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Calibration of a Photomultiplier Array Spectrometer

Steven A. Bailey
C. Wayne Wright
Charles R. Piazza

Wallops Flight Facility
Wallops Island, Virginia

NASA
National Aeronautics and
Space Administration

Goddard Space Flight Center
Wallops Flight Facility
Wallops Island, VA 23337

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Summary

A systematic approach to the calibration of a photomultiplier array spectrometer (PAS) is presented. Through this approach, incident light radiance derivation is made by recognizing and tracing gain characteristics for each photomultiplier tube (PMT).

Introduction

Calibration of any instrument is fundamental to its proper operation. Without calibration, an instrument provides data which is of little use. Calibration of a spectrometer involves relating a known input light source to spectrometer output signal levels. Gain adjustments are usually made by increasing or decreasing the integrating time of the sensor with respect to light.

Calibration of a PAS, as found in the Airborne Oceanographic Lidar (AOL), involves making the relationships described above. However, since the integrating time of this particular device is held constant through discrete components, another means is used to adjust gain; device voltage. This paper describes how those voltages are adjusted to achieve calibration. A study of gain characteristics as voltage changes is also presented. Finally, a process is described whereby true radiance measurements can be made with a PAS using any calibrated voltage combination.

AOL

AOL was a joint effort by NASA and AVCO Everett Research LABS (AERL). It was built by AERL and delivered to NASA in 1977. AOL is installed on a NASA P3-A research aircraft based at NASA/GSFC - Wallops Flight Facility, Wallops Island, Virginia. In its present configuration, AOL supports three modes of operation: Fluorosensing, Passive, and Bathymetry. The Fluorosensing mode resolves laser induced fluorescence[1] spectrally. The Passive mode resolves incident light spectrally. The Bathymetry mode resolves laser backscatter[2,3] temporally with transient digitizers.

Components of Calibration

The spectrometer used in the Passive and Fluorosensing modes of AOL consists of a single array of 36 PMTs. The efforts of this paper are solely concerned with the Passive mode of this dual active-passive device[4]. Preceding the array is a transmission diffraction grating with 11.25 nm channel-to-channel separation. An input beam-split-mirror provides adjustment for wavelength calibration and translation.

The PAS power source is a LeCroy HV4032 32 channel programmable high voltage power supply. It contains an on-board microprocessor used to maintain regulated output voltages. Programming of high voltage arrays is via RS-232.

A multiplexed Analogic 10 bit analog to digital converter (ADC) is used to digitize signals received from the passive side of the spectrometer. This ADC and support circuitry rest on a camac card.

Our calibration source is a 30 inch integrating sphere. It is illuminated by an external 200 watt tungsten halogen lamp with 6 removable apertures. Calibration (traceable to the National Bureau of Standards) of the sphere was done in house for each aperture. Light emitted is measured in microwatts/sq.cm/nm/steradian. Sphere calibration measurements are made from 400 nm to 1100 nm in 50 nm increments.

Calibration Method

Preparations

For our purposes, we need the capability of changing power supply voltages in flight while maintaining calibration. To arrive at a calibrated array of voltages, a common numerical method is employed. However, before this is done, we need to define at which wavelength each channel is centered.

We first position a sodium light (with a peak at 589 nm) between a set of given channels. This is done because the sodium peak is narrower than the channel separation of 11.25 nm. Once our beam-split-mirror has been adjusted for sodium light placement, it is locked in place. We now calculate at what wavelength all other channels reside. Using this information along with given sphere calibration radiance constants, radiance constants are calculated for every channel vs aperture combination. Figure 1 is a block diagram of data flow during calibration.

