ORNL/TM-2019/1448

The Filterscope:
A Technical Guide & User's Manual

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Report Title:
Filterscope Technical Guide and User's Manual

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ACRONYMS

ADC	Analog-to-Digital Converter
BNC	Bayonet Neil-Concelman (Connector)
BS	Beam Splitter
CMOS	Complementary Metal-Oxide-Semiconductor
CVD	Chemical Vapor Deposition
DAQ	Data Acquisition
DAQC	Data Acquisition & Control
DIO	Digital Input/Output
EAST	Experimental Advanced Superconducting Tokamak
F-P filter	Fabroy-Perot filter
FAQ	Frequently Asked Questions
HELIOS	Helium Line-ratio Spectral-monitor
JET	Joint European Torus
LIDAR	Light Detection and Ranging
MIT	Massachusetts Institute of Technology
NI	National Instruments
ORNL	Oak Ridge National Laboratory
PCI	Peripheral Component Interconnect
PDX	Poloidal Divertor Experiment
PMT	Photomultiplier Tube
PPPL	Princeton Plasma Physics Laboratory
PVD	Physical Vapor Deposition
PXI	Peripheral Component Interconnect based Extension for Instrumentation
SOL	Scrape-Off-Layer
TFTR	Tokamak Fusion Test Reactor
TTL	Transistor-Transistor Logic
vi	Virtual Instrumentation
VME	Versa Module Europa
CO	Collection Optics
CL	Collimating Lens
F	Filter
Op-Amp	Operational Amplifier
CMC	Configuration and Mode Control
TC	Tube Control
TF	Tube Feedback
ELM	Edge Localized Mode

ABSTRACT

Low-cost, remote, bandpass radiometers are a powerful spectroscopic tool used in high temperature plasma physics experiments throughout the world, particularly for fusion energy devices, i.e. those producing high levels of radiation. Examples of the measurements made using these types of radiometers are for: A) Core parameters such as the effective ion charge of the plasma, Z_{eff}; B) scrape-off-layer (SOL) plasma temperatures and densities; and C) plasma-wall interaction phenomenon. Over two decades ago, a version of such a radiometer system, the Filterscope, was developed by scientists at ORNL. The Filterscope extends the band-pass radiometer technique to make the instrument extremely modular/expandable, robust, and very-fast (with digitization up to 1 MHz) and has been deployed on fusion devices throughout the world. Additionally, a fast band-pass radiometer has other potential uses beyond fusion plasma diagnosis, e.g. LIDAR, X-ray medical diagnostics, radiation monitoring, and solar radiation measurement.

This technical report is intended as a user's guide and a reference manual for the use of the ORNL filterscope system. It gives an overview of the diagnostic philosophy and design as well as details on the implementation and operation of the complete system.

1 INTRODUCTION

The timeline of a modular, low-cost spectroscopy system, utilizing interference filters and fiber-optics coupling, grew from development work in the 1980s when such a system was installed on the PDX tokomak [1]. Additionally, MIT implemented a similar diagnostic tool in 1982, which was incorporated into the Alcator-C experiment [2]. In 1984, JET also began using a similar fiber-optic system [3] and an analogous system was also established on TFTR at PPPL [4]. These systems influenced the ORNL team's design concept [5] and led to: the first generation filterscope [6]; the HELIOS setup [7]; the 2-filter tungsten erosion fluxes [8]; and, the development of a similar ORNL systems on the long-pulsed Chinese tokamak, EAST [9]. Along with its application in fusion research, it additionally has other potential uses, e.g. LIDAR, X-ray medical diagnostics, radiation monitoring, and solar radiation measurement [10, 11].

This document is arranged in the following way. A brief description of the filterscope concept is described in Section 1.1. A more detailed hardware description of the filterscope system is then laid out in Chapter 2. Chapter 3 discusses the computer and software setup information. Chapter 4 has a step-wise description for the user to start the system and get acquainted with it. The calibration philosophy of the filterscope system is described in Chapter 5 that explains the PMT gain calibration and the normalized radiant flux calibration. Finally, FAQs along with Start-up, Checkout and calibration procedures are described in appendices A and B.

1.1 The Concept of a Filterscope

The "Filterscope" is a radiometric detection tool defined by three main elements: 1) an endoscope-like fiber optic, 2) a narrow band-pass filter, and 3) a photo-detector known as a PMT. The PMTs and DAQC are sensitive to both the ionizing and non-ionizing radiation produced in most fusion devices; therefore, an endoscope-like system allows for highly sensitive measurements of fusion-grade plasmas from remote locations. The narrow band-pass filter is used to detect a specific emission line of interest and/or line-free continuum regions of the visible spectra. The photo-detector and associated electronics are used to convert light into a voltage signal. Along with these, there is a DAQC system that is used for computer-control of the PMT gains as well as for data collection.

