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FLIGHT OF A UV SPECTROPHOTOMETER ABOARD GALILEO II, THE NASA CONVAIR 990 AIRCRAFT

Bach Sellers, et al

Panametrics, Incorporated

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by

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13. ABSTRACT

An ultraviolet interference-filter spectrophotometer (UVS) fabricated for aircraft-borne use on the DOT Climatic Impact Assessment Program (CIAP) has been successfully tested in a series of flights on the NASA Convair 990, Galileo II. UV flux data and the calculated total ozone above the flight path are reported for several of the flights. Good agreement is obtained with the total ozone as deduced by integration of an ozone sonde vertical profile obtained at Wallops Island, Virginia near the time of a CV-990 underpass. Possible advantages of use of the UVS in the NASA Global Atmospheric Sampling Program are discussed.

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FOREWORD

The UV Spectrophotometer (UVS) was originally fabricated for the DOT Climatic Impact Assessment Program for which the Project Manager was Mr. A. J. Grobecker. The Deputy Program Manager was Mr. Samuel C. Coroniti, whose guidance contributed significantly to the overall success of our work on that program, as summarized in the FINAL CIAP REPORT, PANA-UVS-7 (December 1975).

The Convair 990 flight evaluation of the UVS, as reported here, was supported by NASA-Lewis Research Center through the Office of Naval Research. Technical guidance was provided by Mr. Porter J. Perkins of LRC, Mr. Louis C. Haughney was Mission Manager for these Global Atmospheric Sampling Program (GASP) flights, and the in-flight Experimenter was Mr. Daniel C. Briehl. Their effort, and that of their associates, is sincerely appreciated.

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1. INTRODUCTION

As a result of possible environmental degradation due to the SST, the Climatic Impact Assessment Program (CIAP) was initiated under DOT sponsorship in 1970. One of the primary concerns is possible reduction of total ozone, with consequent increases in biologically important ultraviolet (UV) radiation. The results of this program have recently been reported (Ref. 1.1 and associated Monographs). It was concluded that operation of a fleet of about 30 SST's of present design would cause climatic effects smaller than (presently) minimally detectable. It was pointed out, however, that:

> "If stratospheric vehicles (including subsonic aircraft) beyond the year 1980 were to increase at a high rate, improvements over 1974 propulsion technology would be necessary to assure that emissions in the stratosphere would not cause a significant disturbance of the environment."

Additionally:

> "A continuous atmospheric monitoring and research program can further reduce remaining uncertainties, can ascertain whether the atmospheric quality is being maintained, and can minimize the cost of doing so."

One of the recommended actions as a result of the above conclusions was:

> "Develop a global monitoring system to ensure that environmental protection is being achieved. Continue research (drawing on the monitored data) to reduce the uncertainties in the present knowledge of the stratosphere and improve the methods for estimating climatic change and the biologic consequences."

The need for such a monitoring system, and the associated continuing research, is also indicated by potential ozone reductions resulting from high altitude nuclear weapons detonations (Ref. 1.2), intense solar proton events (SPE) (Ref. 1.3) and chlorofluoromethanes (Ref. 1.4). The first two of these can initiate relatively large "local" decreases of total ozone. In the case of the SPE this occurs in the polar regions, and local decreases of about 16% appear to have been observed from the Nimbus satellite BUV (backscattering UV) system during the large SPE of August 1972 (Ref. 1.5). The limited longitudinal and time coverage of the satellite system would not have allowed the type detailed study of ozone distribution following such events suggested by Crutzen et al. (Ref. 1.6) as desirable for study of the associated atmospheric chemistry.

Presently, the global ozone monitoring system is expected to consist basically of the satellite BUV system in association with the ground network of Dobson instrument stations. The satellite system, while global in nature, is limited by longitudinal resolution (~15-20°) due to the ~90 minute orbit, and Pittock (Ref. 1.7) has suggested that ". . . . estimates of the global ozone trend are seriously biased by the distribution of observing stations. . . . ", regarding the ground network.

As part of the CIAP program an extensive upper atmosphere monitoring system was developed (Ref. 1.8) based on use of the high altitude WB57F. One of the instruments included in that system was an ultraviolet spectrophotometer (UVS) developed by Panametrics, Inc. (Ref. 1.9) and flown successfully on more than 80 missions during the course of about three years of measurements. The structure of UV flux vs latitude and longitude was measured in much greater detail than had ever been possible before, and by use of the data (in the Hartley-Huggins bands) computer-based mathematical techniques were developed for deduction of the total ozone above the aircraft.

In order to provide a cost-efficient platform for continuous monitoring of the upper atmosphere, NASA has initiated the Global Atmospheric Sampling Program (GASP) (Refs. 1.10, 1.11) using commercial 747 airliners, the Galileo II (CV-990) and the U2. As presently constituted the package consists basically of in-situ monitors for atmospheric constituents. We believe that the UVS would make a useful addition to both the 747 and CV-990 instrument packages. For purposes of deducing total ozone we believe that the absolute accuracy may be better than that estimated for the BUV (~5%, Refs. 1.12, 1.13) with a repeatability of about 2% (which is not limited by the absolute accuracy of the NBS traceable UV calibration standard). For use on the 747 program it would be possible to obtain great detail on the geographical and time dependent character of the total ozone, which could serve as a basis in itself, and as augumentation for the other total ozone measurements, for determination of global time dependent variations. If placed on the CV-990 many useful experimental measurements could be made including, for example, detailed geographical and time distribution of effects due to SPE's or monitoring the flight corridors of any SST's making routine landings in the U. S.

As a consequence, it was our belief (Ref. 1.14) that the UVS should be tried on the CV-990 for possible use in the 747 package, and that is the basis for the work reported here. Thus, the UVS was slightly modified (basically the mounting) to fly on Galileo II in November-December 1975, and during this period ten successful flights were made from which UVS data were obtained. Data reduction for several flights of interest was carried out and the results are presented in Section 5.

The UVS has been described in detail in Ref. 1.9, and a summary description only is given in Section 2 to clarify the following discussion of modifications to the instrument, its installation and operation on the CV-990. Section 3 is devoted to calibration procedures and standards used for periodic checks of the UVS spectral transfer characteristic. Information about aircraft performance for each flight and corresponding instrument operation are contained in Section 4. This is followed by flight data which is analyzed for 3 pertinent flights in Section 5 and in Section 6 conclusions are drawn for this deployment and possible use of the UVS in the 747 instrument package.

2. INSTRUMENT DESCRIPTION

2.1 Basic UV Spectrophotometer

The instrument was originally designed to measure ultraviolet radiation in the range from 200 to 400 nm on board a WB57 aircraft. The basic instrument together with its Test Console is shown in Fig. 2.1. After minor modifications to its mounting hardware and some additional external circuitry, the UVS was flown on board a CV-990 aircraft. The modifications are described in Section 2.2 and a block diagram of the UV Spectrophotometer electronics is shown in Fig. 2.2.

