J. Richards of GSFC, J. Westberg of CSC, J. Huntington, J. Stafurik, and B. Powell of CSTA, B. Kennedy and J. Maurer of the University of Michigan, and V. Geraci of the General Electric Company.

REFERENCES

[1] H. B. Niemann, R. E. Hartle, W. T. Kasprzak, N. W. Spencer, D. M. Hunten, and G. R. Carignan, "Venus upper atmosphere neutral composition: Preliminary results from the Pioneer Venus Orbiter," *Science*, vol. 203, p. 770, 1979.

[2] H. B. Niemann, R. E. Hartle, A. E. Hedin, W. T. Kasprzak, N. W. Spencer, D. M. Hunten, and G. R. Carignan, "Venus upper atmosphere neutral gas composition: First observations of the diurnal variations," *Science*, vol. 205, p. 54, 1979.

[3] A. O. Nier, W. E. Potter, D. R. Hickman, and K. Mauersberger, "The open-source neutral-mass spectrometer on Atmosphere Explorer-C, -D, and -E," *Rad. Sci.*, vol. 8, no. 4, Apr. 1973.

[4] David T. Pelz, Carl A. Reber, Alan E. Hedin, and George R. Carignan, "A neutral-atmosphere composition experiment for the Atmosphere Explorer-C, -D, and -E," *Rad. Sci.*, vol. 8, no. 4, Apr. 1973.

[5] N. W. Spencer, H. B. Niemann, and G. R. Carignan, "The neutral-atmosphere temperature instrument," *Rad. Sci.*, vol. 8, no. 4, Apr. 1973.

Design and Operation of the Pioneer Venus Orbiter Ultraviolet Spectrometer

A. I. F. STEWART

Abstract—**The University of Colorado's Ultraviolet Spectrometer instrument carried on the Pioneer Venus Orbiter spacecraft is a 125 mm *f*/5 Ebert-Fastie design with a 250-mm Cassegrainian telescope. The instrument has extensive logic to control the grating motor drive and to adapt the basic spectrometer to the constraints and opportunities of the mission. Success has been achieved in reconciling the conflicting requirements of spectroscopic, limb profile, and imaging observations. A description of the instrument operating techniques is given together with representative results of all three types.**

I. INTRODUCTION

THE Pioneer Venus Orbiter Ultraviolet Spectrometer (PV OUVS) instrument was designed, fabricated, tested, and calibrated at the University of Colorado's Laboratory for Atmospheric and Space Physics (LASP). LASP has been actively involved in the study of the atmospheres of the earth and the planets from space since the mid-sixties. Predecessors of the Pioneer Venus instrument include the ultraviolet photometers on OGO-6 and Mariner 5, the ultraviolet spectrometers on OGO-4 and Mariners 6, 7, and 9, and the ultraviolet nitric-oxide experiments on Atmosphere Explorers 3 and 4 [1].

The Pioneer Venus concept of a fully instrumented low-cost mission offered unique challenges and opportunities in instrument design and operation. The primary challenges were: to produce an instrument weighing a few pounds, compared to the 35 lb of its Mariner predecessors; to solve the problems of obtaining spectral and airglow limb profile data from a spinning spacecraft, while taking advantage of the opportunity for systematic imaging offered by the same spinning platform; and to make optimum use of a very restricted data rate (the data rate assigned to the mariner instruments was higher than that for the entire Pioneer Venus payload of 12 instruments). The outstanding opportunity was to study a planet from all ranges between 66 000 km, far outside its tenuous corona of atomic hydrogen, and 140 km, inside the fringes of the atmosphere itself, and to do so continually for at least eight months, at all local times and through the increasing phase of solar activity.