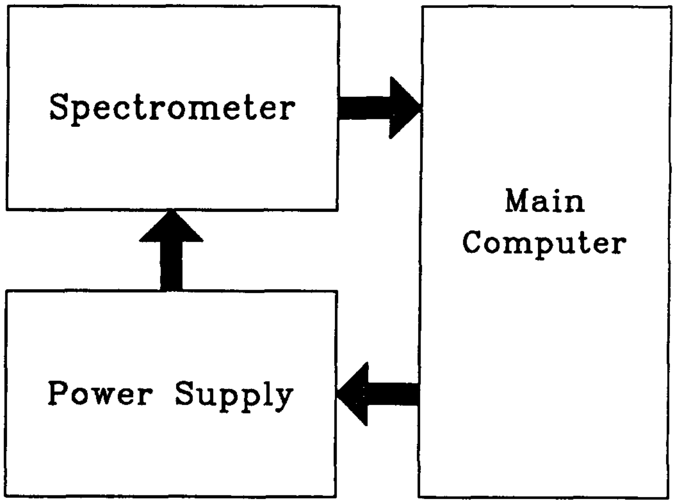

Figure 1. Calibration data flow.

Past technique

At this point, for any aperture used in the cal sphere, we know the center wavelength and corresponding radiance value for each channel of the PAS. The next procedure involves choosing a particular channel as key channel. This key channel becomes our reference point from which all channels are compared. We put an arbitrary voltage on that channel; so gain on that PMT supplies signal enough to register counts from the ADC. Generally, a red channel is used as the key because the cal spheres output is much higher in the red region as shown in Figure 2.

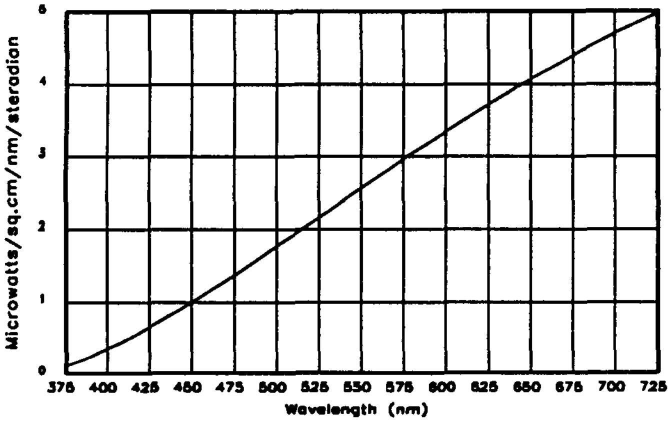

Figure 2. Cal sphere spectra using aperture 0.

In the past, calibration was done at selected voltages. When a spectrometer sensitivity change was needed, one of those preselected voltages was chosen. If a desired sensitivity was not found, a compromise was made. Sensitivity was accepted or calibration files were manually cut and pasted together to achieve desired sensitivity in the chosen channels. This led to considerable work by the user, not to mention storage and documentation requirements for the various voltage combinations.

Current technique

The secant method[5] is the numerical technique used to generate calibrated voltage arrays. This technique quickly finds the root of a function. In this application, the root we are searching for is a voltage which causes desired counts from a particular channel. We set a key channel voltage and note the counts read back. This key is our reference point. The count value read from this key channel is linearly related to the appropriate radiance value. In doing this, we relate known radiance values for all other channels to desired count values. We now iterate (using the secant method) on all other channels to achieve desired counts. Once these count values are found, calibration for that set of radiance constants is complete. Figures 3 and 4 represent spectra before and after calibration has been applied.

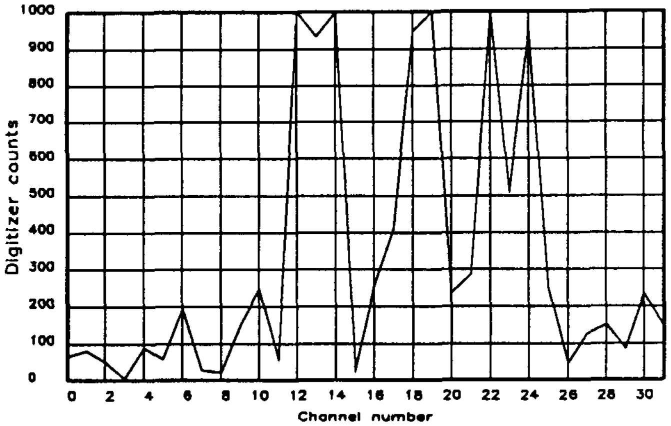

Figure 3. Uncalibrated spectra using constant voltage across all channels.

