THE PHOTONS PAYLOAD, G-494; A LEARNING EXPERIENCE

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ABSTRACT

PHOTONS (Photometric Thermospheric Oxygen Nightglow Study) is an optical remote sensing payload developed for GAS flight by the National Research Council of Canada. The device is extremely sensitive and is suitable for making measurements of low intensity, aeronomically generated atmospheric emissions in the nadir and the limb and of Shuttle ram glow. The unit uses a sealed canister and UV transmitting viewing ports. This is the first GAS payload to use a sealed viewing window. That window was developed by Bristol Aerospace Limited of Winnipeg, Canada. An engineering flight occurred on STS 61-C. During that flight PHOTONS received one hour of operation and aeronomic observations were made. Good diagnostic data were obtained and the science part of the experiment malfunctioned. Post flight inspection revealed that the payload was in perfect working order except for total failure of the photomultiplier detectors. The experiment and the payload are described and the flight results are discussed along with the cause of the malfunctions. It is shown that enough has been learned from the flight diagnostic data and about the cause of the malfunction to conclude that the engineering flight was successful and that subsequent flights of the PHOTONS payload will be productive.

INTRODUCTION

After the Canadian sub-orbital rocket program was terminated in 1984 it was necessary to find a replacement carrier for the affected aeronomy experiments. This carrier might also be expected to serve as a test-bed for other payloads that are developed as part of the Canadian space program. To this end an effort was made to explore the feasibility of using the STS Get Away Special (GAS) as the replacement carrier. The plan devised was to make a simple engineering flight with the requirement that the payload be capable of doing aeronomic science as well. This meant that the unit to be developed had to carry the necessary science instrumentation as well as the broad array of diagnostics required to assess its performance.

Two basic science areas were addressed: oxygen chemistry in the lower thermosphere and Space Shuttle ram glow. Both objectives required the use of extremely sensitive light measuring instruments (photometers) capable of detecting an emission rate less than one Rayleigh. The Rayleigh (R) is an absolute unit defining a column surface brightness for an extended source (Hunten et al., 1956). This sensitivity makes the experiment suitable for measuring the Shuttle ram glow parameters at levels previously unachieved. The science issues are discussed in detail by Harris et al. (1987). Because of the nature of the science problem the experiment is named Photometric Thermospheric Oxygen Nightglow Study or PHOTONS. Flight occurred on STS 61-C (Columbia) in January, 1986 and one hour of operation was achieved. The NASA identification code for this experiment is G-494.

SCIENCE INSTRUMENTS

It was intended that the flight hardware be as simple as possible consistent with a reasonable scientific return. This dictated that the payload would not use imaging detectors and there would be no direct recording of spectra. The observable list in Table 1 requires the measurement of emission rates at 7 wavelengths. It was therefore decided to make the observations with a 7 channel photometer. It was also decided to use 7 parallel detectors rather than a complex filter wheel device. The nominal bandwidths of the selected filters are wide so that there was no requirement for temperature control. The design values are given in Table 1. In addition a field of view of 8° was adopted to maintain adequate sensitivity for nadir work with the Herzberg I band system and also for ram glow observations at sub-Rayleigh emission rates. The photomultipliers used were Hamamatsu photon counting types R943-02 and R212-UH.

Table 1. The observables in PHOTONS and the design instrumental functions at a temperature of -5°C. The measured flight functions are given in Table 4.

Channel	Emitter	Wavelength (nm)	FWHM (nm)
1	$O_2(A^3\Sigma_u^+)$	287.8	8.0
2	$O(^1S)$	557.7	2.0
3	continuum	625.0	1.0
4	$O(^1D)$	630.0	2.0
5	$O_2(b^1\Sigma_g^+)(0,0)$	764.0	3.0
6	continuum	826.0	1.0
7	$O_2(b^1\Sigma_g^+)(0,1)$	865.3	8.0

The absolute calibration and detection limit for each photometer is included in Table 4. The thresholds are well below the signals expected in the nadir nightglow, consequently the signal-to-noise ratios are more than adequate for the science requirements. In flight calibration was achieved through the use of calibrated incandescent sources in front of the filters in the visible and IR channels and a

Table 2. The basic PHOTONS orbit sequence for STS 61-C (SDA is solar depression angle).