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II. INSTRUMENT DESCRIPTION

As can be seen from Fig. 1, the OUVS is of modular design. The instrument is built around the monochromator box, which houses the Ebert mirror, the diffraction grating, the grating drive and associated electronics. In front of the monochromator entrance slit is mounted the telescope assembly with its sunshade; a small limb sensor is mounted in the sunshade. Beside the telescope and in front of the exit slits is the detector module, containing the low and high-voltage power supplies, two photomultiplier tubes, and their associated pulse amplifier and discriminator units. On top of these three modules is the logic box, whose five printed circuit boards contain the spacecraft interface units; the command decoding logic; the pulse counters, word compressors, and data buffer used to process the detector outputs; and the instrument status logic. The monochromator module is attached to the spacecraft via a mounting wedge, at the back of which is found the connectors to the spacecraft wiring harness. The instrument look outwards through a gap in the solar panel skirts and the thermal blanket is attached to the top of the

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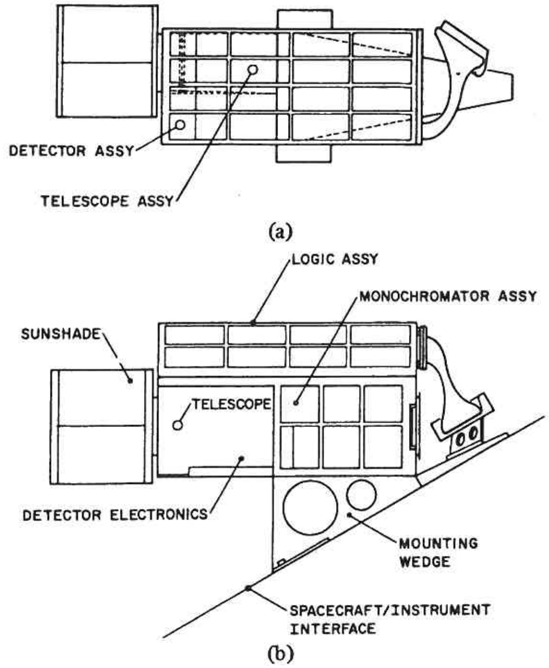

Fig. 1. Layout diagram of the OUVS, showing the modular construction and the mounting wedge.

sunshade. Some instrument characteristics are given in Table I, and a block diagram is shown in Fig. 2.

A. Optics

Light enters the instrument through a 250-mm $f/5$ Cassegrainian telescope, heavily baffled against scattered off-axis light and protected by a cylindrical sunshade. The sunshade has one internal baffle and is lined with a honeycomb material. The telescope focuses light from the planet on the 6 mm by 0.6-mm entrance slit of the monochromator, giving a $1.4° \times 0.14°$ field of view. The monochromator is an Ebert-Fastie design of 125-mm focallength, using a 1-in diffraction grating ruled at 3600 grooves/mm, giving a dispersion of 22 Å/mm in first order at the exit slit plane. The grating is blazed at 1300 Å. Two exit slits of the same size as the entrance slit are used; the spectral resolution is thus 13 Å. All the reflecting surfaces in the optical train are coated with magnesium fluoride, and all scattering surfaces are painted black.

B. Grating Drive

The diffraction grating is rotated on its axis by a step motor, controlled by an optical device using the moire fringes generated by two offset radially ruled gratings. The motor moves the grating through 27° in 512 equal steps of 0.0525°; this step size corresponds to 4.4 Å and the wavelength range at each exit slit is about 2300 Å. The motor may be operated in a scan-and-flyback mode or in a mode in which it steps to a commanded position and holds there.

C. Detectors

The exit slits of the monochromator open directly on to the windows of two EMR miniature photomultiplier tubes. The 510G-09 tube has a cesium-iodide cathode and a lithium-fluoride window; it is sensitive from 1100 to 1800 Å. The

TABLE I
PIONEER VENUS ORBITER ULTRAVIOLET SPECTROMETER

Dimensions:	
Without Sunshade	9.9 x 4.3 x 5.4 in
Sunshade	4.3 x 4.3 in cylindrical
Weight:	
Without Mounting Wedge	6.0 lb.
Power Consumption:	
Average	1.7 watts
Peak	1.9 watts

510F-06 tube has a cesium-telluride cathode and a fused silica window, and is sensitive from 1600 to 3300 Å. This tube was modified to accept a commandable back-bias voltage on the first two anodes reducing the gain by a factor of 32. Each tube has its own pulse amplifier and discriminator unit; the detector trains were found to have 10-percent nonlinearity at about 0.3 MHz.