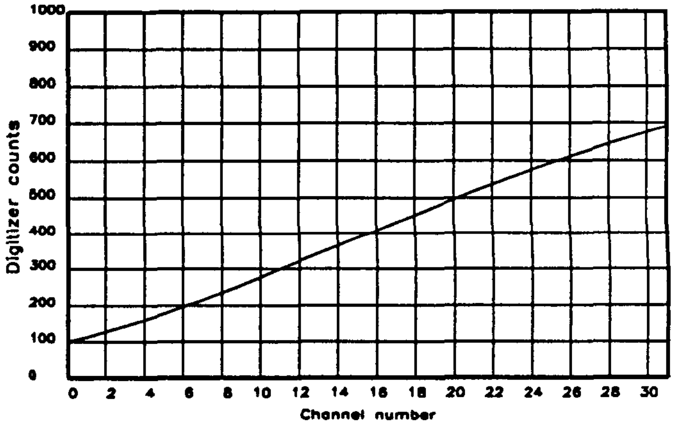

Figure 4. Calibrated spectra using root voltages.

Real world problems force us to modify straight forward numerical techniques such as the secant method. In our case, we must window our iteration limits. If the secant method were left to run unaltered, calibration would probably never occur. We are restricted by limited dynamic range in our digitizer along with upper and lower limits in our power supply.

At present, we perform 6 complete calibrations; all using the same key channel, but with different key voltages. Within the 6 cals, 3 different apertures are used. Apertures are needed to keep key channel signal levels at a reasonable level while adjusting voltage. The reason we use 3 apertures instead of 6 will be discussed in the section on radiance derivation.

We perform 6 cals so a least squares 4th order polynomial[5] can be passed through each set of non-key channel voltages vs key channel voltages. When any key voltage is chosen, a calibrated voltage for any non-key channel can be accurately calculated. Since 1 of the 32 power supply channels is designated key, we must generate 31 polynomials to account for all other channels. As seen in Figure 5, this is necessary because of non-uniform gain characteristics for each PMT.

The result is a 'best' fit through this system of 6 points whereby:

$$y[i] = a0[i] + a1[i]x + a2[i]x^2 + a3[i]x^3 + a4[i]x^4$$

In this case, 'x' is equal to the key voltage and 'y[i]' is equal to the resulting non-key voltage where 'i' is the channel number. Using our calibrated voltage arrays, we generate coefficients 'a0[i]' through 'a4[i]' for all channels using the least squares technique. When selected channels require a sensitivity change, we simply apply a new key voltage to the appropriate polynomials. By applying our set of polynomials to channels that need change, calibrated adjustments to the system sensitivity become a trivial matter.

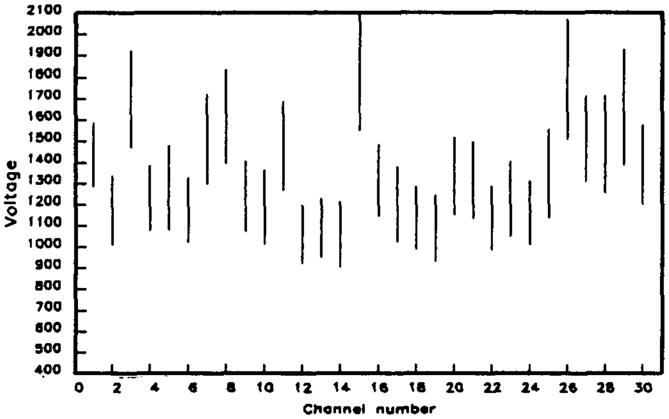

Figure 5. Lines represent calibrated voltage arrays for each channel.

Calibration limits

The blue end of the spectrum is calibrated with a lower number of counts compared to that of the red end. This is because blue light is less intense from the cal sphere. Lower counts are nearer to the noise of the ADC than higher counts. To keep calibration errors to a minimum, 100 counts was found to be the lower limit for any blue channel. Problems also arise on the red end of the spectrum. Counts read from any PMT are a product of gain and incident light. On the red end of the spectrum, there is more incident light. As power supply voltage increases, so does gain. Small voltage changes then produce large changes in counts read back. Because of this large count change, a desired count number may not be reached. Calibration then becomes impossible.

