartment, a solar array and a rotating wheel section. In orbit, the oriented experiment compartment is aligned parallel to the solar vector and the solar array is kept nearly perpendicular to the solar vector by sun sensors and the control system. The spin axis



ORBITING SOLAR OBSERVATORY B

Figure 1

of the satellite is nominally perpendicular to the solar vector throughout the useful lifetime of the spacecraft. This perpendicular relationship is maintained within ±3.5 degrees by means of the control system. However, the spacecraft is not controlled in roll about the solar vector and will precess approximately one degree in 24 hours. This precession will cause the spin axis to sweep an arc through approximately one half of the celestial sphere during the course of the six months satellite lifetime. Similary the plane in which the wheel rotates will sweep over the entire celestial sphere. By mounting the spectrophotometer in the wheel plane, it may therefore cover both the northern and southern hemisphere with high positional accuracy.

The spinning wheel section, which provides gyroscopic stability to the spacecraft, is divided into nine compartments. Five compartments house experiments and the other four contain telemetry, control and command systems.

SPECTROPHOTOMETER

Unlike a laboratory instrument, one must work backwards, by first determining the constraints placed on the spectrophotometer design by the spacecraft and the spacecraft environment. The high rotational rate (30 rps) of the wheel indicates that observations should be made looking parallel to the spin axis to gain sufficient time for accurate measurement of the flux gathered by the instrumental optics. Although this is quite possible, analysis of the satellite motion indicates that only an extremely limited region of the sky would be observed and it appears improbable even to optimize the viewing path through the Galaxy. Therefore, we have mounted the spectrophotometer to look along a radius of the wheel, but with a depression angle of 5° simply to prevent direct viewing of the sun.

The field angle is precisely defined by a slit located at the focus of the paraboloidal objective of a Gregorian type telescope as illustrated in figure 2. The opposed secondary is also a paraboloid, and becomes the collimator for the spectrophotometer. A major draw back of this system is that the field angle is magnified by the secondary or