D. Electronics

The pulses from the detectors enter a 15-bit counter with integration periods of 4, 8, 16, or 32 ms. (A second 4-ms counter is used as part of the F-tube gain control device.) The data word thus formed is compressed by shifting it until the leading bit reaches position 15; a new 8-bit words is then formed consisting of the next 4 bits plus four bits indicating the number of shifts. The stream of 8-bit words is stored in a 256-word buffer; once the buffer is full, no new words are generated until the spacecraft telemetry system has read out the entire buffer.

Electronic logic is provided for the decoding and execution of commands to the instrument. A single discrete command is used to activate the 256-word data buffer after the instrument is turned on; repetitions of this command are used to alternate between the two redundant grating drive control devices. Most of the instrument commanding is done using two 16-bit serial commands. These select the operating modes and parameters of the instrument, as discussed in the next section; in addition, they provide the ability to turn off the high-voltage power supplies while the rest of the instrument operates normally, and a redundant means of commanding these supplies on.

Several instrument monitors and status indicators are included in the telemetry stream. These include low- and high-voltage supply monitors; logic box and detector head temperature monitors; flags indicating the data buffer status, the active grating control unit, the active data channel (F or G tube), and the grating motor mode (fixed on scanning); and event markers reporting the operation of the F-tube gain control device and the data timing system.

Additional logic provides for such functions as the spacecraft interface; voltage regulation; and temperature compensation of devices such as the grating motor control units.

E. Calibration

The OUVS instrument response was calibrated at LASP using tungsten, deuterium, and argon "miniarc" sources derived from NBS standards. Also measured were the response of off-axis light, the nonlinearities in the detector systems, and the instrument polarization. The instrument sensitivity at

