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Hamamatsu R5900-01-L16 Photomultiplier Tube Spectral / Spatial Characterization

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06/1/00

Introduction:

In the field of radiometry the need for accurately calibrated detectors cannot be stressed enough. Only through highly calibrated instruments can there be highly accurate information. In lidar (Light Detection and Ranging) applications the use of a photomultiplier tube (PMT) as a detector is desired because of its fast rise time, linearity, and extremely low signal induced noise. However, an attribute that must be corrected in order to obtain precise variations in the detected signal is spatial uniformity.

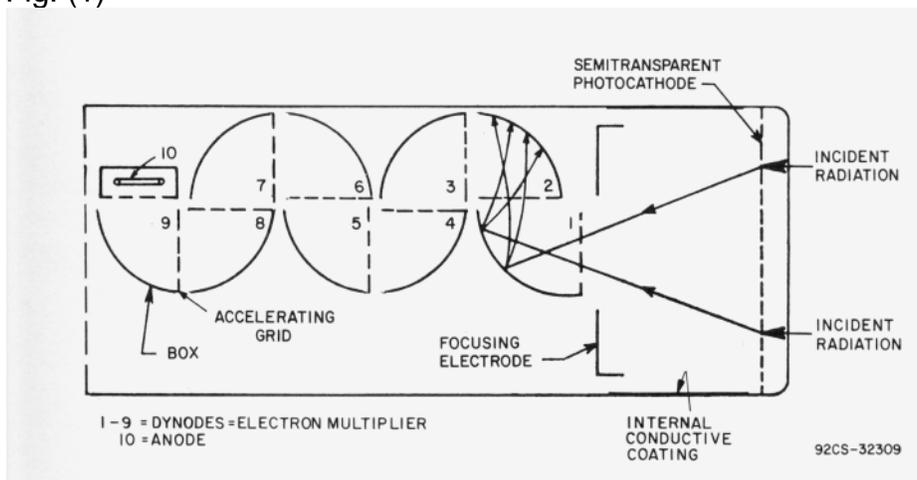
The spatial uniformity of the PMT is described as the variation of sensitivity across the effective area of the photocathode. In developing a lidar system the effects of spatial non-uniformity can be best eliminated by characterizing the spatial properties of the PMT then devising a way to reduce the effects and then calibrate out the rest.

The use of the Hamamatsu R5900U-01-L16 PMT as a lidar detector will be considered. Mainly a spatial uniformity and spectral response characterization will be performed. The PMT to be characterized consists of a multi-anode 16 channel linear array. Each channel contains a spectral filter, which results in spectral dependence of the output.

Background:

The photomultiplier tube is a very sensitive radiant energy detector within the 200-900 nm range of the electromagnetic spectrum. The principle of PMT light detection is illustrated in fig(1). Incident light is absorbed by the photocathode that in turn emits electrons, referred to as photoelectrons. Electrons are directed by an electric field to a dynode. For each incident electron a number of secondary electrons are emitted. The secondary electrons are then directed toward a 2nd dynode and so on. Ultimately an anode collects the electrons and provides the signal current, which can be measured.

Fig. (1)



The typical gain of a PMT is on the order of 10^6 . This high gain eliminates the need for amplifiers and the applied voltage controls its range of gain providing flexibility in operation. The rise time of a typical PMT is in the vicinity of 1 to 2 nanoseconds, depending on the load resistance. The cathode dark current of a PMT is affected considerably by temperature where its sensitivity and gain change very little with temperature fluctuations. Dark current at room temperature are on the order of 10^{-15} amperes at the photocathode and double about every

10 degrees Celsius.

At low light levels the signal to noise ratio will limit detection and measurement. A way of describing the limit to detection is the Noise Equivalent Power (NEP), which is the power into the device, which invokes a signal equivalent to the noise. A typical PMT NEP rating at 1hz bandwidth of 400nm illumination is $7 \cdot 10^{-16}$ watts. The stability of a PMT is less than satisfactory. Although when operated at low anode currents stability is improved, best accomplished by adjusting the supply voltage to best suit the detection situations.