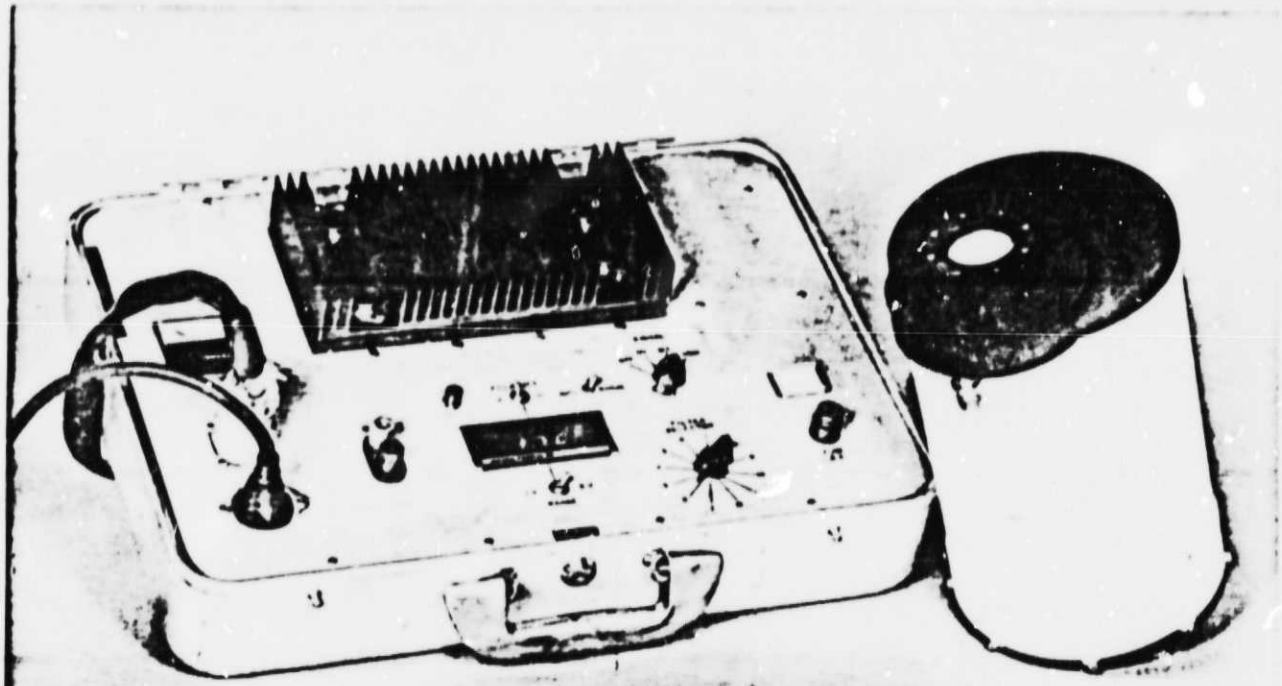


Fig. 2.1. UV Spectrophotometer and Test Console

The sun's radiation enters through the UV grade quartz window and impinges on the optical diffuser. After proper collimation, the light beam passes through a UV band-pass filter system and is subsequently converted to an electrical current by a very sensitive, low dark current photomultiplier. The output of the PM is dc coupled to a logarithmic electrometer with a dynamic range of 5 decades from 10^{-10}A

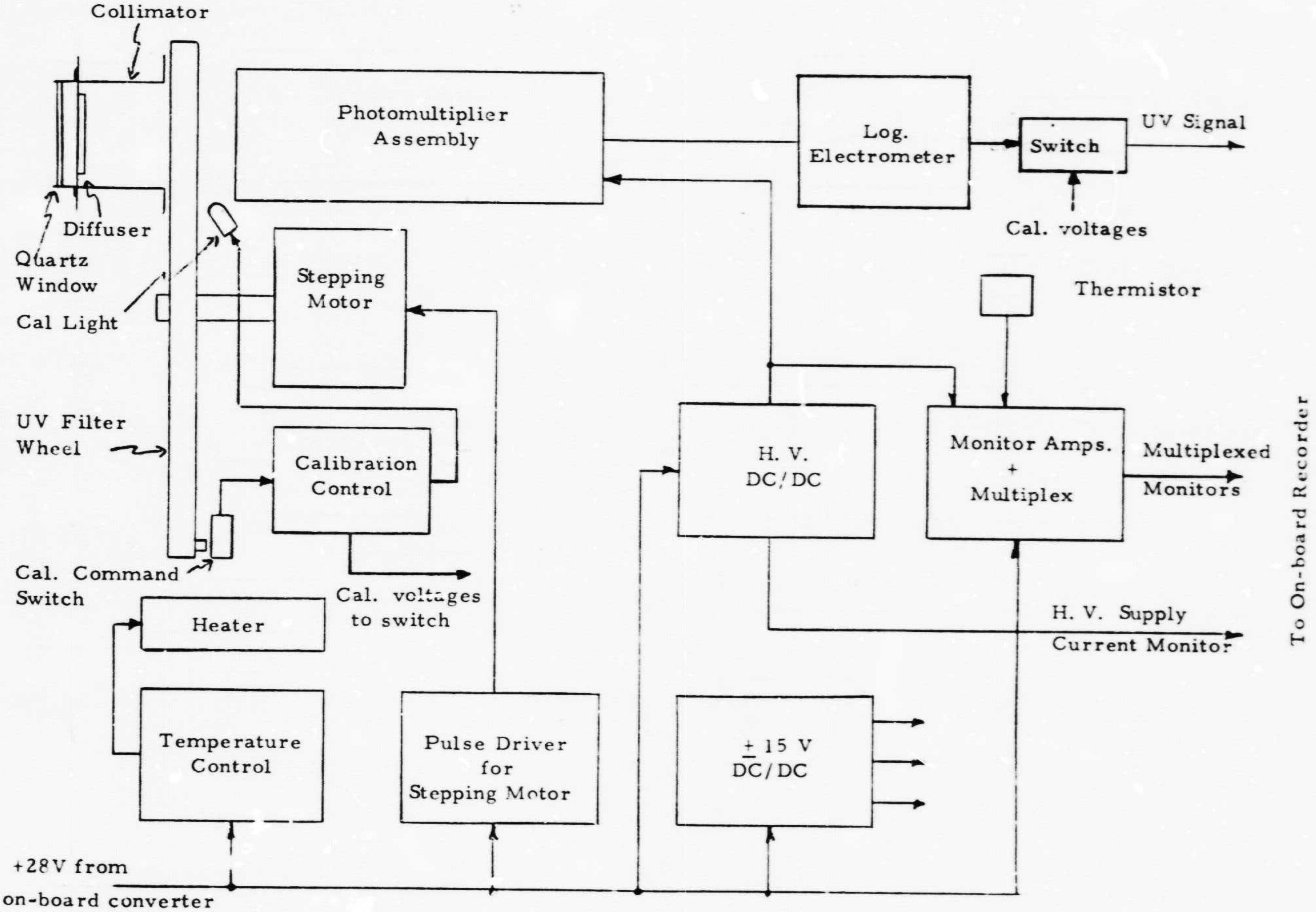


Fig. 2. 2. Block Diagram of UV Spectrophotometer

to 10^{-5} A. The response of the electrometer is 1 volt per decade of input current range, clamped to a maximum +5 V output. The filter system consists of a rotating filter holder, a stepping motor and an electronic pulse driver. The rotating holder accommodates 10 UV band-pass filters plus one blank and one calibrate position, or a total of 12 positions. The free running pulse driver increments the holder via the stepping motor by one position, once every second or every ten seconds, externally selectable. A detailed description of the UV filters is given in Ref. 2.1, while a tabulation of the central wavelength, bandwidth and filter position is given in Table 2.1. When the filter holder is in its blank position, the light transmission is blocked so that the dark current of the PM is measured. While the rotating holder moves into its calibrate position, a switch closure actuates the calibration control. This in turn energizes a light emitting diode in such a manner as to produce two distinct steps of light output for a duration of .5 seconds each, or a sequence of voltage calibration steps (1 V-2 V, etc.). The calibration light is only turned on during the calibration period and cannot interfere with the normal UV measurements or the dark current determination. The light output from the LED is controlled by two sequentially switched current sources. In order to obtain a periodic in-flight voltage calibration, the actuation of the light source is alternated with the periodic connection of the output line to a series of voltage levels of 0, 1, 2, 3, 4 and 5 V. This voltage calibration allows the UVS data to be corrected for any gain or level shifts introduced by the data recording-processing equipment.