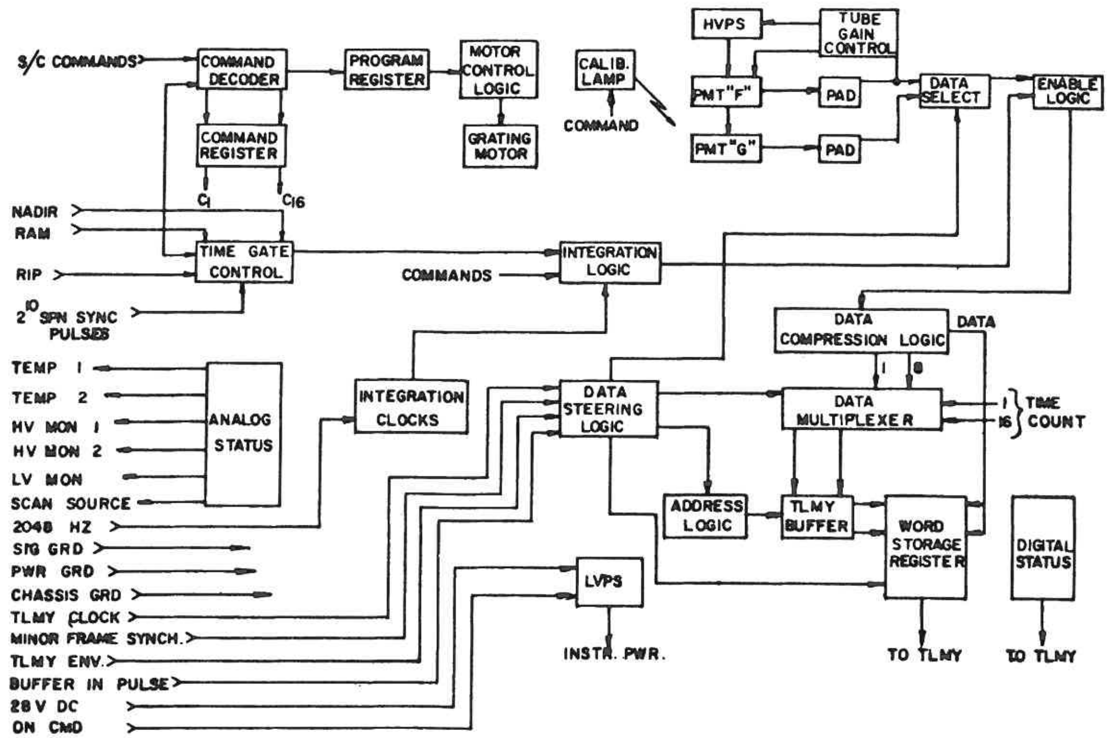

Fig. 2. OUVS electronic block diagram.

TABLE II

	G-Channel		F-Channel	
λ,Å	Sensitivity, c kR^{-1} s^{-1} bb^{-1}	λ,Å	Sensitivity, c kR^{-1} s^{-1} bb^{-1}	Polarization, %
1216	140	2000	49	--
1304	270	2300	78	17
1400	510	2600	63	31
1561	560	2900	23	37
1743	140	3200	3.1	47

several wavelengths is given in Table II, along with the percent polarization. The off-axis response dropped more than 4 decades within 1.5° and thereafter declined more slowly, at about 1 decade per 6°. The measured departures from linearity in the detector systems could be described by an effective dead-time of 300 ns.

III. Commands and Operating Modes

The specification of operating modes for the OUVS was of course heavily influenced by the spacecraft capabilities and the mission design. A data buffer was essential to reconcile the basic instrument data rates of between 2048 and 256 b/s (depending on the integration period) with the OUVS allocation in the spacecraft telemetry stream, which is typically 80 b/s (although it could be as high as 512 b/s). This low duty cycle also requires careful timing of the acquisition of a bufferload of data (a "data arc"), so that the scientific content of the data can be maximized. The acquisition of spectral data also poses a problem, since the spacecraft (and therefore the OUVS line of sight) rotates through 60° during the 2 s required for a complete spectral scan; this motion causes gross changes in the viewing and illumination geometry during the acquisition of the spectrum and renders interpretation difficult.

Data-arc timing is accomplished by accepting spatial reference pulses from the spacecraft and by providing a commandable time-delay device. The spatial reference pulses are issued when the spacecraft *X*-axis passes through the planes containing the spin axis and the velocity vector (RAM pulse), the planet-spacecraft vector (NADIR pulse), and the 270° ecliptic longitude vector (RIP pulse). The instrument limb sensor also generates pulses at the leading and trailing edges of the planet's illuminated disc. The spacecraft issues 1024 "sector pulses" per rotation, and the time delay is accomplished by counting a commanded number of these pulses after receipt of the selected spatial reference pulse, before beginning to load data words into the buffer. The length of the "data arc" is determined by the integration period; at 4 ms the buffer fills in 1 s, or 30° of spacecraft rotation; while at 32 ms it takes 8 s or 240°.

The size of the data buffer means that spectra are acquired in two halves, with an interval between the halves for the telemetry system to read out the buffer. The problems caused by the variation in line-of-sight during the data acquisition are minimized by taking spectra only when the spacecraft is near periapsis, so that the disc subtends much more than 30° at the instrument; and by using the NADIR pulse to begin the data arc 15° before the line-of-sight crosses the nadir plane (the arc then ends 15° beyond this plane). This procedure reduces the variations in lighting and viewing angles during the acquisition of the spectrum.