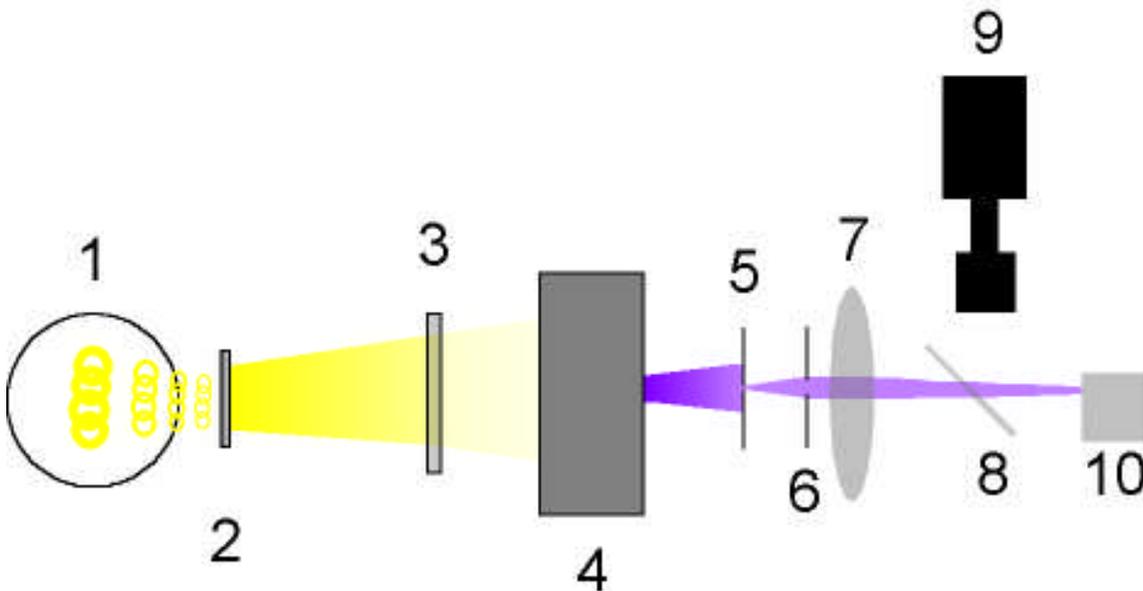
Experimental Methods:

Light Source Characterization:

Determining the characteristics of the light source that will be used in the calibration of any light detector is crucial in order to obtain reliable results. The important characteristics of the light source used to characterize the Hamamatsu PMT will be spectral radiant intensity at the image plane for each step of the monochromator over the range of 300-800nm, and light spot diameter at the image plane.

Figure (2) illustrates the optical path. Below is a listing of the optical components.

Fig. (2)



- 1: 32 Volt, 210 Watt GE Tungsten Bulb
- 2: Ground Glass
- 3: Neutral Density Filter
- 4: Monochromator
- 5: Pinhole
- 6: Aperture
- 7: Cemented Doublet Lens
- 8: 50:50 Beamsplitter
- 9: CCD Camera
- 10: CCD/Radiometer/Photomultiplier Tube

The optical path begins with a tungsten source emitting a Planck color temperature of about 2000 K. The light is first scattered by ground glass to produce a fairly even solid angle of flux. Since the optical detector under inspection will be a highly sensitive photomultiplier tube a neutral density filter is placed in the optical path to reduce the incident light upon the photocathode. Preliminary image plane irradiance measurements will be taken with a radiometer without a N.D. filter in place in order to characterize the source. The light flux is

then attenuated by the monochromator resulting in a narrow bandwidth of light. The flux leaves the monochromator through an exit slit then passes through a pinhole, which will provide the "image" of a spot. Next an aperture is put in place to cut out any stray light that may make it to the lens and blur the image. The lens used will be a cemented doublet, which shall provide accurate chromatic focusing within a very shallow depth of focus. Element 8 is a beamsplitter that will be discussed shortly, for now the light flux transmits through the beamsplitter and focuses to a point in space.

The beamsplitter and 2 CCD video cameras are used in finding the focal plane of the setup. First I use a CCD camera without a lens in position 10 of figure (2) and adjust its location until a crisp image of the spot is viewed on the video monitor. I then use the second CCD camera in position 9 and focus upon the CCD chip of the first camera. I now know that the CCD camera in position 9 is focused in the image plane of the optics setup. I can now remove the cameras at position 10 and precisely place another element into the image plane by adjusting it's location until it is focused through the CCD camera in position 9.