The complete filterscope diagnostic system can be divided into multiple parts as shown in Figure 1.1. Each highlighted section in Figure 1.1 is detailed in the sub-sections of Chapter 2. Collection optics focus the plasma emission onto fiber optics (Label 1) that transmit the collected light to the control hall where the filterscope system is located (typically many meters away from the plasma generating device hall). The light passes through a collimating lens system, possibly containing beam splitters or collection holders (Label 2) that directs the light through a narrow band-pass Fabry-Perot interference filter (Label 3). The light then enters the PMT (Label 4) creating an electrical current that enters a trans-impedance integrated circuit changing this current to a voltage (Label 5). The voltage is then conditioned via an amplifier and a buffer circuit (Label 5) and is sent to the DAQC (Label 6). The DAQC will then acquire the data and send it to a LabVIEW program (Label 6) to receive and visualize the data.

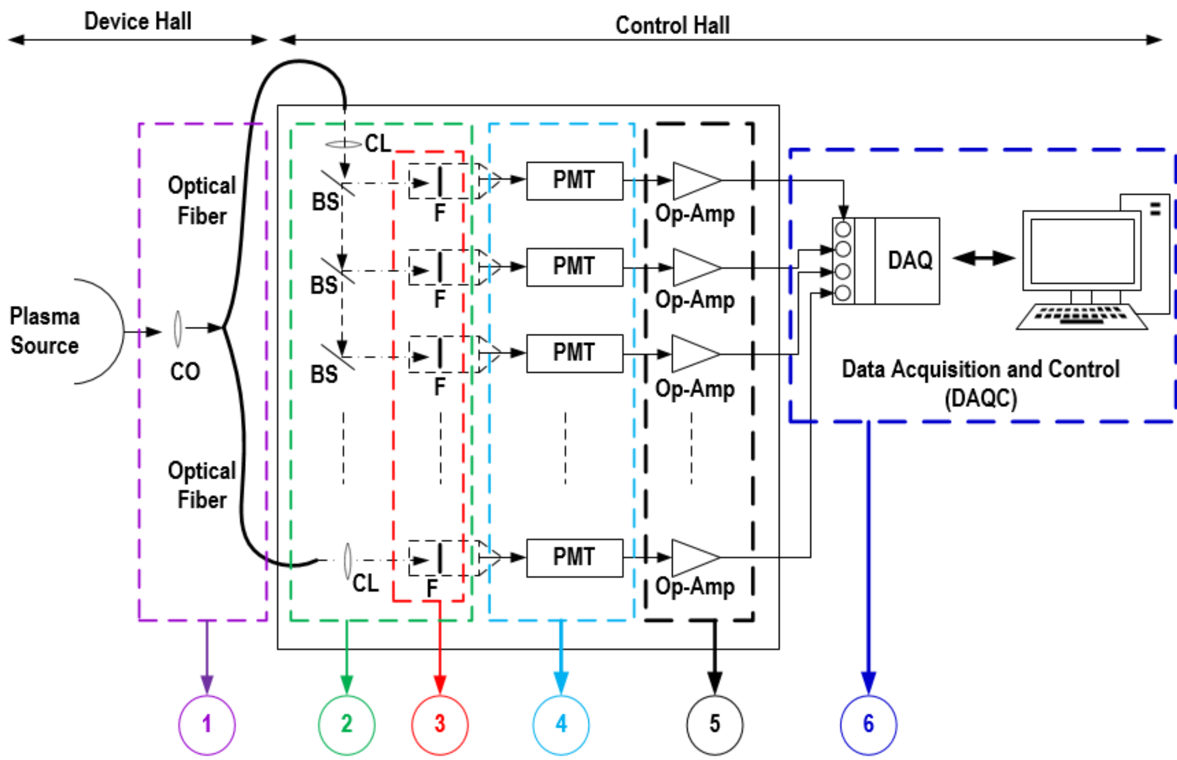


Figure 1.1: *A generalized schematic of the ORNL filterscope system. Radiation from the plasma (far left side) is captured with the collection options (CO); (Label 1). The light is transferred through fiber optics to a collimating lens (CL); (Label 2) to a filter (F); (Label 3). The filtered radiation is converted to an electrical signal (Label 4) through a photo-multiplier tube (PMT). The signal is then amplified (Label 5) and is recorded (Label 6).*

2 SYSTEM COMPONENTS & OVERVIEW

Each component of the system, as shown in Figure 1.1, will be detailed in this chapter. The intent is to give basic background and motivation for each sub-system to clarify the design choices and operational constraints of the system.