To insure calibration, an upper limit of 700 counts was found to be the cut off point for red channels given any aperture. This is a number found after observing a PMT in the red region known for its high gain characteristics. As seen in Figure 6, the line representing the largest aperture for this PMT has the greatest slope. Also note the exponential relationships for each of these lines. As voltage increases, counts read back increases at an exponential rate. When light and voltage (gain) are at their greatest, the exponential rate is also greatest.

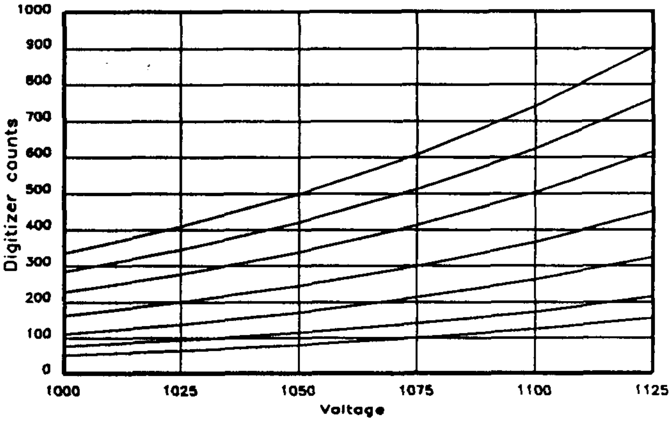

Figure 6. Exponential relation of calibrated voltage arrays vs counts for AOL ch. 28 (690 nm).

Radiance Determination

Radiance preparations

In our calibration, we linearly related counts to radiance. If calibration were made to 0 percent error, this relationship would continue. However, due to a 5 percent error in calibrating, a quadratic relationship was found to be more appropriate when making radiance determinations. It was found as voltage changes on a PMT, the relationship of counts vs radiance also changes. Due to this change, a quadratic representing counts vs radiance must be found for every desired voltage. Figure 7 is an example of lines representing quadratic relationships at various voltages.

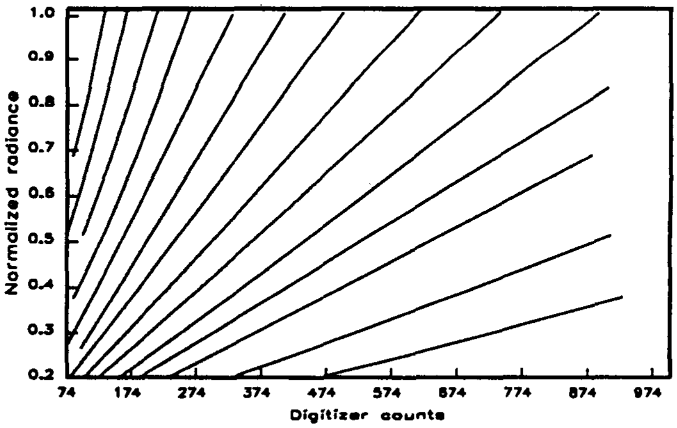

Figure 7. Quadratic relation of counts vs normalized radiance for AOL ch. 28 (690 nm).

Radiance derivation

Using data collected from calibration, we relate counts vs radiance quadratically with an equation of the form:

$y[i] = a0[i] + a1[i]x + a2[i]x^2$

Coefficients 'a0[i]'...'a2[i]' represent the gain vs incident light characteristics for channel 'i' at a particular voltage setting. Variable 'x' is equal to counts read and 'y[i]' is equal to calculated radiance. For every key voltage selected, we need to generate an appropriate quadratic. Once we have a quadratic for each key voltage, we can pass a least squares 4th order polynomial through each set of coefficients. Then, given a desired voltage, we can calculate the appropriate quadratic. However, before these quadratics can be generated, at least 3 data points of counts vs radiance for each key voltage must be found. Since we use 6 key voltages, a total of 18 data points are needed for every channel.

Due to limitations of hardware, we take 6 data points per channel instead of 18. Again, we are limited by inadequate dynamic range. This is the reason for 6 cals, using 3 apertures; 2 cals per aperture. A relationship must be found between counts vs voltage for all apertures used. This relationship implies a certain gain. By direct study, it was found that gain from a PAS can be expressed exponentially. Therefore, it will take a minimum of 2 data points to determine the appropriate exponential fit of the form:

$\ln y[i] = \ln b + mx$ or $y[i] = b[i]e^{m[i]x}$

By taking the natural log of both 'y[i]' and the y-intercept 'b', this function can be treated as linear. Again, the least squares technique is used. The importance of this is we can now accurately predict, given a voltage and known radiance (aperture), what the resulting counts will be.