Determination of Spectral Radiant Intensity at Image Plane:

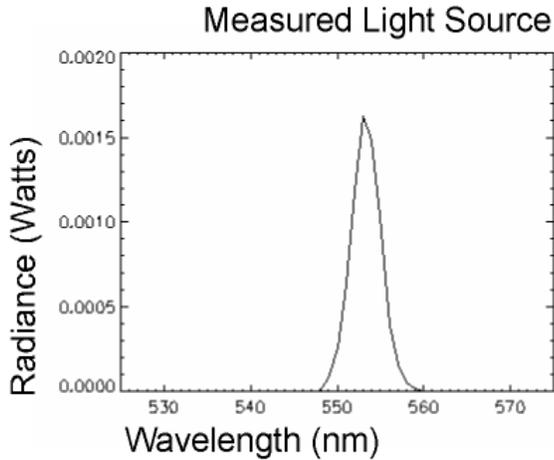
In determining the radiant intensity at the image plane a highly sensitive radiometer (ASD) was used to measure the light. I allowed the bulb to warm up while dissipating 210.87 watts and allowed the sensor of the ASD to cool for 60 minutes to improve stability. The fiber optic bundle was placed into the image plane by the method described above then I scanned the optic bundle across the imaged light spot until a high signal to noise ratio was received from the radiometer. The spot illuminated 3 of the 19 fibers within the bundle that collect light in the visible region. After collecting spectra from 380nm to 860nm in 1nm increments post

processing was necessary to adjust the signal units from: $\frac{Watts}{m^2 sr}$ to: *Watts*. First to multiply out the steradians unit I must determined the solid angle subtended from a field of view of 20 degrees. This relationship is shown in equation (1).

Eq. (1)
$$\Omega = 4\pi \sin^2\left(\frac{1}{2}\Theta_{1/2}\right)$$

Where $\Theta_{1/2}$ is one half of the field of view. Next the spectrum was multiplied by a factor of $\frac{19}{3}$ to account for the spot illuminating only 3 of the 19 fibers that collect visible light. Then the spectrum can be corrected for the true area of illumination by multiplying by the area of the spot. Figure (3) illustrates a spectra after processing.

Fig. (3)



Determination of Spectral Throughput of Photocathode Filter:

One of the unique features of the Hamamatsu R5900U-L16 PMT is that it has 16 separate photocathodes. A different spectral filter precedes each photocathode so that the 16 signals obtained from a read out correspond to irradiance from a band of the spectrum. It would be of importance to determine the spectral transmittance of each filter so that processing of the output signals lends more information. In the case of oceanographic lidar applications, multi-spectral imaging is important due characteristic emission spectra of the water's constituents.

To determine the spectral transmission of each filter, certain characteristics of the system shall be considered. In understanding the signal received from the PMT's anode one must consider the illuminating energy source, the throughput of the optical path, the properties of any filter preceding the photocathode, the photocathode radiant sensitivity, along with the gain of the PMT. In most situations the energy source or illumination onto the PMT is unknown; hence the use of the device to measure it. In this case if all other parts of the system is known the 'inverse problem' can be solved to determine the characteristics of the incident energy. Equation (2) is a mathematical expression relating the incident radiant intensity, $p(\lambda)$, the spectral transmission of the filter, $f(\lambda)$, the photocathode radiant sensitivity, $r(\lambda)$, and the gain, g , to the output signal, s .

$$\text{Eq. (2)} \quad g \cdot \int_{-\infty}^{\infty} p(\lambda) \cdot r(\lambda) \cdot f(\lambda) d\lambda = s$$

In this problem a 'dc' signal is obtained. If the spectral properties of the light source were to vary we would expect the signal, s , to vary, even if the overall radiant intensity remained constant. This would result from the characteristics of the filter and the photocathode; the gain itself remains constant and can be divided out for simplicity. If we were to vary the spectral properties of the light across the detectable range of the filter/photocathode and measure the signal from each step of $p(\lambda)$ we would have a group of signals correlated with the wavelength of light used to obtain those readings. We can call this constant function, $s(\lambda)$. Equation (3) describes this relationship.

$$\text{Eq. (3)} \quad p(\lambda) * (r(\lambda) \cdot f(\lambda)) = s(\lambda)$$

Where $*$ describes a convolution.