Sequence Elapsed Time (s)	Details	SDA°*
0	GCD experiment activation at local sunset	0
360	initiate warmup	24
420	initiate calibration	28
450	initiate dark count	30
480	initiate MDA open	33.5
503	initiate data acquisition	118.5
1777	initiate MDA close	120
1800	initiate calibration	120
1830	initiate dark count	122
1860	sequencer termination	124
2460 ±600	GCD experiment deactivation	---

* 0°-90° depressed sun, sunset
90°-180° depressed sun, sunrise

light emitting diode behind the filter for the UV photometer. These sources were operated according to the sequence given in Table 2.

ENGINEERING REQUIREMENTS

Because the experiment was intended to do optical remote sensing a motorized door assembly (MDA) was required for mechanical protection. The door also allowed a controlled environment for the in flight calibrations and dark count determinations. The door weighs 15.9 kg and that figure had to be included in the overall payload weight envelope. This coupled with the weight of the viewing window assembly required careful planning in order to not exceed the 90.7 kg limit. The flight weight achieved was 84.8 kg.

One of the major design decisions in order to maintain a simple philosophy for the experiment was to have the instruments look through a window so that the GAS canister was maintained at nominal atmospheric pressure. This unit was developed under contract by Bristol Aerospace Limited. The window plate is shown in Fig. 1. It contains four viewing ports. Two have diameters of 16.5 cm and the remaining two have diameters of 7.6 cm. One of the smaller ports is for the bright light protection sensor which is described later. All the windows are UV transmitting. The window material is Dynasil UV1000 having a cutoff wavelength below 185 nm. The weight of the entire device is 7.7 kg.

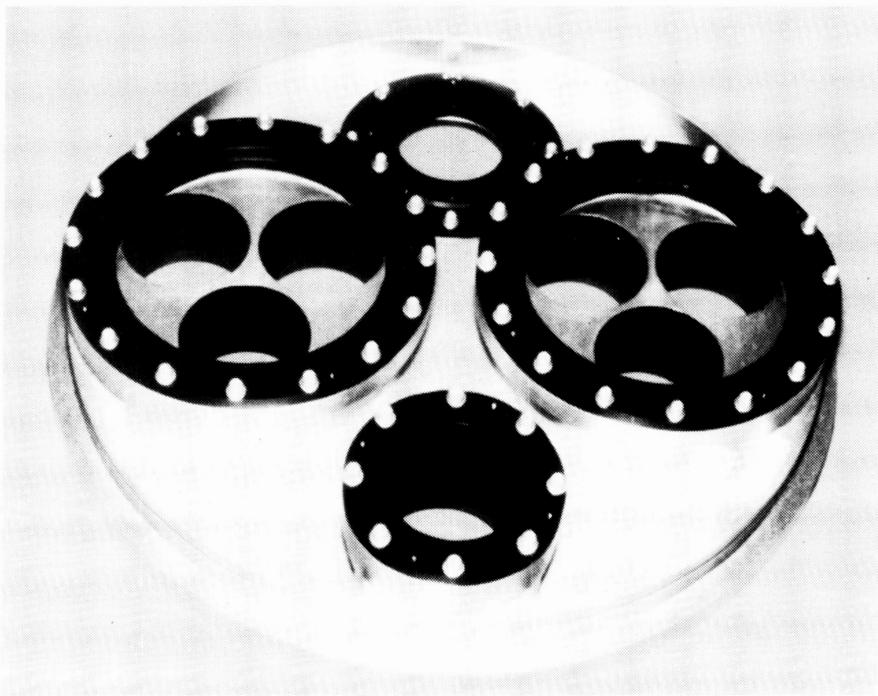

Fig. 1. Inside view of the payload viewing window.