The complete list of commandable instrument functions and parameters, in addition to those mentioned in the previous section, is as follows: grating motor mode (scan or fixed-position); data channel select (*F*-tube or *G*-tube); spatial pulse

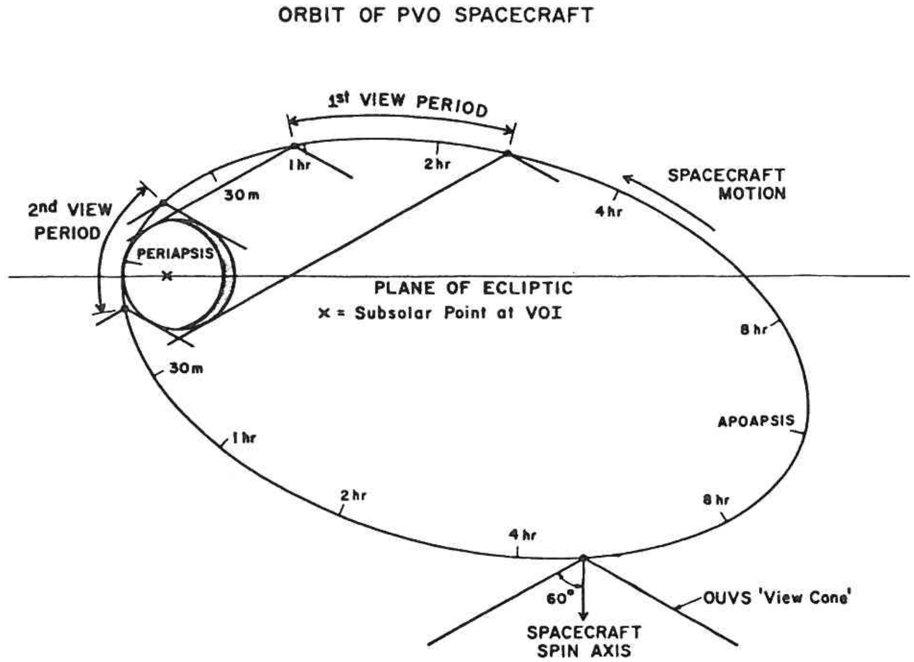

Fig. 3. The PV orbit around Venus and the OUVS line-of-sight geometry, showing the approximate OUVS view periods.

select (RAM, NADIR, RIP, +Limb, or -Limb); grating motor position (0-511); calibration lamp mode (on or off); data timing delay (0-1023 pulses); integration period select (4, 8, 16, or 32 ms); and a buffer override select which causes fresh data to be acquired on each spacecraft spin, whether or not the telemetry system has emptied the buffer.

These commands are used to configure and control the instrument in five operating modes, as follows:

F. Cold-Start Mode

This is achieved simply by applying power to the instrument, and it does not use the command capability nor the data buffer. Words are supplied to the telemetry system on demand; after each word, the grating motor advances one step. The data channel is changed at each flyback.

G. Discrete Spectral Mode

This is achieved from Cold-Start by sending the discrete command. The buffer is used to acquire and read out spectra; the data arcs start upon receipt of the NADIR pulse.

H. Lyman-Alpha Mode

This is achieved from Cold-Start by sending the two serial commands. The data buffer is not used; words are supplied on demand. The timing portions of the serial commands are ignored, and the mode is intended for use with the grating motor in its fixed-position mode.

I. Spectral and Wavelength Modes

These are the primary operating modes of the instrument. The spectral mode is similar to the discrete spectral mode except that the data-arc timing can be commanded and the data channel is selected by command, instead of alternating at each flyback. The wavelength mode uses the grating motor in its fixed-position mode, and the data channel, integration period, and data-arc timing are all commandable. These modes are achieved from Cold-Start by sending the discrete command and the two serial commands. Once the instrument is configured, individual parameters can be reset by the appropriate command; a complete reconfiguration is not necessary.