For diagnostic purposes, five pertinent system parameters are monitored during the operation of the instrument. They are the +5 V regulator, the high voltage, the system temperature, the +28 V external power supply and the H. V. converter supply current. The high voltage monitor yields information about the stability of the H. V. converter, whereas the supply current monitor would be useful in determining high voltage arcing or corona, if it occurred. The remaining 3 monitors determine whether or not the system is operating within the specified limits of supply voltage and temperature. Of the five monitor signals, only the converter supply current is measured continuously while the remaining voltages are multiplexed. Sampling time is 10 seconds each, followed by an equal period of the zero-volt reference. All signals are clamped to +5 V and are output short-circuit protected.

Power requirements for the instrument are 20 W at +28 V for a stepping rate of 1/sec and 9 W for a rate of one every 10 seconds. Low voltage and high voltage DC/DC converters supply the necessary regulated power to the electronics and the photomultiplier, respectively. The stepping motor is fed by the +28 V line directly.

Table 2.1

UV Spectrophotometer Characteristics Summary

Measurement technique: Omnidirectional measurement (up to 75° from vertical) by a diffuser, movable wheel containing band-pass filters, and special UV photomultiplier. Intensity measured up to 4 orders of magnitude down from the unattenuated solar flux. Wheel has 12 positions sampled at 1 position/sec or 1 position/10 sec, externally programmable.

Position	Central Wavelength nm	Effective Bandwidth nm
1	210	15
2	287	2
3	291	2
4	298	3
5	305	2
6	310	2
7	319	2
8	329	2
9	363	26
10	393	28
11	Calibration checks	
12	Blank - for photomultiplier dark current measurement.	

Power Consumption: 20 W at rate of 1 pos./sec
(From +28 V) 9 W at rate of 1 pos./10 sec

Weight: 12 lbs

Size: 6" diameter x 10" deep cylinder

The three outputs - UV data, multiplexed monitors and the H. V. supply current monitor - are available at the output connector, while the 28 V power is applied through a separate input connector. Both connectors are located at the bottom of the instrument housing, which is a cylinder of 6" diameter and 10" length. The weight of the instrument is 12 lbs. It is mounted by means of a morman clamp, which mates with the offset mounting flange of the top cover and the adapter plate described below. A summary of the basic UV Spectrophotometer characteristics is given in Table 2. 1. In order to satisfy environmental and mounting requirements of the CV-990 aircraft minor modifications of the instrument had to be made. They are described in Section 2. 3.

2. 2 Signal and Power Interface

The circuitry and connectors which interface the UVS to peripheral equipment and the aircraft power mains are contained in the test console shown in Fig. 2. 1. A single cable connects the UVS to the test console via a multipin connector. The three output signals - UV data, multiplexed monitors and H. V. supply current monitor - are available at the console's front panel. One BNC supplies the UV data while the remaining 2 signals are connected to a binding post with a selector switch. A built-in 4-1/2 digit DPM facilitates monitoring of the three signals via the selector switch. The choice of manual or free running operation of the filter wheel, as well as its two sampling rates (1 position/sec or 1 position/10 sec), is also controlled from this console. The +28 V power for the instrument is supplied by the integral power supply operating from the 115 V, 60 Hz aircraft mains. An analog panel meter measures the 28 V input current as an added check on proper instrument operation. To make the test console compatible with the requirements of the CV-990 aircraft, it had to be slightly modified. These modifications are discussed below.

2. 3 Modifications for CV-990 Operation

The spectrophotometer was originally designed for installation in the unpressurized tail section of the high altitude WB57F aircraft. It was attached to the inside of the plane's fuselage with the instrument optics protruding through the plane's skin. Hence, an unobstructed view angle was achieved, making full use of the optical acceptance half-angle of approximately 75° from the vertical. The severe and changing environment encountered on these flights required that the electronics and optics were heated and pressurized. This was achieved with an internal temperature controlled heater and high quality O-ring pressure seals.

The installation of the instrument on Galileo II differs in two aspects from that of the WB57F: (1) the photometer is located inside the pressurized and temperature controlled main cabin, and (2) the optics view through a 1" thick quartz window, which is integral to the airplane, and mounted in the ceiling. For these two reasons the design had to be modified as far as temperature control and mounting was concerned.

The 20 W of power dissipated by the electronics gives rise to a temperature increase inside the housing of 15°C at ambient room temperature. This corresponds to a 5% gain change of the photomultiplier and at least a fourfold increase of its dark current relative to its performance at the design center temperature of +20°C. These deviations were considered unacceptable in view of the desired overall system's accuracy over the spectrum range 280-400 nm. It was therefore decided to cool the instrument with thermoelectric coolers.

Four Cambion thermoelectric modules (TEM) are mounted on the circumference of the housing. Each module has a heat pumping capacity of max 5 W for a 20°C temperature differential (ΔT) between the cold and hot side of the module. Thus, a total of 20 W at a ΔT of 20°C can be removed from the housing. Since it is desirable to maintain the instrument at or below +20°C, the hot side of each module must not exceed +40°C. This is achieved by attaching a heat sink to each TEM and forced air-cooled by means of a blower. Laboratory tests confirmed that this arrangement is adequate to control the photometer temperature at +20°C with ambient temperatures up to +26°C. Figure 2. 3 shows the mounting arrangement of the TEM's and heat sinks on the outer surface of the housing. Power for the TEM's is derived from a specially designed dc power supply. It is a variable voltage source with a maximum current capability of 3. 5 A. The current delivered to the 4 TEM's in series is monitored with an analog panel meter. The second modification involves the mounting configuration of the UV spectrophotometer. It's mounting flange is mated to an adapter plate by means of a morman clamp. This plate in turn is rigidly attached to a 1/4" thick aluminum base with four standoffs. Figure 2. 4 shows the completed assembly together with the blower mentioned above.

The interface console described above is modified to be compatible with the on-board data acquisition systems. This involved the simple addition of three triaxial connectors to the front panel of the console. Two of the outputs (multiplexed monitors and H. V. current monitor) interface with the Airborne Digital Data Acquisition System (ADDAS), while the UV data output connects to the analog data tape recorder. The console itself is adapted with special hardware for rack mounting.

Fig. 2. 3. UV Spectrophotometer with Thermoelectric Coolers and Adapter Plate Attached.