A major concern during the payload design was the uncertain effects arising from the temperatures that the unit might experience during storage and flight. Remote sensing through a GAS window from Shuttle was completely new. A temperature of -5°C was used as the baseline for design. The effect of temperature cycling of the filters was carefully monitored through a number of temperature sensors and by making preflight measurements of absolute sensitivity and transmission functions over the flight design temperature range of -30° through +30°C. A large array of other housekeeping information was also taken. This included payload pressure and all the voltages and currents required to establish that the payload was in good operating condition. Pressure was an important diagnostic parameter because of the high voltages present within the canister. To protect the experiment against bright light sources such as the sun and the sunlit atmosphere, a redundant bright light detector, using a Motorola MRD450 NPN silicon phototransistor, was included in the payload.

Redundant data storage systems and a single data acquisition system utilizing a multiplexer strobed at 2 Hz were used. The data storage systems were EPROMS and a Sea Data model 633M/80 tape recorder. The EPROMS were the primary data set because of their superior error rate relative to the recorder. The system was designed for a maximum of five observation sequences; one of these is outlined in Table 2. This requirement determined the memory size at 320 kilobytes. Photometer sample counts were made with a 24 bit counter. Those data words were then formatted into 2 bytes including the 11 most significant bits, 4 bits to record the number of right shifts used in the data compression and one parity bit. The sample window was 50 milliseconds in all cases.

The timing of each Gas Control Decoder (GCD) event is recorded with a timing precision of ±1 min. In addition the timing precision adopted by NASA for scheduled GCD events, e.g., switch actions, was ±2 min. This constraint caused serious difficulty in calibrating the real time clock. It was planned to obtain experiment pointing from the spacecraft attitude file after the flight. In order to do this with adequate precision, time had to be known with a maximum error of ±2.8 s. The clock had to be set approximately 3 months prior to flight, therefore the expected clock drift before flight could not be accurately estimated. It is estimated that for a storage temperature of 23°C and a storage period of 106 days the clock would be ahead by about 5 min during flight. The uncertainty in this number is ±25 s which is clearly an inadequate timing precision. The other available alternative was to calibrate the clock as soon as possible after the flight. This involves a period of only 2 weeks and a resulting uncertainty of only ±3 s; this was the approach used.

MISSION REQUIREMENTS

The mission requirements for the engineering flight tests were very simple. Success would be signified by satisfactory operation of the payload, in the science mode, over one or more observation periods. This involves correct sequencing of the science instruments, data acquisition and recording of diagnostics. There were two science mission requirements. The first was to make measurements of the airglow components listed in Table 1 over at least one orbit. The second was to make ram glow measurements at the same wavelengths while looking in the local zenith. The latter permits the ram glow to be studied and provides any corrections required for the airglow results. All of these observations were to take place in shadow with the photometers looking out of the payload bay along the Orbiter -Z axis.

A series of observations of the Earth's limb was considered to be the most desirable data set, however, complex pointing manoeuvres such as scans are not available to GAS experiments on demand and can only be achieved as targets of opportunity. In addition simple pointing directions are normally provided with typical errors of ±15°. These pointing errors made it impractical to try for predictable positioning of the field on the limb but were quite acceptable for nadir and zenith work. Consequently the flight plan was built around nadir and deep space operations, all the while hoping that an opportunity would arise for one or more limb scans to be recorded. In the event that altitude distributions of emissions could not be determined directly from the data the backup position was to determine the total column emission rate in the nadir and infer height profiles from previous sounding rocket measurements.

The orbit flight sequence for both science mission requirements is listed in Table 2. The sequence elapsed time is given in column 1. The full sequence begins with the astronaut activated GCD relay operation at the Orbiter sunset or a solar depression angle of zero degrees. Solar depression angle (SDA) is given in column 3. The solar depression angles are based on an assumed low inclination circular orbit at 300 km altitude and an orbit period of 90 minutes. Because shadow observations were required it was decided to key the entire sequence on local sunset as it was an easy event for the responsible Payload Specialist to identify. The 6 minute wait at the beginning serves only to delay observation until a SDA of about 30° is reached. The full sequence allows for pre- and post-observation calibrations and dark count determinations and 1274 seconds of data acquisition. The 600 second error accompanying the time for GCD deactivation is included because NASA could not guarantee a timing precision greater than this. The event was therefore delayed so that it would not impact on the observations.