IV. Observations and Sample Results

In orbit around Venus, the spacecraft spin rate is 5 rev/min with the spin axis pointed nominally at the south ecliptic pole. The orbit is highly eccentric ($e = 0.843$); periapsis and apoapsis altitudes are approximately 150 km and 66 000 km, and the latitude of periapsis is 18°. The inclination is 105°. The OUVS line-of-sight is offset 60° from the spin axis (this angle was chosen to be as large as possible consistent with the sunshade providing adequate protection for the detectors), and the planet is in view for two periods (Fig. 3): the first, from P - 125 min (i.e., 125 min before periapsis) to P - 35 min is used for global imaging, since the planet subtends less than 40°, while the second, from P - 15 min to P + 10 min, is used for high-resolution mapping, spectral work, and limb profile measurements, i.e., those observations that must be made at close range. When the planet is not in view, the atomic hydrogen corona can be observed from P - 5 h to P + 1 h, and outside this period, stars and interplanetary hydrogen can be observed around the small circle at 30° south ecliptic latitude.

A. Spectral Data

Although the spinning spacecraft renders quantitative spectroscopy somewhat difficult, the OUVS has had two outstanding spectroscopic successes: the detection and measurement of absorption features due to sulfur dioxide in the spectrum of sunlight reflected from the Venusian cloud layer [2], and the measurement of the recombination emission spectrum of nitric

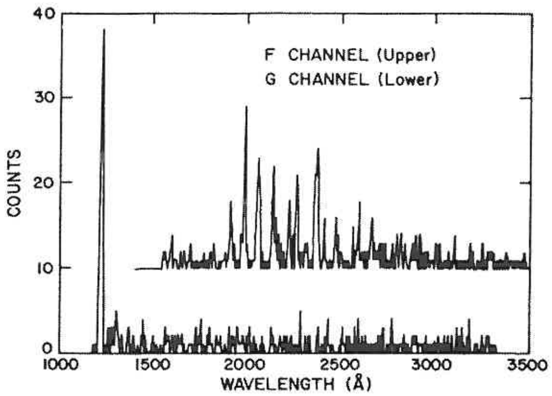

Fig. 4. Sum of 96 raw spectra of the night airglow of Venus, in the two data channels. The F spectrum is displaced upwards for clarity.

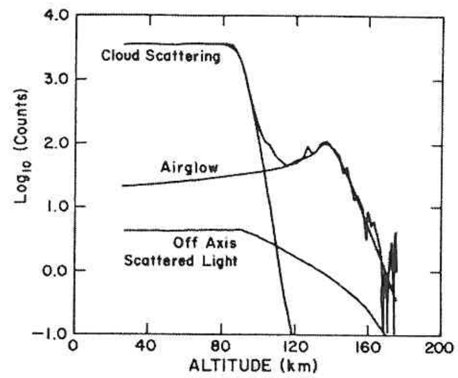

Fig. 5. Limb intensity profile of the (0, 1) Cameron band of CO. Smooth curves show the best-fit contributions from Rayleigh scattering, off-axis scattered light, and the airglow itself.

