Calibration of the Receiver Channel for the GOPEX Precursor Experiments

A. Biswas
Space Materials Science and Engineering Section

Calibration measurements for the cooled (253 K) photomultiplier tube (PMT) detector, used on the receiver channel of the transmit/receive (T/R) switch for GOPEX, were conducted in the laboratory. A pulsed frequency-doubled neodymium:yttrium-aluminum-garnet (Nd:YAG) laser was used to direct 532-nm light on the PMT. By monitoring the energy per pulse of the light incident on the PMT, the minimum number of photons detected could be determined. These results agreed with the photon flux back-calculated from the PMT output waveform. Approximately 700 incident photons arriving during a temporal pulse width of ~65 nsec were detected with a signal-to-noise ratio (SNR) of ~1. Other receiver channel characteristics, such as PMT dark currents, optical transmission, and interference filter sensitivity to angle of light incidence, were also measured.

I. Introduction

GOPEX was successfully concluded on December 16, 1992. Key to the success of this experiment were the precursor experiments that preceded GOPEX. These experiments were used to calibrate the laser transmitters from both the Starfire Optical Range (SOR) and Table Mountain Facility (TMO) sites, by retro-reflecting the laser beam from specifically targeted Earth-orbiting satellites. The retro-reflected signal was detected using a gallium arsenide (GaAs) PMT. A polarizing beam splitter was used at SOR and a holey mirror was used at TMF to separate the T/R signal paths.

This article describes the calibration of the T/R switch that was used at TMF to detect the satellite return signals. The switch, shown in Fig. 1, consisted of a 10-cm diameter, dielectrically coated reflecting surface (R > 99 percent at 532 nm for 45-deg incidence) along with two similarly coated relay mirrors that were used to relay the signal to the PMT. An interference filter was positioned in front of the PMT to reduce the amount of background light detected. The receiving train was characterized both on a component level and as an integrated system. The results of these tests are presented here. The T/R switch was characterized over the range of signal levels expected for the satellite returns. These ranged from tens of photons for the distant Etalon satellites (20,000 km) to thousands of photons for the close Earth-orbiting Ajesai satellites (1500 km).

II. Objectives

The four objectives of this work were:

(1) Characterize PMT at room temperature (295 K) and after cooling to 253 K.

(2) Measure optical transmission at 532 nm for the T/R switch with and without the 532-nm interference fil-

ter. This measurement allowed a determination of the transmission losses of the interference filter.

(3) Measure the sensitivity and dynamic range of the PMT using single laser pulses and assess recovery time for the PMT. Scintillation effects due to atmospheric turbulence can result in large variations in the return signal strength. This measurement would enable evaluation of the detector's linear range.

(4) Measure transmission of the 532-nm interference filter as a function of the angle of incidence. This measurement would provide a better estimate of detected signal strength for less than optimal alignment of the relay mirrors, i.e., non-normal incidence of return signal on the filter.

III. Experimental Setup

The optical arrangement depicted in Fig. 2 was used to measure the sensitivity and dynamic range of the receiver channel detector. A Q-switched, frequency-doubled Nd:YAG laser operating at a pulse repetition rate of 3.5 kHz, and a temporal pulse width full width at half maximum (FWHM) of ~65 nsec, was directed through the optical receiving path of the T/R switch and brought to incidence on the GaAs photomultiplier tube (PMT) detector.[1] The PMT output was displayed on an oscilloscope.[2] The 1.06-μm high-reflectivity (HR) flats shown were used to filter the residual fundamental frequency (1.06-μm wavelength) laser light from the signal. The power/energy meter[3] was used to measure the beam energy to the T/R switch. The beamsplitter (BS) reflected a fraction of 532-nm light onto a fast photodiode,[4] the output of which was displayed on the oscilloscope. This photodiode signal served as a reference. A 10× attenuation filter was used in front of the photodiode to extend the range of laser energies over which measurements could be made without saturating the fast photodiode detector. A 532-nm pass interference filter was positioned at the T/R switch exit port. A green-light-blocking filter[5] served as a fixed attenuator at the entrance port of the T/R switch, while neutral density (ND) filters were used to attenuate the beam to the desired power level.

[1] Manufactured by Burle Electron Tubes (PMT Serial number 96684, base serial number 31304/0076/0588; 1874-92).