FLIGHT PERFORMANCE

The experiment achieved two observing periods or approximately one hour of operating time from a 325 km, circular orbit inclined at 28.5° to the equator. The first period was devoted to the nadir viewing mode and the second included a limb scan as an experiment of opportunity instead of zenith observations. Following post flight recovery of the payload the data were inspected with rather unexpected results. Firstly there was no evidence of any data having been recorded during the first pass. In addition there was a complete data set corresponding to the second pass and all the diagnostics were valid but all the photometer counts were zero. This initiated a comprehensive study of the payload mainframe hardware, software and the science instruments. The problems were identified and are discussed below.

The first observation sequence was initiated but not executed because of an error in the sequencer program. The error, while simple, went undetected in the preflight tests. When a sequence is terminated prematurely a flag is set in the PHOTONS sequencer that prevents the next sequence from initiating. All the next sequence initiation accomplishes, following premature termination, is to reset the flag so that the next set of observations can take place normally. This reset permitted the second set of flight observations to be made. A premature termination of measurements during payload testing following preflight integration at Goddard Space Flight Center caused that flag to be set. That particular bug in the program escaped attention during the otherwise detailed preflight tests, i.e., it was never tested because it could not happen during flight and all real flight possibilities were tested.

The reason for the photometer failures was that all the photomultipliers had lost vacuum and it was initially believed that they had sustained mechanical damage during the powered portion of the flight. Further study revealed that they all had been poisoned only by helium. There was no spectrographic evidence of any other gas in the envelopes, which verified that the tubes had not leaked. Two tubes, one of each type, were further checked by Hamamatsu who confirmed the absence of mechanical damage. These tests verified that the tubes were suitable for surviving the environmental conditions encountered on Shuttle flights. The cause for the helium poisoning was the GAS canister overpressure, at 34.5 kPag using helium, which NASA applied in order to verify that the canister seal was tight. It is known that synthetic fused silica, the tube envelope material, is very susceptible to penetration by helium. The canister was later purged with dry nitrogen and stored at a nominal pressure of one atmosphere until flight.

Further testing of the circuitry involved replacing the tubes with good ones. When this was done the photometers functioned normally. This result proved that the electronics had survived Shuttle Flight conditions. Thus, it is known that the photometers would have provided data had it not been for an identified programming error and an unfortunate choice by NASA for the type of leak test applied to the canister. Detailed testing of the payload mainframe showed that it performed flawlessly after the flight except for the software error noted above.

Table 3. Temperatures experienced in four GAS payloads on three missions. All data except those for G-494 (PHOTONS) are from Butler (1986). Columns 3 and 4 show temperatures at a MET of 54 hours and the mission minimum respectively. See text for details.

Payload	Mission	T °C 54 hr MET	T °C minimum
G-345	STS 7	-7	-19
G-347	STS 8	-8	-11
G-470	STS 61-C	-5	-11
G-494	STS 61-C	+1	---

The first recorded night side pass was initiated at a mission elapsed time (MET) of about 54 hrs and 13 minutes. Until then the payload had not dissipated power. The array of temperature sensors in the payload all indicated a temperature of 1°C at that time. Selected temperature data from four GAS payloads, including PHOTONS, are given in Table 3. Temperatures corresponding to the MET of PHOTONS operation are listed in column 3 and the overall mission minima are shown in column 4. These results all correspond to dissipation free canisters. It can be seen that at 54 hrs MET PHOTONS was between 6° and 9° warmer than the others. The results also suggest that the minimum temperature reached by PHOTONS was in the range of -11° to -19°C, or warmer, if its temperature profile was comparable with those for the other GAS payloads. Unfortunately, the minimum temperature was not recorded. The PHOTONS measured internal temperature, and probably the entire flight profile, were well within the design operating range of -30° to +30°C for the photometers. Typical temperature variations throughout the payload were +2°C with area extremes ranging between 0° and +9° during the one data set recorded. The typical change of +2° corresponds to the extreme expected for 70 W input to an assumed equivalent of 84.8 kg of aluminum for 30 minutes with no external heat losses.