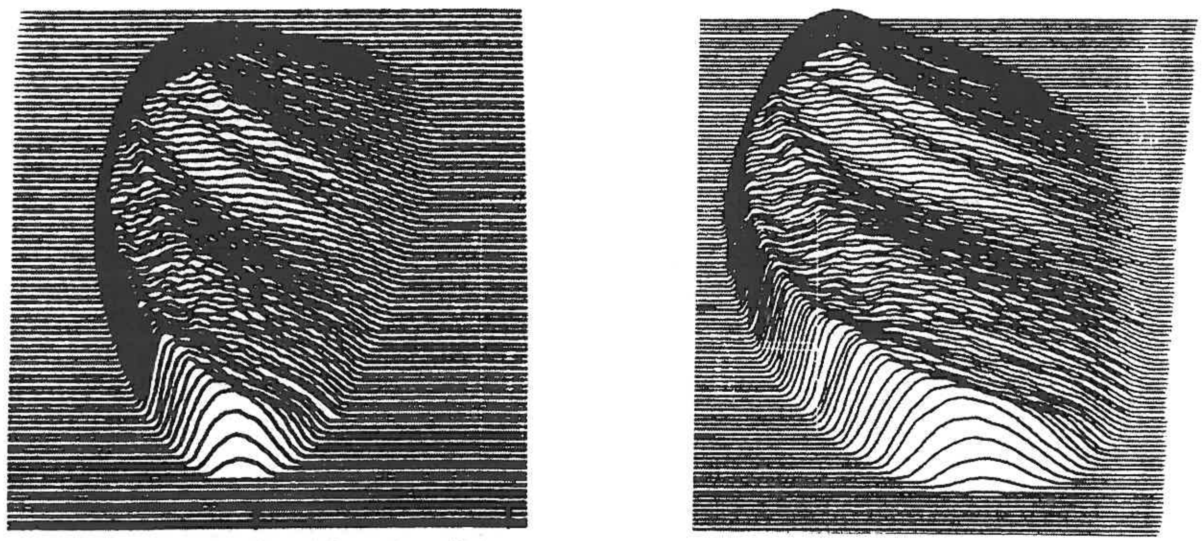

Fig. 6. Unrectified (left) and rectified (right) "three-dimensional" images of the gibbous disk of Venus, at 2068 Å.

oxide on the night side of the planet [3]. Careful analysis of the SO_2 spectrum showed that the SO_2 is transported upwards through the clouds and is rapidly destroyed (by oxidation and hydration to sulfuric acid) upon entering the photochemically active region at the cloud-tops [4]. The night-side NO spectrum is produced by the recombination of atoms of N and O, which are carried over from the sunlit side by the circulation of the upper atmosphere; the emission provides a tracer of this circulation. Fig. 4 shows the sum of about 100 raw night-side spectra in the two channels. The upper spectrum (F-channel) shows the emissions of NO beginning at 1908 Å. The lower spectrum (G-channel) does not, because the photomultiplier is insensitive beyond 1800 Å; only the Lyman-alpha emission of atomic hydrogen at 1216 Å is significantly above the noise. The dark-count level in both channels is about 4 s^{-1}. The dynamic range of the instrument is illustrated by the successful acquisition of spectra on both the night side, at count rates of 0.02-0.4 $(4\ ms)^{-1}$, and the day side, at count rates of 100-4000 $(4\ ms)^{-1}$.

B. Limb Profile Data

Measurements of the limb intensity profiles of selected day-side airglow emission yield information on the temperature and composition of the upper atmosphere and on the intensity of the solar ionizing radiation. The rectangular OUVS field of view (1.4° × 0.14°) is parallel to the limb only when the viewed limb is near the equator: fortunately periapsis is also close to the equator, and altitude resolution adequate for limb profile measurements is obtained from about $P - 2$ min to about $P + 4$ min. Fig. 5 shows a typical profile, taken at 2160 Å. The airglow feature is the (0,1) Cameron band of carbon monoxide. Also contributing to the profile below 90 km are Rayleigh scattering from the lower atmosphere and Mie scattering from the aerosols of the cloud deck; and at all altitudes there is a scattered-light contribution from the bright disk of the planet. This contribution was evaluated using observations from around $P - 90$ min, when the line-of-sight also crossed the planet's limb near the equator but from a much greater range, so that the limb appeared sharp and the airglow contribution was negligible. The smooth curves in Fig. 5 show the three contributions to the signal. The altitude resolution is about 5 km.