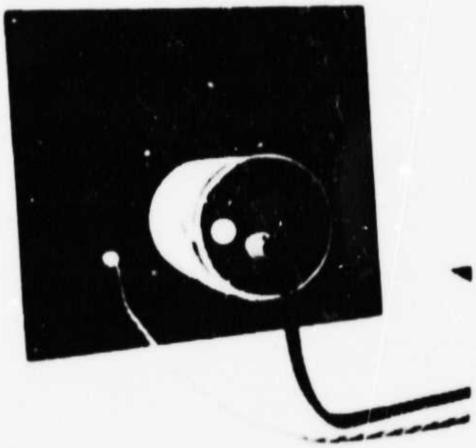
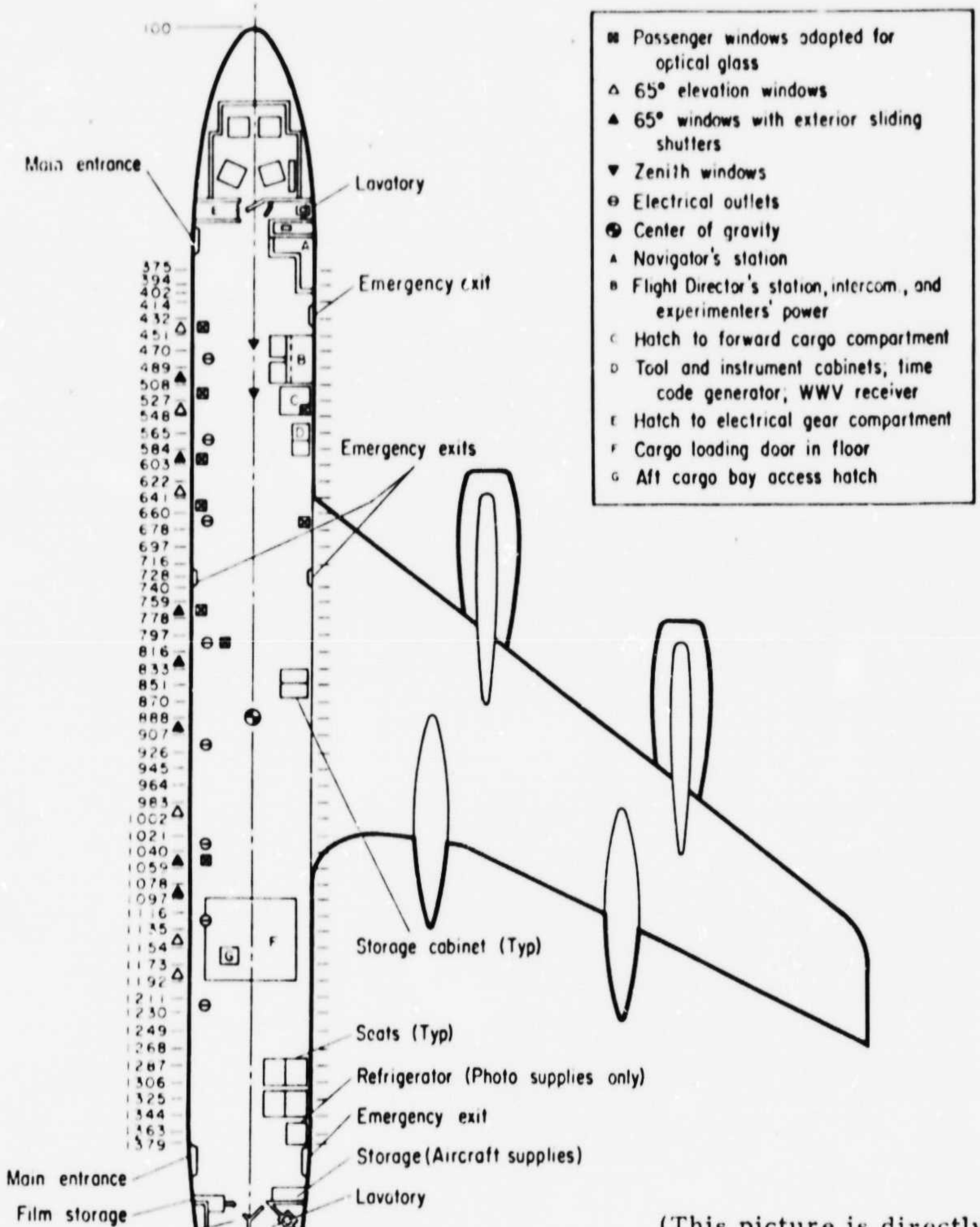


Fig. 2. 4. Mounting Configuration of UVS for Galileo II (CV-990) Aircraft Installation.

2.4 Installation

The UV Spectrophotometer system which was installed on Galileo II (NASA CV-990) consists of the modified UVS, the interface console, the dc supply for the TEM's, and a two channel strip chart recorder. Figure 2.5 shows a general layout of the cabin in which the system was installed. More detailed information about this aircraft is given in Ref. 2.2. Figure 2.6 shows the console, dc supply and the recorder mounted in the equipment rack on board the plane between stations 465 and 492. Power for this equipment is from the 115 V, 60 Hz aircraft converter. The console (bottom of picture) supplies regulated +28 V power to the UVS and interfaces the 3 output signals with the on-board data acquisition system, as well as with the strip chart recorder (center). Manual control of the 2 filter wheel sampling rates (1 pos./sec or 1 pos./10 sec) is accomplished with a toggle switch on the front panel of this console. The recorder has two analog channels which record the real time UV data and the multiplexed monitor signals, respectively. Although this seems to be a redundant recording system, it serves two purposes: (1) it is a real time monitor of instrument performance, and (2) it is used as quick-look data to determine the usefulness and time frame of measured UV fluxes. From this information the digital printout can be referenced and those parts selected which are of particular interest and are within the constraints of the UVS characteristics. The top of Fig. 2.6 shows the dc power supply and controls for the thermoelectric modules.

The UVS, mounted to its base plate (see Fig. 2.4), was installed at the second zenith port, located between stations 508 and 527 of the aircraft. The port is equipped with a 1" thick UV grade quartz plate. A detailed view of this port is shown in Fig. 2.7. The safety window shown here was removed, however, for this application. The base plate is bolted to 4 hard points of the airframe structure, leaving a space of approximately 1/8" between the base and the window frame. To eliminate light and air leaks, this space was sealed with foam rubber. The necessary air flow for the cooling of the TEM's is supplied by the normal cabin air-conditioning system through several small ducts, located just below the inner surface of the window. The blower, which is mounted in an opening of the base plate, circulates this conditioned air past the heat sinks of the TEM's and expels it into the cabin. This air circulation kept the heat sink temperature below +40°C (see Section 2.2) and at the same time prevented condensation of water vapor on the quartz plate. Visual inspection of possible condensation problems is facilitated through a viewing port in the UVS base plate. Since the optics of the UVS had to clear the inner surface



(This picture is directly taken from Ref. 2.1)