2.1 Electronics Housing

A complete chassis assembly contains a multi-channel filterscope electronics housing (also known as a Filterscope module) and a digital control housing (also known as the Filterscope central board) as shown in Figure 2.1. The DAQC computer can handle up to four filterscope instrument chassis linked together to form a single measurement system, having up to 96 channels with capabilities of acquiring high sampling rates (typically 100kHz, but up to 1 MHz in special setups) for long periods (up to 20 minutes) [11]. The chassis communicate to the DAQC through a serial input connector, and each chassis needs to be addressed separately via a chassis number switch — both of which are labeled in Figure 2.1. The Filterscope assembly depicted in Figure 2.1 consists of two modules/24 channels showing both optical layout types: the direct collection holder connection (left half) and the beam splitters attachment (right half).

The electronics housing is a 6U VME form-factor chassis (ANSI/IEEE 1014-1987) and provides a housing to the optical lenses, filters, beam splitters, PMTs, and analog electronics to the DAQC system. This DAQC system is based on a PXI, an extension for instrumentation NI PCI, and consists of a 6250 PXI and/or 6358 PXI ADC that is connected to the DAQC system (section 2.4) via an NI cable (see section 2.5) that is connected at the “output” connector shown in fig. 2.1.

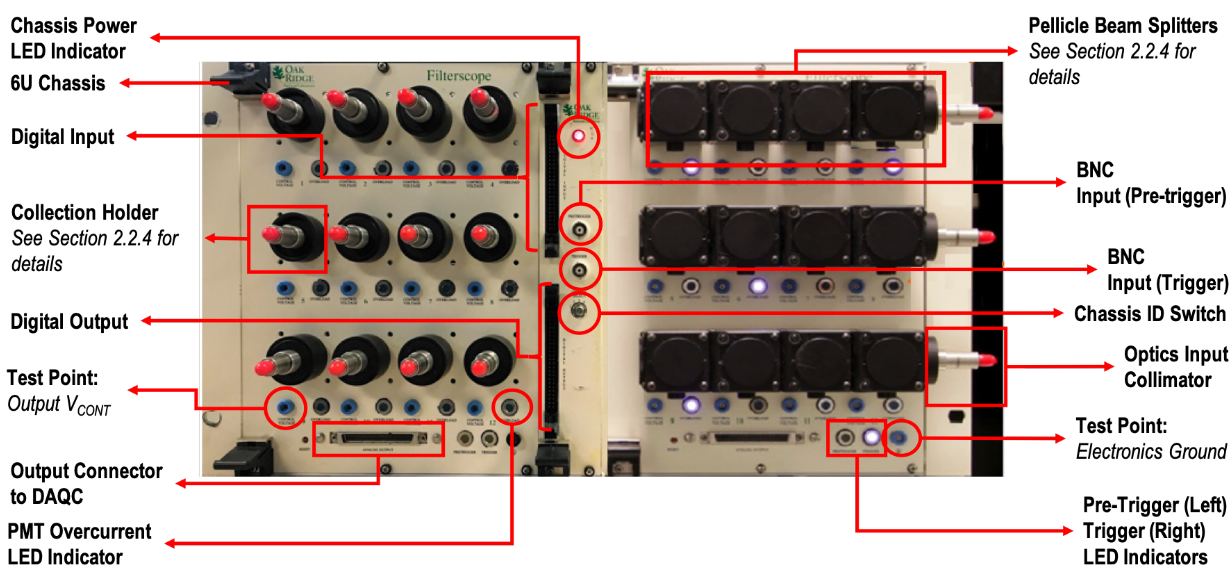


Figure 2.1: *A multi-channel filterscope chassis depicting various digital and analog components in the system.*

Each chassis has a digital housing that is also a 6U VME form-factor chassis (ANSI/IEEE 1014-1987) and accepts 2 BNC connectors for arming triggering. There are also connectors for the DIO that use standard 24-pin ribbon cables and connectors. These connectors can be used to daisy-chain up to 4 chassis, as mentioned above, using the digital input/output plugs.

2.2 Optical Components

The filterscope optics consist of three basic stages. Stage 1 is the collection optics at the device, detailed in the next section (Section 2.2.1). Stage 2 is the fiber optic taking the light from the device outside the radiation bio-shield into a diagnostic hall. Finally, Stage 3, which includes a collimating lens assembly, potentially with pellicle beam-splitters and band-pass filters.

2.2.1 Collection Optics

There are two optical assemblies needed in this system: 1) the collection optics that are usually placed near the plasma source; and 2) the coupling optics in the control hall. The two optical setups are connected by fiber optic cable that can be 10s of meters long and decouples the device from the diagnostic hardware. This is needed — in most cases — because the device is a high radiation environment. The collection optics consists of a lens, focus slide, lens holder, and body (see Figure 2.2). The plano-convex lenses used in this telescope optics system are usually high purity fused silica (e.g. Melles-Girot 01-LPQ-001). The focus slide holds the fiber, which is enclosed by a metal cap. The metal cap is clamped concentrically inside the slide, and the fiber itself is clamped on the focus slide to relieve the metal cap from excess strain [4]. Generally, the telescope is in the device/test hall as seen in Figure 1.1 (Label 1).