C. Imaging Data

The spinning of the spacecraft combined with the motion along its orbit allows the optical instruments to obtain spin-scan images of the planet. In the case of OUVS this is possible at all wavelengths between 3300 and 1200 Å, and the technique has been used to image the cloud-deck itself, the day and night airglow emissions and the atomic hydrogen corona. The raw images are highly distorted, due to several factors, including the changing range, the changing velocity, and the motion along the inclined orbit during the 90-min imaging period. A simple rectification algorithm is used: effectively, each scan of the disk is projected on to a cylinder which passes through the center of the planet and whose axis is the spacecraft spin axis, the cylinder is then rolled flat to produce the rectified image. Fig. 6 shows "three-dimensional" plots of the unrectified and rectified versions of an image of the gibbous sunlit disk at 2068 Å. The planet appears tilted 30° towards the viewer, and the upper and right-hand edges of the image are formed by the terminator. The large (1.4°) north-south component of the field of view precludes high-resolution imaging; hence the main value of these OUVS images lies in the comparison of images acquired simultaneously at two or three wavelengths by cycling the grating motor through a sequence of positions every few minutes. Such comparisons have shown that the bright and dark markings seen in Fig. 6 occur at all wavelengths above 2000 Å, but that the contrasts are greater at wavelengths where SO_2 absorbs. Thus SO_2 is associated with the dark markings, probably because they represent thinnings in an overlying cloud layer and allow the instrument to see to lower altitudes where SO_2 is more abundant.

Acknowledgment

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References

[1] C. A. Barth and E. F. Mackey, "OGO-4 ultraviolet airglow spectrometer," *IEEE Trans. Geosci. Electron.*, vol. GE-7, pp. 114-119, 1969.
J. B. Pearce, K. A. Gause, E. F. Mackey, K. K. Kelly, W. G. Fastie, and C. A. Barth, "Mariner 6 and 7 ultraviolet spectrometers," *Appl. Opt.*, vol. 10, pp. 805-812, 1971.
C. W. Hord, C. A. Barth, and J. B. Pearce, "Ultraviolet spectroscopy experiment for Mariner Mars 1971," *Icarus*, vol. 12, pp. 63-77, 1970.
C. A. Barth, D. W. Rusch, and A. I. Stewart, "The UV nitric oxide experiment for Atmosphere Explorer," *Radio Sci.*, vol. 8, pp. 379-386, 1973.

[2] A. I. Stewart, D. E. Anderson, Jr., L. W. Esposito, and C. A. Barth, "Ultraviolet spectroscopy of Venus: Initial results from the Pioneer Venus Orbiter," *Science*, vol. 203, pp. 777-779, 1979.

[3] A. I. Stewart and C. A. Barth, "Ultraviolet night airglow of Venus," *Science*, vol. 205, pp. 59-62, 1979.

[4] L. W. Esposito, J. R. Winick, and A. I. Stewart, "Sulfur dioxide in the Venus atmosphere: Distribution and implications," *Geophys. Res. Lett.*, vol. 6, pp. 601-604, 1979.

Radiometer for the Pioneer Venus Orbiter

J. DELDERFIELD, J. T. SCHOFIELD, AND F. W. TAYLOR

Abstract—**A review of the design and operation of a radiometer to study the upper atmosphere of Venus from the Pioneer Venus orbiter is presented.**

Introduction

On Venus, as on Earth, the state of the atmosphere is dynamic, complex and on such a range of scales that even sophisticated computer models can only forecast weather patterns approximately. Therefore, to study meteorology, an appropriate instrument aboard a planetary orbiter is required because observation of large-scale features over an extended space and time frame is then possible.

This paper describes such an instrument, known by the acronym VORTEX (Venus Orbiter Radiometric Temperature EXperiment).[1] The radiometer employs optical techniques to isolate ten wavelength intervals between 0.4 and 60 μm, chosen so that it senses thermal emission from the Cytherean atmosphere and sunlight scattered from both haze layers and the upper levels of the cloud deck. Some 800 000 soundings were recorded during Pioneer's first 72 orbits round Venus between December 5, 1978, and February 14, 1979. Each sounding consists of radiance measurements in seven of the ten available wavelength intervals. The term "sounding" is

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[1] Referenced in Pioneer project documents as Orbiter Infrared Radiometer (OIR).