[2] Tektronix DSA 602A.

[3] Photodyne Model 300 head connected to Model 66XLA readout.

[4] Newport Model 877.

[5] LASER-GARD series LGA, supplied by Newport Research Corporation.

IV. Results

(1) Characterization of the PMT at room temperature and at 253 K.

The PMT dark current was measured using an ammeter,[6] first at room temperature and then at ~253 K. At room temperature the dark current increased monotonically with increasing anode voltage and was ~8 nA at 1400 V. At 253 K and 1400 V, typical dark currents were 0.007 nA with occasional spikes registering as much as 0.02 nA. These measured values were consistent with the manufacturer's specifications. The PMT dark pulses were typically 10 nsec wide (FWHM).

(2) Measurement of the optical transmission.

The first step in measuring the optical transmission of the T/R switch at 532 nm with and without the 532-nm interference filter was to maximize the PMT output signal.

This was done to ensure optimum alignment of the optical train. With the holey mirror rotating at 30 Hz, the PMT signal was observed on an oscilloscope.[7] The expected waveform resulting from periodic light blockage confirmed the optical alignment. The holey mirror for the T/R switch was then disconnected and fixed so as to reflect all the laser light to the PMT. Light transmission measurements, with and without the interference filter, were made using the power/energy meter; these results are shown in Table 1. From the data in Table 1, the return path transmission of the T/R switch was calculated at 75 percent, and at 48 percent with the interference filter.

(3) Measurement of the sensitivity and dynamic range of the PMT using single laser pulses.

The photodiode reference signal was calibrated against the Photodyne energy meter by operating the laser in a single pulse mode and comparing the peak voltage of the detector to the output of the energy meter. This calibration was accurate to within 14 percent; the shot-to-shot variation of the laser pulse width. Figure 3 shows the calibration data. Linear regression of the data yielded a slope of $5.93 \times 10^{-4} \pm 7.84 \times 10^{-5} \mu J/mV$. The calibration constant was used to convert peak millivolts detected by the photodiode to laser energy incident at the T/R switch.

[6] Keithley Model 485.

[7] Tektronix Model 2215A.

Figure 4 shows typical simultaneous acquisitions made with the reference photodiode (positive-going pulse) and the PMT (negative-going pulse) positioned as shown in Fig. 2. The FWHM measured on both traces is approximately 65 nsec. The laser after pulsing detected by the photodiode was not detected by the PMT because of the large attenuation in the optical train of this detector. The alignment of the reference detector (fast photodiode) with respect to the split fraction of light incident on it was maintained and periodically checked to ensure accurate determination of actual laser pulse energies incident on the T/R switch.

Figure 5 is a plot of the PMT response as a function of the microjoules of incident energy. Each data point represents a single 65-nsec FWHM laser pulse. The data indicate that for pulse energies greater than $\sim 1.5 \mu J$, the PMT response becomes nonlinear. A linear regression of the data in Fig. 5 over the expected operating range (1 nJ – $1 \mu J$) yields a slope of 0.85 $V/\mu J$.

A LASER-GARD filter was used at the T/R switch entrance to attenuate the incident laser beam and enable characterization of the T/R switch at the low photon levels expected in the retro-reflected returns from the higher satellites. The filter's optical density was 6.53 at 532 nm, and it enabled calibration of the receiver down to a few hundred photons incident on the PMT. The results are shown in Fig. 5 where the PMT peak voltage is plotted against the energy incident on the PMT and against the number of photons on the upper horizontal scale.

The number of photons incident on the PMT was confirmed from a calculation of the area under the waveform. This was done as follows: The FWHM of the laser pulse was multiplied by the anode current (determined from the peak voltage divided by 50 ohms, the output impedance of the PMT). This product represents the charge on the anode. The anode charge was divided by the gain (1.2×10^5) to determine the number of photoelectrons generated at the cathode. This was then divided by the PMT quantum efficiency (QE$\sim$0.145) and the energy per photon to determine the number of photons incident on the cathode. Table 2 shows the results.

The noise equivalent power (NEP) estimated from the low level signals was 10^{-13} W. The recovery times of the PMT over the range of pulse energies used during the investigations were found to be excellent in that no "ringing" was observed.