Fig. 2.5. General Cabin Layout of Galileo II

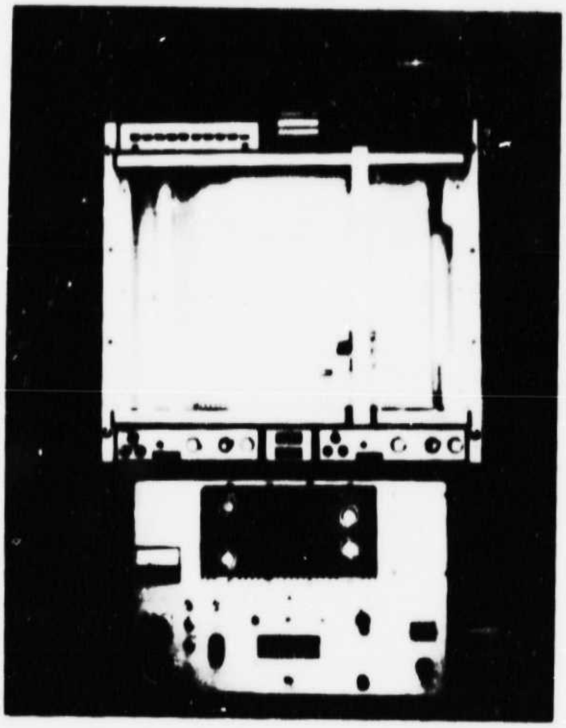
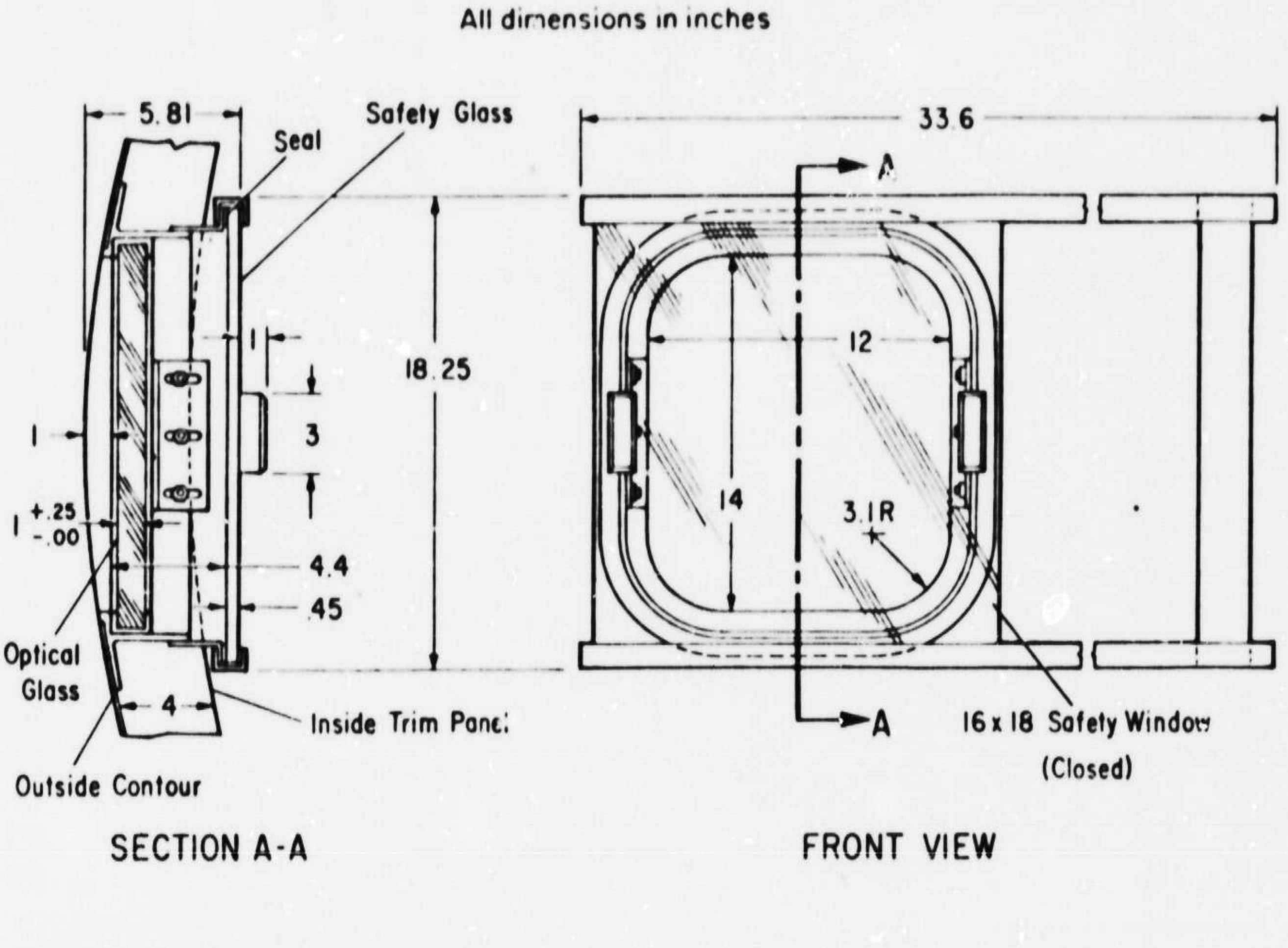


Fig. 2.6. Rack-mounted Support Equipment for UVS on Galileo II (CV-990).



(This picture is directly taken from Ref. 2.2)

Fig. 2.7. Zenith Port Window on Galileo II

of the quartz plate by at least 1/2", the normal acceptance half-angle of the instrument (75°) is reduced to 68° by the zenith port dimensions. A further reduction of the angle to 59° by means of a collimator is necessary to block out reflections from the edges of the quartz plate and its supporting frame. This is substantially below the desired 75° half-angle and, as noted in Section 5, made it impossible to view the direct sun during significant portions of several flights.

2.5 System Operation

The system is entirely controlled from the equipment rack and requires a minimum of maintenance after installation.

After all equipment power is turned on the two channels of the strip chart recorder are referenced to ground with the inputs shorted out. The gain of the channels and the chart speed are set and fixed to convenient values. The UVS is set for the desired automatic sampling mode of its filter wheel, and the sampling rate is selected. The flight missions of the UVS on Galileo II were such that it was logical to select a rate of 1 position/10 sec. The supply current for the thermoelectric coolers is manually adjusted with the control knob of this power supply according to the internal temperature monitor of the UVS. This monitor voltage is available from the strip chart record at any time. Results from all flights indicate that very few adjustments of the TEM current had to be made to maintain a stable temperature inside the UVS housing.

During each flight the continuously recorded UV data and monitor voltages are periodically checked to assure proper system operation. In addition, the zenith window is checked for water vapor condensation through the viewing port provided in the base plate of the UVS assembly. During the last few flights a problem with the strip chart recorder developed. It showed excessive drift in both channels due to worn parts in the pen positioning servo. However, no loss of data occurred, since all signals are also recorded by the on-board data acquisition system.

The only periodic maintenance required for the UVS is a photometric calibration and a dry nitrogen flush before a flight series. The calibration procedure is described in Section 3. The dry nitrogen flush assures extremely low water vapor concentration inside the pressure-tight housing. In addition, a cartridge of drierite material is inserted into the air volume of the instrument. The latter is intended to absorb any residual moisture which might be evaporated as a result of adsorption on potting compounds or wiring insulation. This precaution prevents water condensation on the optical surfaces, especially the protective entrance window of the UVS, which is exposed to the ambient cabin air of possibly lower temperature than that of the inside of the instrument. Because of the pressure sealed construction of the instrument a one-time nitrogen flush is effective for approximately 4 weeks.

3. INSTRUMENT CALIBRATION

The UV Spectrophotometer (UVS) is calibrated with a Standard of Spectral Irradiance (SSI) before and after each series of flights. The SSI is a 200 W tungsten halogen lamp with a quartz envelope, and its calibration is traceable to the National Bureau of Standards. Since the unattenuated solar spectrum differs slightly in shape from the SSI spectrum, a small correction is made to the SSI calibration to provide a calibration for the solar spectrum. More details about the calibration procedure are given in Refs. 1.9 and 2.1. In general, it has been found that the calibration shifts only a few percent over several months, so the SSI accuracy of several percent is not compromised.

The UVS calibration for the GASP flights in Nov. - Dec. 1975 is given in Table 3.1. This calibration uses the voltage output of the logarithmic amplifier converted to an input current, with 0 V = 10^{-10}A and 5 V = 10^{-5}A.

Table 3.1

UVS Calibration for GASP Flights in Nov. - Dec. 1975

Filter wavelength (nm)	Filter band-pass (nm)	Solar spectral sensitivity $(A/(W/(cm^2\text{-}nm)))$
393.0	26.4	3.423×10^{-3}
363.0	28.0	1.986×10^{-3}
329.2	2.2	9.997×10^{-3}
319.3	2.0	2.386×10^{-2}
310.3	1.8	2.264×10^{-2}
305.3	2.0	3.528×10^{-2}
297.8	3.0	7.733×10^{-2}
290.7	2.4	1.723×10^{-1}
287.3	1.8	2.911×10^{-2}
214.0	28.0	4.732

4. DEPLOYMENT

4.1 Flight Information

Table 4.1 gives a complete listing of all GASP flights of Galileo II, including those conducted for the Jet Propulsion Laboratory (JPL) for the period November 25 to December 16, 1975. Columns 1-3 give the flight number, description and date of this flight series, respectively, while Column 4 indicates the range of latitude and longitude for each mission. The UV Spectrophotometer was on-board and operational for the entire flight series. The instrument was attended by Panametrics personnel during flight Nos. 2, 3 and 4. During all other missions, including the test flight on November 25, 1975, personnel from NASA-Lewis Research Center operated the instrument successfully.