As discussed, for every key voltage, there is an appropriate quadratic that relates counts to radiance. To produce one of these quadratics, a minimum of 3 points is needed for every key voltage. By using 2 key voltages per aperture, we are able to exponentially determine counts found at the other 4 key voltages. Using 3 different apertures, we are now able to generate the 3 required data points per key voltage. This gives us the 18 data points needed for each channel. Figure 8 illustrates those 18 points and how they are determined.

Due to calibration constraints, 6 complete calibrations are made using 3 apertures. The exponential relation of voltage vs counts is used to extrapolate count values that are outside the ADC range. We now can fulfill our requirement of 3 data points for every key voltage. A quadratic least squares fit is passed through these 3 points to make a 'best' fit. Now, with a quadratic for every key voltage, we need a way to generate a quadratic for any voltage. This is easily done using least squares again.

At this point, we have generated 6 quadratics for every voltage of the PAS. Each quadratic corresponds with a key voltage selected when calibrating. Since each quadratic is unique and possesses 3 coefficients each, we must relate all of the first coefficients with the key voltages. Likewise, we must relate all of the second coefficients with the key voltages. Finally, we must relate all of the third coefficients with the key voltages. By passing a least squares 4th order polynomial through each coefficient-voltage pair, quadratic generation for any non-key voltage is now possible. By choosing any voltage within bounds of the key, we can generate the correct coefficients which make up our needed quadratic for that particular voltage. Now, with this quadratic, we can solve for radiance given counts read from the PAS.

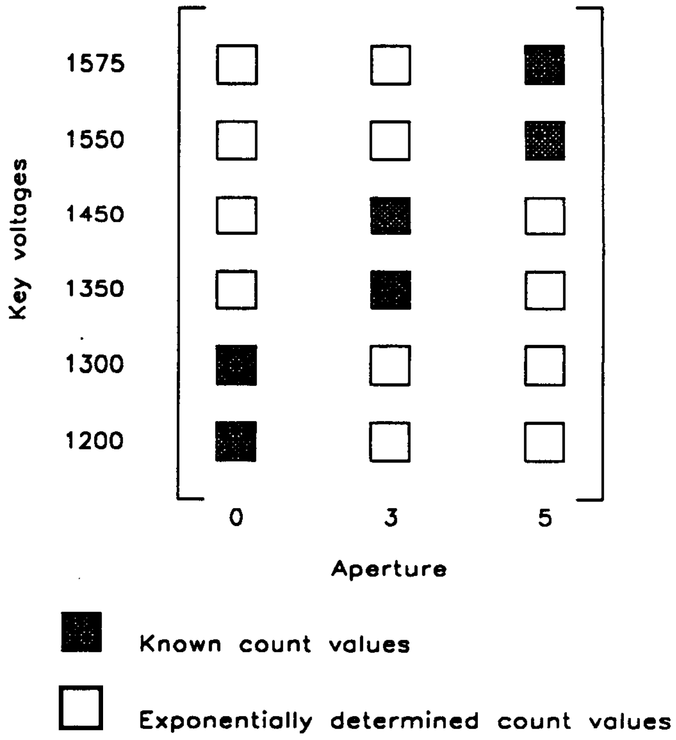

Figure 8. Calibration data points for AOL ch. 30 (712.5 nm).

Concluding Remarks

Calibration of this particular device is a multi-step operation. Considerations must be made to insure both a good calibration for sensitivity adjustments and sound data for radiance derivation. When radiance measurements were taken immediately following a complete calibration, a 5 percent error was found using the cal sphere as a reference. Since there is a 5 percent error in calibration of the sphere, our total error is 10 percent. Improvements in the cal sphere calibration and use of a higher resolution ADC should reduce this error.

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Steven A. Bailey, C. Wayne Wright, and Charles R. Piazza: Wallops Flight Facility, Wallops Island, Virginia.

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