The experiment flew pressurized with dry nitrogen at a nominal pressure of one atmosphere. The pressure level set by NASA prior to flight is not accurately known but two very useful measurements by the internal transducer do exist. During flight at a MET of 54.2 hrs and a temperature of 1°C the internal pressure was 87.7 kPa. A second measurement was made after payload recovery, but prior to opening the unit, i.e., before breaking the seal. That measurement was 94.6 kPa at 23°C. Application of the thermodynamic gas equation to the flight measurement in order to normalize the 23° increased the value to 94.6 kPa. This value agrees exactly with the post flight atmosphere in the canister. It is therefore reasonable to assume that there was no significant leakage of gas from the payload after the second flight turn on and that the seal on the viewing window worked well.

Table 4. PHOTONS transmission function and calibration data prior to and after the flight.

	PREFLIGHT				POSTFLIGHT	
Channel	λ_0 (nm)*	FWHM (nm)	Sensitivity (R/count)	Threshold (R)	λ_0 (nm)*	FWHM (nm)
1	288.3	7.3 ± .2	.27	1.3	288.0	7.2 ± .2
2	558.2	2.33 ± .07	.048	.19	558.3	2.41 ± .07
3	625.5	1.15 ± .04	.044	.20	625.3	1.11 ± .04
4	630.5	2.19 ± .07	.071	.14	630.4	2.22 ± .07
5	764.6	2.79 ± .09	.13	.41	764.8	2.66 ± .09
6	826.3	.92 ± .03	.079	.73	826.4	.96 ± .03
7	865.2	8.2 ± .3	.20	.45	865.2	7.9 ± .3

*The uncertainty in each center wavelength (λ_0) is ±.2 nm

The transmission function data before and after the flight are given in Table 4. It is possible only to give the absolute calibrations and instrument thresholds prior to flight because of the tube contamination by helium. Comparisons with new tubes would be meaningless because sensitivity changes could be much larger than those considered here. The center wavelengths (λ_0) for each channel are given in Table 4 in columns 2 and 6 for pre- and post-flight respectively. The maximum error in each measured value for λ_0 is estimated to be ±0.2 nm. It can be seen from the results that both sets of measurements agree within error limits. The pre- and post-flight measurements of the bandwidths are tabled in columns 3 and 7 together with the estimated maximum error in each measurement. The two sets of results agree with each other within error limits in all cases. It is therefore concluded that no irreversible changes occurred in the transmission functions as a result of the flight.

The digital tape recorder produced a good copy of the primary EPROM data set and it will be incorporated in at least one more future Shuttle flight of this payload.

CONCLUSIONS

(i) A sensitive Shuttle GAS payload that is suitable for making optical observations of nighttime terrestrial atmospheric emissions in the nadir and the limb and of Shuttle ram glow has been developed and has completed a successful engineering test flight. The science demands for such a GAS payload should not exceed specific limitations that are characteristic of the GAS carrier. Those limitations are:

(a) a pointing accuracy of no better than ±15°
(b) small data sets
(c) no complex shuttle manoeuvres.

(ii) A functional sealed viewing window assembly with UV transmitting ports has been developed for the experiment.

(iii) The single event temperature observed within the payload after 54.2 hrs of passive flight time on Shuttle was 1°C. This temperature is between 6° and 9° warmer than corresponding flight temperatures in three other non-dissipating GAS payloads.

(iv) No irreversible changes were observed in the instrument transmission functions following the flight.

(v) The Sea Data digital tape recorder worked well as a backup data recording device.

(vi) A reflight of the payload should yield the desired scientific return provided that the difficulties experienced during this flight are not permitted to recur.

(vii) The significance of ground operations in a program of this type should not be underestimated.

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