Table 4.1

Summary of Flights on Galileo II, Nov.-Dec. 1975

Flight		Date (1975)	Range
No.	Description	Month-Day	(Lat. -deg. N, Long. -deg. W)
1	Local test	Nov. 25	(37, 122)
2	W to E Chase	Nov. 28	(37, 122) - (43, 83)
3	Wallops/Balloon	Dec. 2	(28, 80) - (39, 74)
4	JPL	Dec. 4	(28, 80) - (31, 77)
5	"	Dec. 6	(28, 80) - (30, 79)
6	"	Dec. 8	(28, 80) - (40, 78)
7	"	Dec. 10	(28, 80) - (30, 80)
8	"	Dec. 12	(28, 80) - (38, 77)
9	"	Dec. 14	(28, 80) - (31, 81)
10	"	Dec. 15	(28, 80) - (31, 82)
11	E to W Return	Dec. 16	(30, 82) - (37, 122)

The local test flight (No. 1) was intended as an operational check of all instrumentation aboard the aircraft and the UVS was only turned on for 2 short periods of time. Its operation proved to be satisfactory, and the instrument was deemed flight worthy. The flight west to east (No. 2) was a chase flight in the wake of a United Airlines 747 from Moffet Field, California to Patrick Air Force Base (PAFB), Florida. Number 3 was a step profile flight over Wallops Island, and was coordinated with the launch of a balloon borne ozone sonde from that island. Although flights 4 through 10 were mainly conducted for JPL to test various radar equipment, the UVS was operational during those missions as well. The return trip from the east to the west coast concluded this flight series.

4.2 Operational Analysis

As mentioned above, the performance of the UVS was continuously monitored by means of a 2 channel strip chart recorder. Of particular interest as far as the performance within the specified limits is concerned are the monitor signals from the instrument. Figure 4.1 shows a typical strip chart record. The bottom trace (with voltage scale on right side) represents the UV flux data, calibration voltages and the dark current. The outputs from the ten band-pass filters (210 nm - 390 nm) can clearly be identified. The dark current is nearly 1 decade below the logarithmic (1 V/decade) signal range of the UV flux data. The calibration voltages, from 0-5 V in groups of two, are useful during data reduction to compensate for drift and gain variations of the recording system. The top trace (with voltage scale on left) is the output from the instrument's multiplexer, and shows the following monitors: low and high voltage DC/DC converters, instrument temperature and +28 V input voltage. The spaces between monitors are at ground level except for one which is a synchronization pulse at -1.2 V.

The records from flights 1 through 3 show the following: The low voltage DC/DC converter is operating within the specified regulation characteristics. The H. V. DC/DC converter indicates that the output voltage is steady at 2550 V during all flights. The +28 V input voltage remains constant at all times. The internal temperature holds steady within ± 1 °C for any particular period when the instrument was turned on. Comparing the mean temperature of one period with another shows a difference of max 4.5°C, namely, from 16.5° to 21°C. This is largely the result of the ON-OFF operation of the instrument during a flight, which was chosen to keep the amount of data at a level consistent with the purpose of these tests: namely, an operational evaluation of the instrument. During the OFF period the temperature monitor is not available, hence no meaningful correction of the TEM temperature controller is afforded. Based on the measured differential of 4.5°C between ON periods the photomultiplier gain will change by less than 1.5%. Although a relatively small error, it can be taken into account by the periodic in-flight gain calibration data. The fact that the lowest temperature

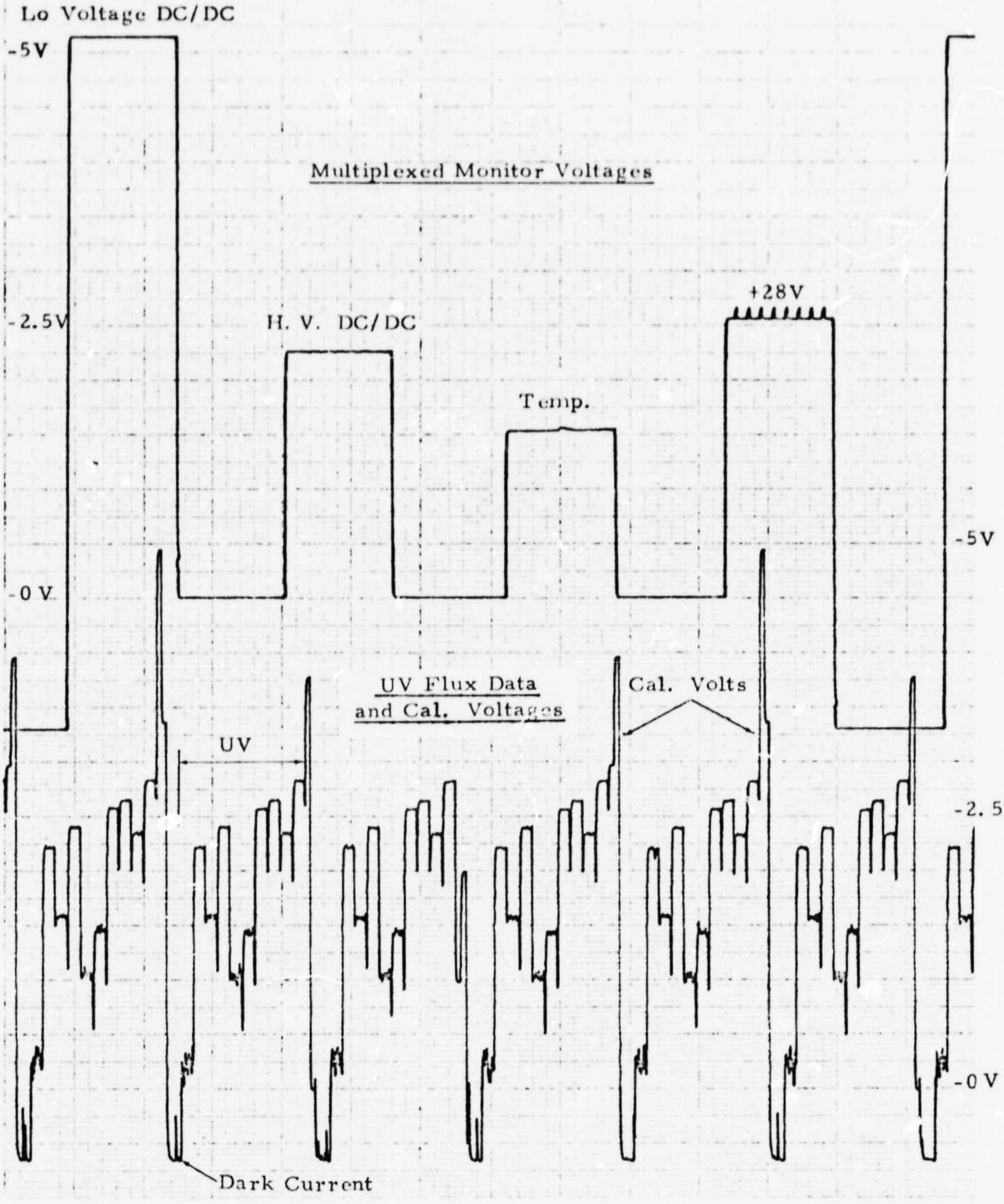


Fig. 4.1. Typical Strip Chart Record of UVS Data and Multiplexed Monitor Voltages.

achieved is below 20°C confirms the desired design goal for the TEM controller.

Beginning with flight number 4 and for the rest of the series the strip chart recorder developed a severe drift problem (see Section 2.5). Analysis of these analog records is not possible. However, the digital printout of the monitor voltages is not affected by this problem and it is used for performance analysis. Essentially the same results are obtained from the digital data for the remaining flights as were observed for the first 3 flights.

In summary, the UVS performed within specifications during the entire series. The UV flux data, when not limited by the 59° acceptance half-angle, are of high quality. A detailed analysis of selected flights is given in Section 5.

5. FLIGHT RESULTS

5.1 Data Reduction Procedure

The data reduction procedure for the UVS was first presented in Ref. 1.9, and the final, updated version was given in Refs. 5.1 and 2.1. For the present data this procedure must be modified because of the additional collimation necessary to reduce interference from light reflected by the mounting for the quartz window in the aircraft skin (see Section 2). This was done by cutting off the mathematical integration for Rayleigh scattered light, and by tapering off the relative diffuser efficiency for direct sunlight, at a 59° angle to the UVS diffuser normal.