(4) Measurement of transmission of the 532-nm interference filter as a function of angle of incidence of the laser beam.

To measure the angular dependence of the interference filter transmission, the filter was mounted on a precision rotary mount, ensuring normal (0-deg) incidence by checking for auto-collimation (Fig. 6). The rotary stage was used to increment the angle of incidence while monitoring the transmitted laser power through the filter. Data were recorded by the power/energy meter for clockwise and counterclockwise angular rotation of the filter. The data show that the filter transmission remains >90 percent for up to a 4-deg angle of incidence. These results show that there is no significant loss in signal strength for small (<3 deg) deviations in incident angle introduced as the relay mirrors steer the return beam to the PMT.

V. Conclusions

The T/R switch used for detecting the retro-reflected signals from target satellites was characterized. The results show that the detector assembly would readily measure return signals from low Earth orbiting satellites, such as Ajesai. The PMT's 10^{-13} NEP indicates that this system can measure the tens of photons in a 10-nsec pulse expected from the high Earth orbiting Etalon satellites.

This article also gives the results of the measurements of (1) the performance of the PMT at room temperature versus that at 253 K and (2) the angular dependence of the interference filter transmission. The data show that cooled PMT operation is mandatory if one is to detect the anticipated low signal levels and that the transmission losses through the interference filter remain within 90 percent of peak for angle of incidence less than 4 deg.

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Table 1. Measurement of optical transmission at 532 nm for the T/R switch with and without the 532-nm interference filter.

Power meter location	Mean pulse energy, μJ
Entrance of the T/R switch	34.54 ± 1.76
At the exit port, with the 532-nm interference filter	16.67 ± 2.03
At the exit port, without the 532-nm filter	25.9 ± 2.5

Table 2. A comparison of the number of photons calculated using the deduced single shot laser energy from the photodiode measurement and estimated from the waveform simultaneously recorded by the PMT.

Peak, mV photons	FWHM, nsec	Number of incident photons measured using calibration curve from Fig. 5	Number of incident photons measured using the PMT waveform
2	18	700	638
36	67	1.56×10^4	1.73×10^4
175	63	5.70×10^4	7.92×10^4
412	55	1.55×10^5	1.63×10^5
461	68	1.71×10^5	2.27×10^5
629	60	2.39×10^5	2.72×10^5
2106	78	1.18×10^6	1.18×10^6