ASTRONOMICAL ULTRAVIOLET SPECTROPHOTOMETER

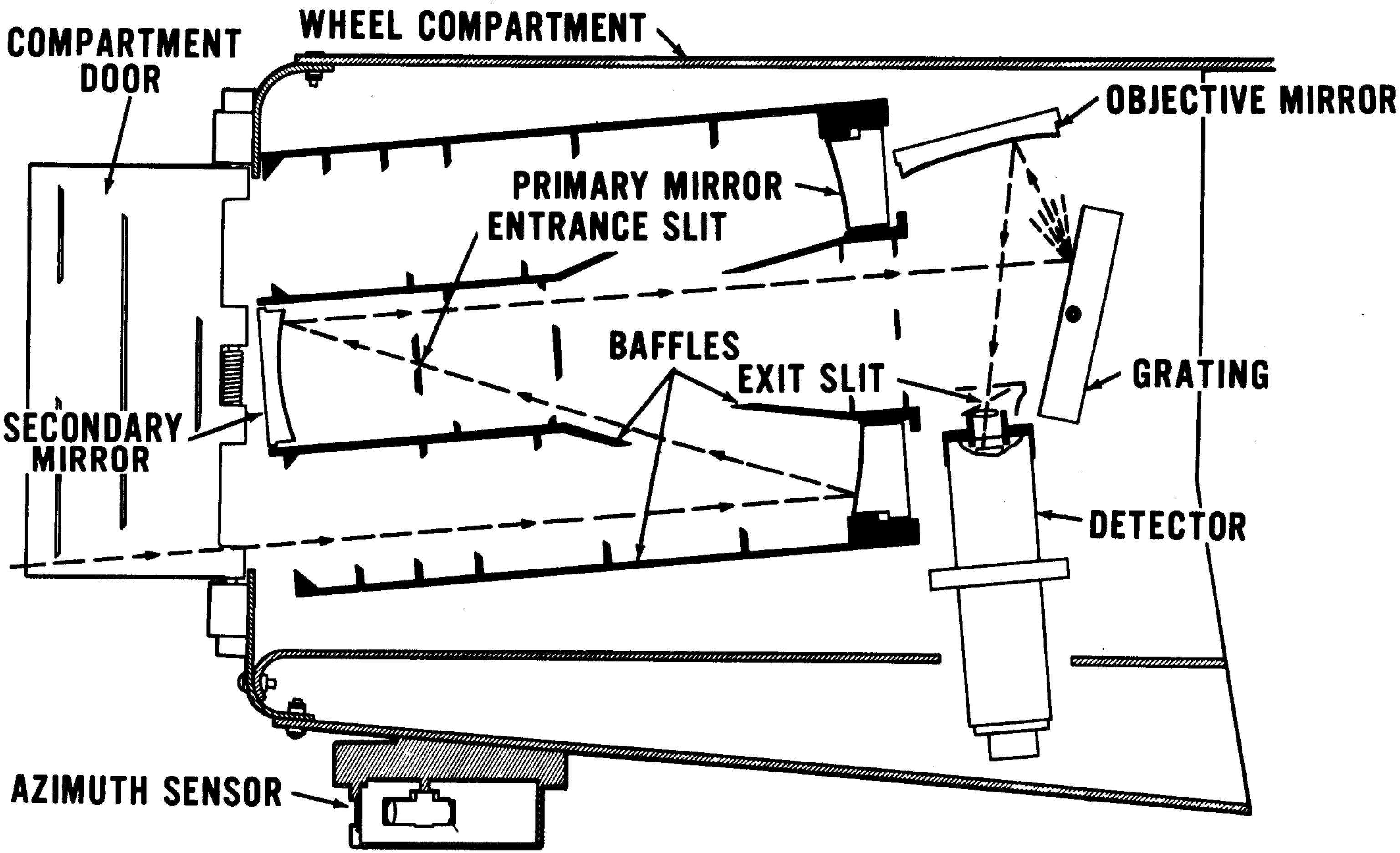


Figure 2

collimating mirror. As the field angle is increased the angular dispersion of the monochromator must be increased to maintain a constant spectral resolution. The diameter of the secondary mirror must also be sufficient to prevent vignetting of the field, even though this decreases the free area of the primary mirror. Because of these factors, the diameter of the collimated beam from the secondary that passes through the central hole in the primary is nearly independent of the focal length of the secondary.

An overall light rejection ratio on the order of 10^{-8} to 10^{-11} must be achieved to protect the sensitivity of the instrument to starlight while bathed in sunlight. Doors on the spacecraft rim panel increase the baffling length to the entrance pupil at the primary mirror, thus allowing useful operation closer to the sun. The incident solar radiation, which is reduced by diffuse scattering from baffles painted with Parson's Optical Black Laquer, must incur at least two reflections before passing through the hole in the primary mirror.

The primary mirror maximum diameter is limited to six inches due to tipping of the optical axis and restricted mounting space. To minimize obscuration of the primary mirror by the secondary mirror and for optimization in packaging the objective, the design ratio of their focals lengths is weighted against the effective area and focal ratio of the primary mirror.

The optimal azimuth field angle θ and elevation field angle φ are largely determined by the spacecraft rotational and orbital motion. The satellite performs about 15 orbits per day or on the order of 29000 usable spacecraft rotations per day. To prevent gaps in scanning succesive 180° azimuthal arcs of the celestial sphere as they are shifted due to the daily precession of the spin axis, one is left with 80 looks per degree of azimuth. The 80 looks per degree are then subdivided into X looks per spectral bandpass $\Delta\lambda$ for each of Y adjacent bandpasses. X, Y, $\Delta\lambda$, θ, and φ are then chosen by the expected sensitivity of the total spectrophotometric system, by the anticipated flux and spectal energy distribution of stellar sources, by their average separation on the plane of the sky, and by the characteristics of the OSO data handling system.

Several factors must be considered in the monochromator design. The dispersive element, collecting mirror and detector must be packaged behind the Gregorian objective. The entrance slit must be wide enough to assure field overlap from one scanned band in the sky to the next precessed one, and the angular magnification due to the monochromator collimator must be limited to permit sufficient linear dispersion across the exit slit without spectral overlap.