The list of flights in Table 4.1 shows that the UVS data were taken north of 28°N latitude. The solar declination in Nov.-Dec. is about 22°S, so the minimum solar zenith angle is about 50° at local noon. Thus, much of the UVS data were taken at solar zenith angles greater than 59°, where only the Rayleigh scattered component can be measured. The analysis procedure still gives a value for the total ozone above the flight level, but this value becomes inaccurate at high altitudes where most of the Rayleigh scattering takes place in the ozone layer.

Since the object of these flights was to prove the suitability of the UVS for making solar UV and total ozone measurements in the CV-990 operational environment, reduction of a sufficient amount of data to demonstrate this capability is all that was required. Thus, although the UVS operated properly on all flights, only a few flights have had a portion of their data reduced to actual ozone thicknesses.

5.2 Wallops Island - Flight 3

UVS data were obtained from a flight over Wallops Island on 2 December 1975, in conjunction with a balloon launch to measure the vertical ozone profile. The balloon was released at 1904 GMT while the CV-990 made overflights at several altitudes. Since Wallops Island is at about 38°N, the 59° cutoff angle of the UVS resulted in all measurements over Wallops Island being made on only Rayleigh scattered light. The results are thus more uncertain than from the normal mode of measurement, but nevertheless are of reasonable quality and show that the UVS was operating properly.

The results of several UVS measurements are given in Table 5.1. The first measurement at 30.8°N latitude was on the flight to Wallops Island and is the only measurement made with direct sunlight on the UVS diffuser. The two measurements at 40 kft are the least accurate, since the method of analysis (described in Refs. 1.9, 5.1 and 2.1) was designed primarily for direct sunlight and not for the weak Rayleigh scattered component at high altitudes. Flux accuracy at 393 nm is about 10%, worsening to 15% for the 35 kft data and 50% for the 40 kft data. Blanks in Table 5.1 are where the ozone has so strongly attenuated the solar flux that the measurement accuracy is worse than 50%.

The total ozone values calculated from the UVS data of Table 5.1 are compared with the integrated balloon profile in Table 5.2. The 31 kft and 35 kft measurements are in excellent agreement, although the UVS total ozone has an uncertainty of about 5%. The 40 kft measurements give about 20% less ozone, a deviation to be expected in the Rayleigh scattered component. The balloon data show that the ozone layer is primarily between about 60 kft and 100 kft. Since the pressure scale height is about 15 kft over the 30 kft to 100 kft altitude range, an important fraction of the Rayleigh scattered light originates partially in the ozone layer. At large solar zenith angles the ozone attenuation raises the effective ozone thickness, thus producing the effect seen at 40 kft. Measurements made with direct sunlight become more accurate at high altitudes, so if the UVS had been mounted flush with the aircraft skin the 40 kft measurements of total ozone would have been more accurate. The data in Table 5.2 show, however, that the UVS functioned properly and gave useful data.

The UVS total ozone values in Table 5.2 have been corrected for ozone absorption at about -50°C. This is the approximate average temperature of the ozone layer as measured by the balloon. Because the UVS measurements were made with only Rayleigh scattered light

Table 5.1

Solar UV Fluxes Measured on the Wallops Island Flight of 2 December 1975

Data type	Average time of measurement (GMT hrs-min)					
	1604	1822	1836	1853	1917	1926
Lat (deg N)	30.8	38.4	37.2	37.9	38.3	37.3
Long (deg W)	78.0	75.1	75.9	75.4	75.3	75.9
Alt (kft)	33.4	31.1	31.1	35.0	40.0	40.0
Solar zenith angle (deg)	54.4	64.0	63.7	66.3	69.3	69.3
Measured total ozone (atm-cm)	0.197	0.312	0.310	0.319	0.250	0.233

Wavelength λ (nm)	Solar flux at λ in $W/(cm^2\text{-}nm)$* ($6.27\text{-}5 \equiv 6.27 \times 10^{-5}$)					
393.0	6.27-5	5.09-5	5.88-5	5.97-5	2.76-5	2.82-5
363.0	5.55-5	3.85-5	4.34-5	4.53-5	2.37-5	2.32-5
329.2	5.50-5	2.99-5	3.41-5	3.28-5	2.04-5	2.01-5
319.3	2.76-5	1.31-5	1.52-5	1.47-5	8.19-6	8.75-6
310.3	1.32-5	3.98-6	4.67-6	4.19-6	2.32-6	2.48-6
305.3	5.41-6	1.14-6	1.38-6	1.13-6	6.29-7	6.83-7
297.8	3.00-6	-	-	-	-	-
290.7	1.86-6	-	-	-	-	-

*This is the total (direct + Rayleigh scattered) downward flux.

Table 5. 2

Comparison of UVS and Balloon Total Ozone Measurements at Wallops Island, 2 December 1975

GMT (hrs-min)	Alt (kft)	Solar zenith angle (deg)	UVS ozone (atm-cm)	Integrated balloon ozone (atm-cm)	$\left(\frac{\text{UVS } O_3}{\text{Bal } O_3}\right)$
1822	31.1	64.0	0.312	0.312	1.000
1836	31.1	63.7	0.310	0.312	0.994
1853	35.0	66.3	0.319	0.307	1.039
1917	40.0	69.3	0.250	0.301	0.831
1926	40.0	69.3	0.233	0.301	0.774

the excellent agreement with the balloon data is partially fortuitous, since the UVS total ozone has about a 5% uncertainty at 31 kft and 35 kft, and at least 20% at 40 kft.

The one UVS total ozone measurement at 30. 8°N latitude gives 0. 197 atm-cm at 33. 4 kft. The change of about 0. 11 atm-cm total ozone between 30. 8°N and 38°N is about twice that of the 11 year average distribution for December (Ref. 5. 2, Fig. 1-13), but is not unreasonable when the large daily variations are considered (see, e. g. , Ref. 5. 3). A total ozone measurement eight days later gave 0. 260 atm-cm at 29. 6°N latitude, more in agreement with the 11 year average for November (see next section). The Wallops Island flight data show the suitability of the UVS for CV-990 solar UV measurements, and verify the accuracy of the total ozone values derived from the UV fluxes.

5. 3 Other Test Data

Of the 11 flights listed in Table 4. 1 some UVS data from flights 2 and 7 have also been reduced to solar UV flux values and total ozone above flight level. For flight 2 on 28 November two sets of data have been reduced and are given in Table 5. 3, while for flight 7 on 10 December one set of data has been reduced and is also given in Table 5. 3.

The flux values for 2018 GMT on 28 November have an uncertainty of at least 25%, because the solar zenith angle of 60° is very close to the 59° collimator cutoff. The total ozone value is still accurate to 5%,

Table 5. 3

Solar UV Fluxes Measured on the Flights of 28 November and 10 December 1975

Parameter	28 November		10 December
Time (GMT hrs-min)	2018	2129	1723
Lat (deg N)	38. 3	39. 9	29. 6
Long (deg W)	119. 5	111. 2	81. 2
Alt (kft)	29. 1	37. 0	32. 9
Solar zenith angle (deg)	60. 0	68. 9	52. 4
Measured total ozone (atm-cm)	0. 300	0. 231	0. 260
Wavelength λ (nm)	Solar flux at λ in $W/(cm^2\text{-}nm)^*$ ($8.23\text{-}5 = 8.23 \times 10^{-5}$)		
393. 0	8. 23-5	4. 37-5	6. 71-5
363. 0	6. 43-5	3. 38-5	5. 74-5
329. 2	5. 46-5	2. 96-5	5. 47-5
319. 3	2. 53-5	1. 31-5	2. 69-5
310. 3	8. 27-6	3. 80-6	1. 08-5
305. 3	2. 42-6	1. 12-6	3. 96-6
297. 8	2. 03-6	-	2. 71-6
290. 7	1. 52-7	-	1. 67-7

*This is the total (direct + Rayleigh scattered) downward flux.

however, since it is determined from flux ratios. The value of 0. 300 atm-cm is in good agreement with the 11 year average for November (Ref. 5. 2, Fig. 1-12). The data for 2129 GMT give more accurate flux values at the longer wavelengths (10% for λ > 319 nm), but since only Rayleigh scattered light is detected and the altitude is 37 kft the total ozone is an underestimate (see previous section for a more detailed discussion).