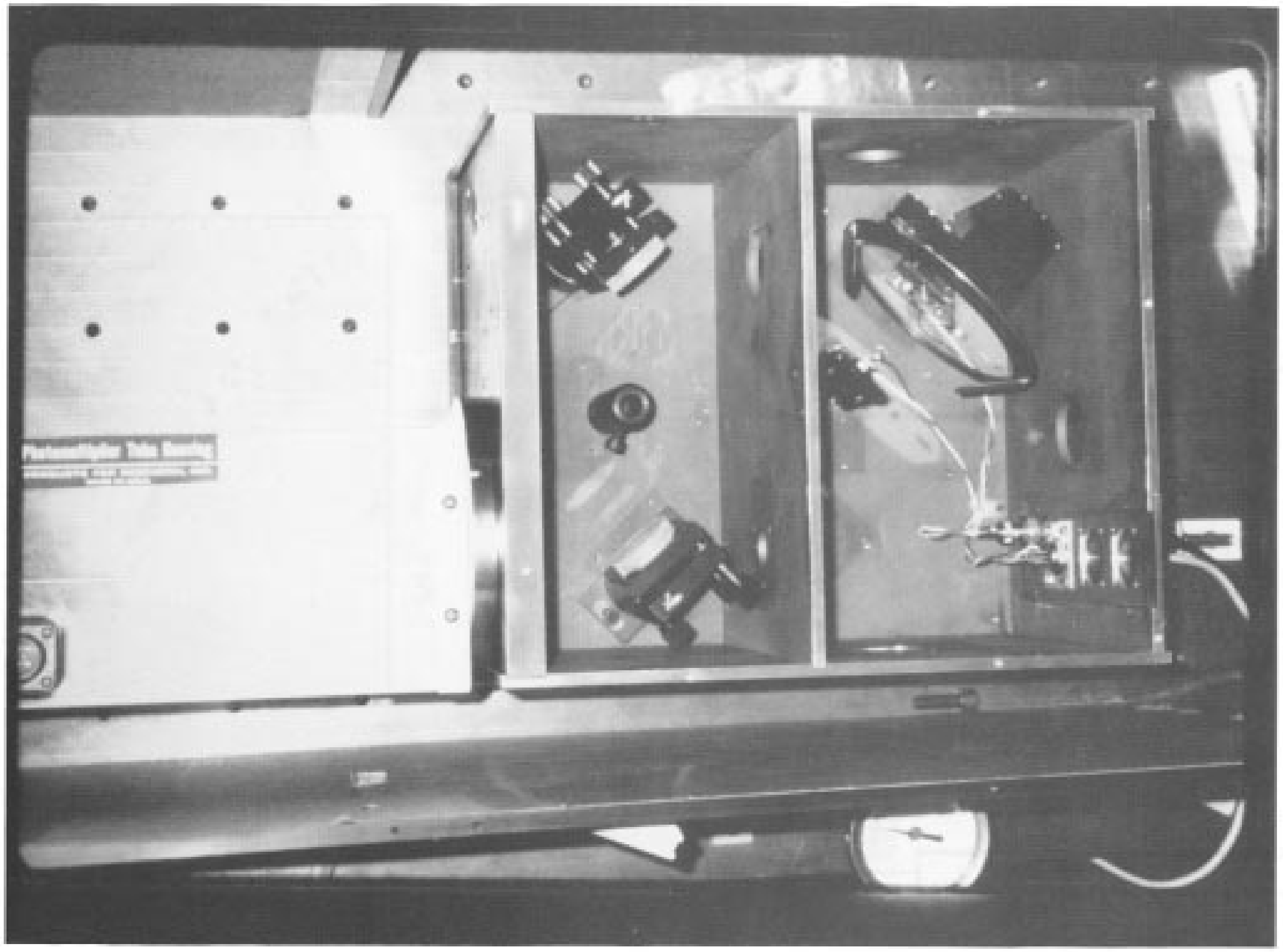

Fig. 1. Photograph of T/R switch with top cover removed. The 10-cm holey mirror consisting of a dielectrically coated surface is shown in the right chamber. The two relay mirrors that direct the return signal to the photomultiplier tube are shown in the left chamber tube. A polarizing beam splitter at SOR and a holey mirror at TMO were used to relay the return beam to the detector.

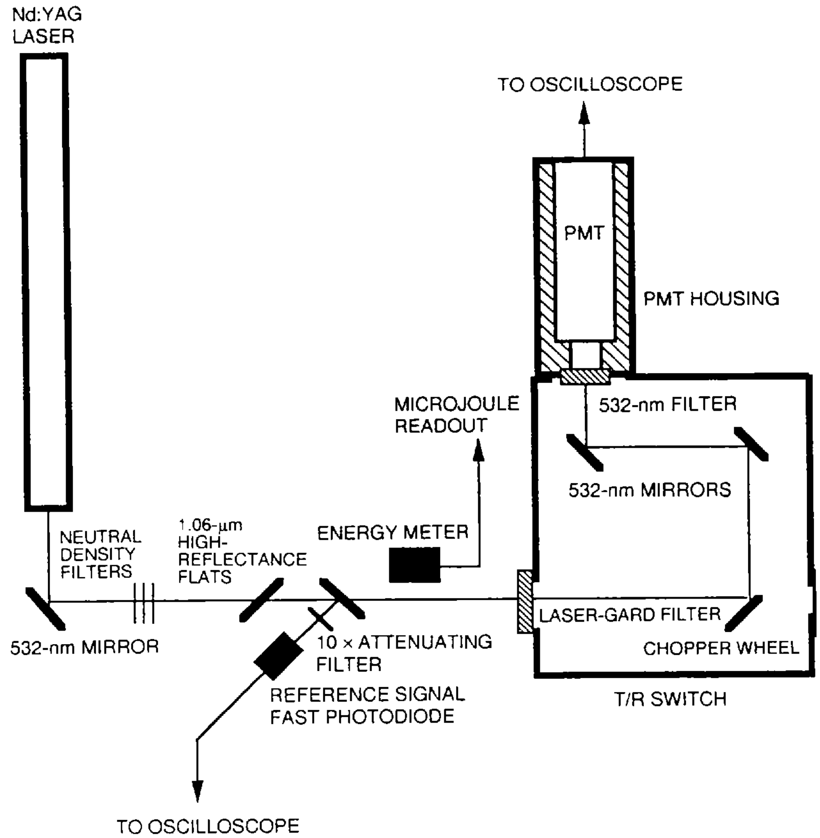

Fig. 2. Schematic experimental arrangement used for calibration of the receiver channel of GOPEX.