At present, original reflection diffraction gratings are the most reliable spectral resolvers in space applications. Hass[1] has shown that the reflectivity of ultraviolet coatings changes less than 1% when irradiated by 1 MEV electrons and 5 MEV protons. In addition, Hass had made coatings with a reflectivity of 85% at 1400 Å. Gratings blazed in this wavelength region are available with ultraviolet coatings. An original grating was selected for use because at this time data concerning the deterioration of the more efficient replica gratings in high vacuum is inconclusive.[2]

The working angle of the grating was chosen to maximize the spectral purity. Because of the compactness of the dispersing system, second order spectra must be rejected by meticulous baffling as shown in figure 2.

An off-axis f/.65 paraboloidal collector mirror with a focal length of 9.6 cm is used to obtain a linear dispersion of 64 Å/mm. Ten adjacent bandpasses 180 Å wide are scanned from 1498 Å to 3298 Å without second order overlap. This should be sufficient resolution, to study nebular emission sources in primary spectral detail, as predicted by Daub[3] and Osterbrock[4]. With a resolution of $\frac{\lambda}{\Delta\lambda} = 10$, a bandpass of 180 Å separates many of the anticipated lines except for doublet structure.

An Ascop 541 photomultiplier tube with a cesium telluride photocathode on a sapphire window was selected as the detector because of its combined ruggedness and spectral sensitivity. The tube has a gain of 17 x 10^6 at 2750 volts, and a peak quantum efficiency of about 10% at 2500 Å. Photocathode non-uniforunity is decoupled from variations of source brightness within the field by use of a calcium fluoride field lens behind the exit slit to image the primary mirror onto the photocathode. This lens also prevents vignetting by the photocathode and gains clearance between the grating and photomultiplier.

The output of the photomultiplier tube is gated into the photo-pulse counter by an azimuth phase sensor which consists of a very small auxilliary telescope mounted on and perpendicular to a rotating shaft below the spacecraft heat shield. This azimuth shaft, which is parallel to the spacecraft spin axis, is rotated back and forth about its' own axis through an arc of 180 degrees, in one degree increments, by a Bendix stepping motor. The telescope has a 1.2 cm diameter entrance aperture and a 2.6 cm focal length. The 0.5° wide slit located in the telescope focal plane is mounted with its edges parallel to the rotating shaft. A Texas Instrument photoconductive silicon diode senses a solar image scanning across the telescope slit each rotation of the spacecraft. This signal is used to gate the output pulses of the spectrophotometer photomultiplier into a counter for the image scan duration of 5.5 milliseconds. Then the rotary positions of the Bendix indexing head, which has a repeatable positional accuracy of ±5 arc-minutes, and of the diffraction grating are read out. After 80 rotations of the satellite, the azimuth shaft rotates one degree, and on the next 80 rotations, the adjacent 1°.0 x 0°.44 element of the sky will be observed. This scanning mode permits 8 looks per degree of azimuth for each of the ten adjacent bandpasses of the spectrophotometer. More than one look is required to build statistical accuracy of the data.

With a primary mirror area of 128 cm^2, the above scan rate results in a statistical error in the output of 2% for an input flux at 2537 Å of 4×10^{-9} erg/sec-cm^2-Å. A flux of 8×10^{-11} erg/sec-cm^2-Å may be determined with a 10% error, making a dynamic range useful in the observations of stars 5 stellar magnitudes fainter than the brighter ones.

It was found that repetitive pulses of ultraviolet radiation, of about the same spectral intensity as predicted by Green[5] for the Earth's albedo, saturated the photomultiplier tube causing a cumulative increase in the dark current level. Recovery times to dark current levels which were much longer than one rotational period of the satellite were most effectively reduced by reversing the bias between the photocathode and first dynode.

Sensing of the Earth's albedo is accomplished by employing a telescope optically identical to that used in the azimuth sensor. The telescope slit was rotated so that an 8° field is viewed in a plane parallel to the azimuth plane of the spectrophotometer. Before the spectrophotometer is to view excessive albedo flux levels, a sensing circuit attached to the albedo telescope reverses the first stage bias for the scanning period. This technique is adequate to preserve the sensitivity of the experiment more than 95% of the time.

The gate width and/or photomultiplier gain may be checked in orbit by Cerenkov radiation induced in the field lens and photomultiplier window by a 5 microcurie strontum 90 source. This source is located on a lever arm which upon command pivots in front of the exit slit.

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