The 10 December data for 1723 GMT are for a location near that of the 1604 GMT data for 2 December (Table 5. 1), and the flux and total ozone values are accurate to 10% and 5% except where the ozone attenuation is severe. The total ozone value of 0. 260 atm-cm is close to the 11 year average for December (Ref. 5. 2, Fig. 1-13). The change of about 0. 06 atm-cm from 2 December to 10 December is well within normal day-to-day variations observed by others (see, e. g., Refs. 5. 3 and 5. 4). The 10 December measurement is for a solar zenith angle of 52. 4°, and thus is far enough from the 59° collimator cutoff to demonstrate proper operation of the UVS in its normal mode of operation with direct sun illumination of the diffuser.

The data presented here are only a small amount of the total UVS data obtained on the 11 flights listed in Table 4. 1. These data have been reduced to flux and total ozone values to show proper operation of the UVS. Contract limitations do not allow analysis of additional data, but a cursory examination of the data shows that the UVS operated satisfactorily at all times. The major difficulty in further data analysis is the change required in computer programs, already operational, to handle more efficiently the format of the analog and inertial data on the magnetic tapes from the GASP flights. Once the necessary changes have been made, and checked for errors, the analysis of the large amount of remaining data would be comparatively straightforward.

6. CONCLUSIONS

The CIAP UV Spectrophotometer developed by Panametrics, Inc. has been successfully tested during a series of ten GASP flights on the Galileo II (CV-990). One of the principal reasons for these tests was to evaluate the UVS for possible inclusion in the Boeing 747 instrument package. Mechanical limitations on the CV-990 installation caused the acceptance cone half-angle to be only ~59°, which made it impossible to obtain direct solar irradiation of the diffuser during most of the flight time. (This is primarily because the flights were made at latitudes of 30°-40° N near the winter solstice, when the solar declination is about 22° S. During summer months a much larger amount of data with direct solar illumination of the diffuser would be obtained with the UVS in this

CV-990 mounting configuration.) At some times full solar irradiation of the diffuser was possible, while at others the view angle was too close to 60° to provide great confidence in the data. If it had been possible to install the instrument with its normal 75° acceptance half-angle, much more high quality data could have been obtained. When the sun was completely outside the 60° cone it was possible to derive the total ozone above the flight path by use of only the Rayleigh-scattered light; at times of full solar irradiation the total ozone derivation was made in the usual manner. An estimated error of ± 5% was placed on these values of total ozone as a result of the nonoptimum optical configuration. We believe that this measurement can, ultimately, be made with somewhat greater precision - especially during periods of full irradiation - although it will be necessary to study the problem in greater depth in order to determine this limit of precision.

The total ozone is deduced from the ratios of the UV intensities that are highly attenuated by ozone to those that are not. Hence, it is not limited to the accuracy with which the individual UV flux intensities can be measured (including the absolute error in the standard of spectral irradiance), but, rather, by the accuracy with which relative values of the intensities can be measured. As noted, we believe that the ozone determination can be made to better than ± 5%, and it could approach the 2% upper limit of the accuracy ascribed to the Dobson instrument (Ref. 6.1, p. 434). If so, these results, when integrated with the Dobson network results, would prove of very significant value in measurement of quasi-biennial and long-term ozone trends (see Refs. 6.1-6.3 for presently used approaches and results). By providing measurements over a series of Dobson stations during a single flight, it also would be possible to correlate results of the stations and hence remove ambiguities that now exist regarding intercalibration (Ref. 6.1, p. 434) and disagreements that occur between stations in close proximity to each other (Ref. 6.2, p. 12). The accuracy of the satellite-borne BUV (backscatter ultraviolet) system for measurement of total ozone has been estimated at 6% (Ref. 6.1, p. 434). Additional important benefits would be the detailed total ozone data available for input to models and checking the results of model predictions. For example, the predictions of profiles over the oceans, where there presently is a lack of observations (Ref. 6.2, p. 10) and determination of the natural horizontal variability that is necessary to evaluate the significance of a model's results (Ref. 6.2, p. 1).

The total ozone determination depends on UV flux measurements in the 280-400 nm region. During the CV-990 flights the flux measured at 210 nm was extremely low, as is expected at the flight altitude of the CV-990 and the Boeing 747. This measurement was originally included for use at the WB57F flight altitude (> 60 kft), and it is still retained for balloon flights. Its elimination for the 25-40 kft region flights would make it possible to replace the photomultiplier/H. V. supply combination with a sensitive UV photodiode/low voltage combination that has recently become available. It was the very low intensity at 210 nm that made it necessary to use the high sensitivity photomultiplier. This change could necessitate modification of one electronic board (the electrometer), but it certainly will not cause any changes in the housing, stepper motor and filter wheel, monitors or other signal conditioning electronics. We believe that for long term unattended application on either the 747 or CV-990, greater reliability would then result, without compromising the UV flux measurements in the important region (280-400 nm).

The method of cooling the UVS by means of thermoelectric coolers proved adequate, although for use on the 747 it may be possible to obtain suitable temperature control simply by use of fans. This possibility will be enhanced by use of a UV photodiode, since it would then be possible to eliminate the high voltage supply that uses about 7 watts. Hence a total dissipation of only about 3 watts is all that would be required if the filter switching rate used is 1 per 10 secs, which is adequate for the long-term monitoring applications anticipated.

As a result of the foregoing we recommend the following course of action:

1) The photomultiplier in the present UVS should be replaced with a photodiode (probably of the vacuum type) and a modified electrometer board constructed, if necessary. The instrument should be calibrated and installed on the CV-990 for at least one test flight. The objective is to confirm that the in-flight operating temperature is as low as expected and that the required 280-400 nm UV flux data are still of high quality. The flight should occur at a time when the solar zenith angle is $\leq 50^\circ$. Any mechanical or minor electrical modifications that may be required to interface the UVS for permanent-type installation in the Boeing 747 or CV-990 packages should be determined. Methods of reducing and storing the data should be investigated, including magnetic type handling and modification of the presently existing computer programs.

2) The photodiode version of the UVS should be constructed and calibrated for the CV-990 and Boeing 747. It would be desirable to have one more UVS than the total number of instrument packages. This would allow a periodic maintenance and calibration procedure to be established without necessitating loss of data.

3) Assistance in the field for the initial installation and periodic inspection should be provided by Panametrics personnel. The need for such in-field assistance should diminish rapidly, but periodic maintenance and calibration of the UVS instruments versus wavelength and solar irradiation angle should continue. For this purpose Panametrics maintains complete optical calibration facilities, including a Standard of Spectral Irradiance traceable to NBS and a quartz monochromator-deuterium light source combination for testing the interference filters individually.

4) The total ozone and UV flux detailed geographical distributions should be reported, and methods of utilizing and integrating the results with those of other techniques should be investigated. The ultimate accuracy of the total ozone measurements should be determined, and comparisons should be made with Dobson network results. Short term effects due to solar proton events should then be monitored and correlated with those predicted based on measured proton fluxes and atmospheric chemistry models. The utility of the total ozone geographical data for use as indicators of global or hemispherical trends should be investigated, and these data should be integrated into other long-term ozone monitoring programs.

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