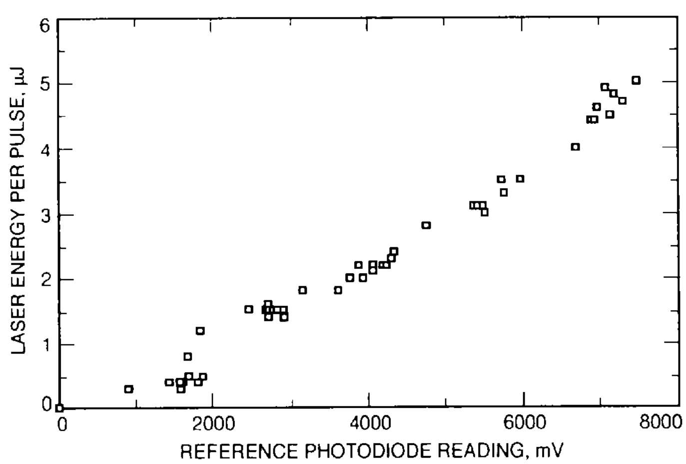

Fig. 3. The calibration curve used to convert photodiode-pulse peak heights to laser energy.

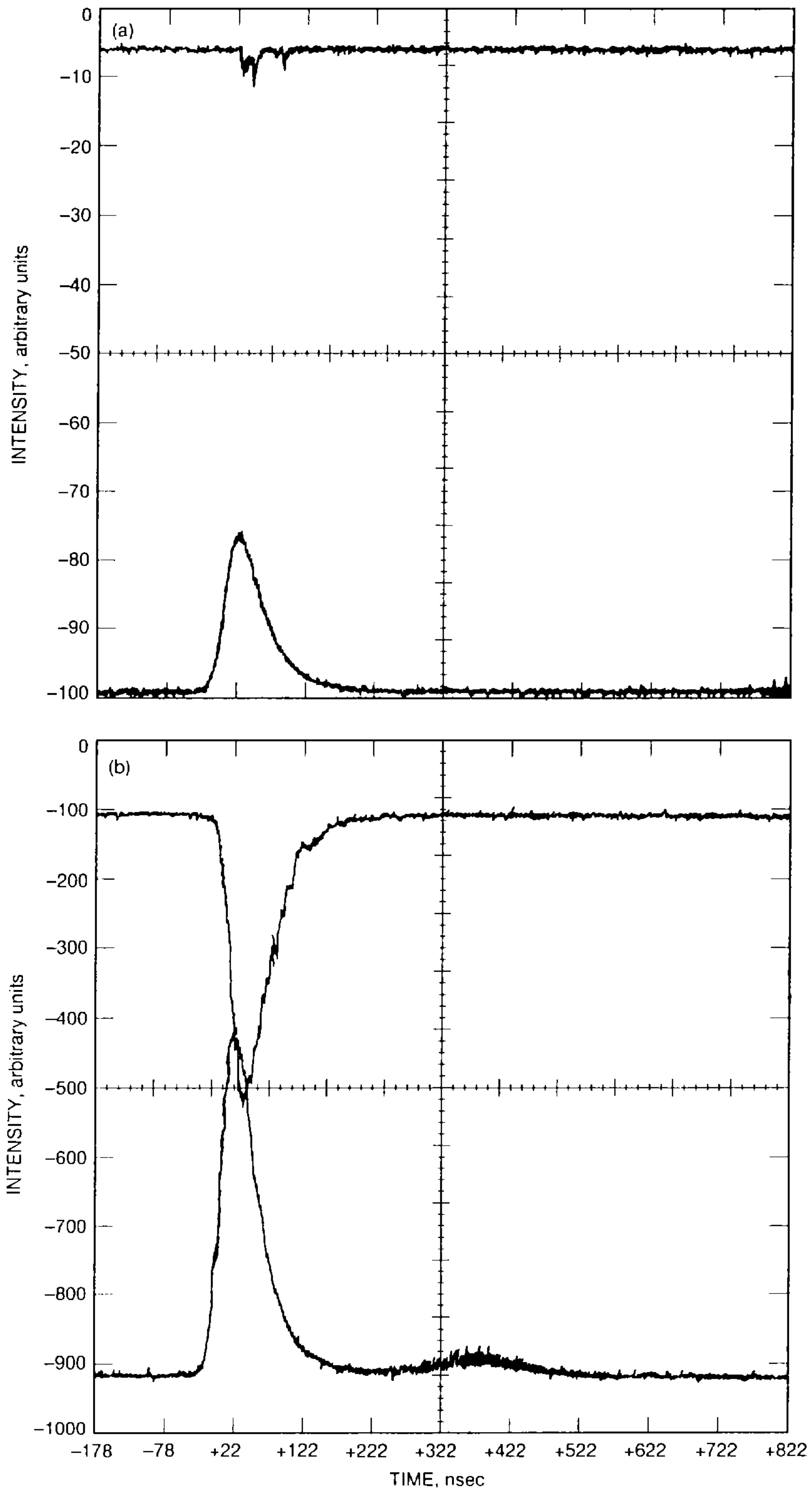

Fig. 4. Representative simultaneous data acquisitions made on the PMT (negative-going pulse) and reference signal (positive-going pulse) using the Tektronix DSA 602A oscilloscope: (a) ~0.001-μJ incident energy, and (b) ~0.3-μJ incident laser energy.

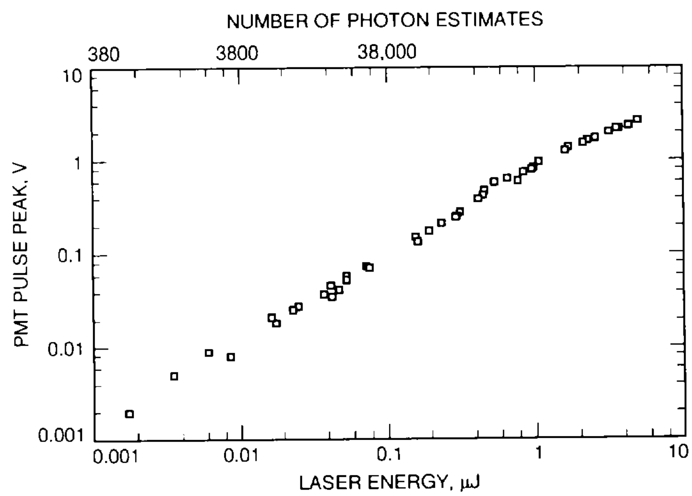

Fig. 5. The PMT response to 532-nm, 65-nsec single laser pulses. The abscissa shows the laser