To restate our objective, we are looking to find the spectral transmission of the filter, $f(\lambda)$. We can perform Fourier analysis in order to deconvolve the effects of the light source upon the system. But first to simplify the expression lets combine some terms.

$$\text{Eq. (4)} \quad h(\lambda) = r(\lambda) \cdot f(\lambda)$$

This gives us:

$$\text{Eq. (5)} \quad p(\lambda) * h(\lambda) = s(\lambda)$$

After Fourier analysis and the application of the filter theorem:

$$\text{Eq. (6)} \quad P(\xi) \cdot H(\xi) = S(\xi)$$

Again $H(\xi)$ is unknown, so we must use the expression of Equation (6) and multiply each side by the inverse of $P(\xi)$ to isolate $H(\xi)$.

$$\text{Eq. (7)} \quad \frac{1}{P(\xi)} \cdot P(\xi) \cdot H(\xi) = \frac{1}{P(\xi)} \cdot S(\xi) \quad \text{therefore} \quad H(\xi) = \frac{S(\xi)}{P(\xi)} = M(\xi)$$

To continue we must perform Fourier synthesis to the return to the space domain.

$$\text{Eq. (8)} \quad h(\lambda) = m(\lambda)$$

Insert the equality of Equation (4).

$$\text{Eq. (9)} \quad r(\lambda) \cdot f(\lambda) = m(\lambda)$$

Finally we can solve for the spectral transmittance of the filter.

$$\text{Eq. (10)} \quad f(\lambda) = \frac{m(\lambda)}{r(\lambda)}$$

There are some things to take into account when solving for $f(\lambda)$. First for $f(\lambda)$ to be recovered perfectly the transfer function or as we have called it, the incident radiant intensity, $p(\lambda)$ must be known and have nonzero magnitude everywhere. $p(\lambda)$ is known but has finite bandwidth, thus must have zeros, therefore perfect recovery will not be possible, although a precise estimation can be obtained. Also there must be no uncertainty in $p(\lambda)$ or $s(\lambda)$ such as noise. For this application the PMT has a very high signal to noise ratio so precise approximations are possible.

In the past analysis of the system there has been an assumption; that the incident

radiant intensity of the source is constant across the spectrum under analysis, 400-800 nm. For the tungsten source used in the experiment the spectral radiant intensity is not constant and the obtained PMT signal must be adjusted to account for the non-uniformity. To do this the radiant intensity of the source will be normalized then used to divide the raw output PMT signal. The result will be an adjusted signal corrected for the non-uniformity of the sources power spectrum. The following procedure will be accurate due to the linearity of the PMT response.

Determination of Photocathode Non-uniformity:

The spatial non-uniformity of a PMT is defined as the variation of its sensitivity across its effective area. In order to determine the uniformity of the photocathode a spot source will be used to illuminate a finite area of the photocathode and an output measurement taken for that position. The source will be raster scanned across each channel in spot diameter increments, and a measurement taken at each step. A comparison of the outputs will lend information as to the non-uniformity of the photocathode. In order to compare all channels, which are preceded by different filters, some simple corrections will be applied to the outputs.

For a given channel, the source spectrum of maximum transmission will be used to test uniformity. From this and other information about the spectrum an expected output will be calculated, see equation (???). The measured output will be divided by the calculated output, which in turn will yield a metric comparable with measurements from all channels. This signal adjustment divides out light source, filter transmission, and radiant sensitivity characteristics leaving the variation in radiant sensitivity as a function of position.

Continuation of Characterization:

The characterization of the Hamamatsu R5900U-01-L16 PMT was not completed due to time constraints, although the information contained within this report coupled with the accompanied lab notes and knowledge of the science will supplement another's effort in completing the characterization.

Recommendations for continuation would be to recalibrate the light source so that changes in the efficiency of the bulb over time will not introduce error. If this is done light source post-processing will be affected and will need to be reconsidered, reference to section 'Determination of Spectral Radiant Intensity at Image Plane'. Basically a full understanding of the source at the image plane is needed for precision. The ASD radiometer possesses sufficient detection characteristics to detect the light at the image plane, again post-processing will be required to assign units to the signal.