energy incident on the LASER GARD filter at the entrance of the T/R switch. The corresponding photodiode pulse peak heights are shown on the ordinate. The upper right horizontal axis indicates the actual number of photons incident on the PMT after correcting for the attenuation of the LASER GARD filter and T/R switch transmission.

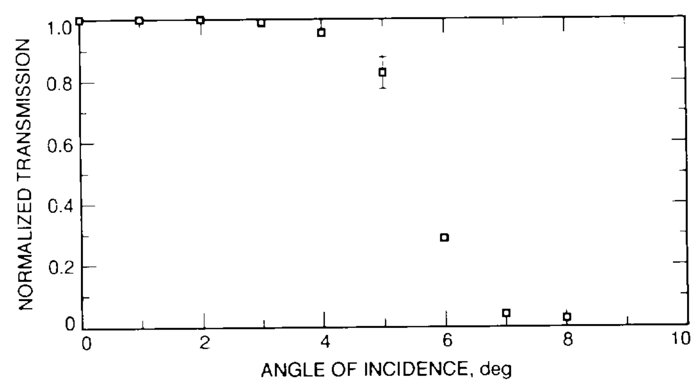

Fig. 6. Transmission of the interference filter as a function on the angle of incidence. The filter transmission remained greater than 90 percent for angles of incidence of 4 deg and less.