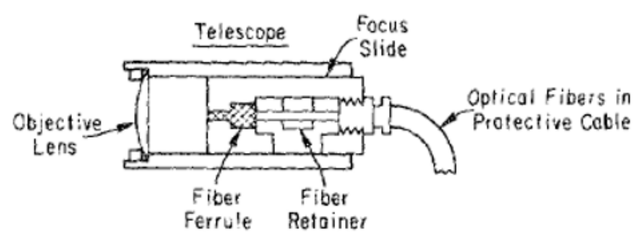


Figure 2.2: *Example of an optical lens sssembly used to make the collection telescope as labeled as Label 1 in Figure 1.1. Taken from [4].*

The coupling optics transfer the light from the fiber of each view-chord to the PMT. The optics consist of a collimator and two re-imaging configurations that are implemented to let the light pass to the PMTs through the filters. The first configuration consists of single collimating lenses coupled to a Fabry-Perot filter (Section 2.2.4). This setup allows individual spectral lines to be measured from individual view-chords at the device. Another configuration consists of four detectors in series with a single collimating lens, filters, and beam splitters (e.g. a Thor-Labs Cube-Mounted Pellicle Beam Splitters [12], see Section 2.2.4) and allows precise measurement of multiple spectral lines from a single view chord at the experiment. This combination of experimental accessibility, optical flexibility and high data sampling rates for long duration make this instrument a unique diagnostic in fusion research [11].

2.2.2 Optical Fiber

Fiber optic cables are long, thin strands of glass about the diameter of a human hair and are used for guiding light signal from one end to the other — typically visible light (~400–700 nm). The fiber optics or "the fiber" have three main parts: 1) the Core, 2) the cladding, and 3) a buffer coating. The core is a thin glass center of the fiber where the light travels, and the cladding is an outer optical material surrounding the core that reflects the light back into the core make up the foundation of the fiber. The buffer (or jacket) coating protects the fiber from damage and moisture while additional protection can also be included through armor (a steel/metal sheath over the buffer) for installations. The recommended fiber for use with the filterscope system has a core of pure fused silica (SiO_2) with a size of 600 microns or larger [13]. For radiation (neutron and/or gamma-ray) resilience, the core/cladding should use low hydroxide (OH) silica [14]. Additionally, the effects of radiation damage have been shown to be minimized through: heating the fiber to temperatures higher than 200°C; passing UV light though the fiber between discharges; and/or using larger core diameters because gamma radiation is attenuated after ~200 microns into the core/clad.

2.2.3 Interference Filters (Fabry-Perot Type)

Interference filters are multi-layered thin film optical devices whose optical properties are derived from Snell's law. The method to deposit the thin films onto an optical glass substrate is through vacuum deposition. The precise method of deposition is either though CVD (a "soft" coating method) or through PVD magnetron sputtering (a "hard" coating method). Each deposition method is repeated multiple times using different film materials, a multi-layered filter is produced which provides multiple interference at which light is reflected or refracted [15]. Soft-Coated filters "age" with time i.e. the transmission properties change with time and are prone to degradation due to humidity. Hard-coated filters are less prone to aging and humidity damage.

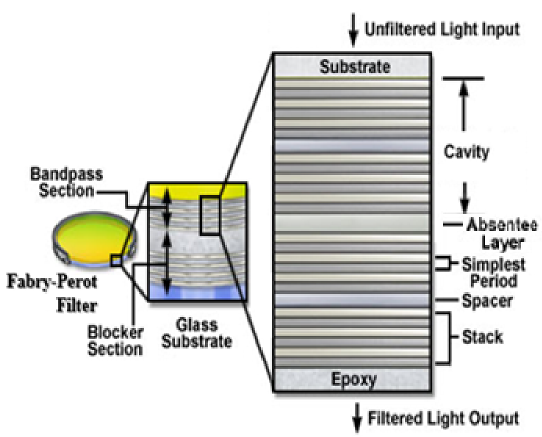


Figure 2.3: *A progressive breakdown of a 2-cavity Fabry-Perot filter that is used in Label 3: Figure 1.1*

The simplest band-pass filter based on interference principles is a solid thin-film Fabry-Perot filter. These filter types are used extensively in the filterscope system. The spectral properties of the interference optics can be customized over a very broad range by choosing dielectric refractive index, thickness of the layer, and the number of layers appropriately [15].

Figure 2.3 shows the anatomy of a Fabry-Perot filter [15]. These filters are constructed by separating two thin-film reflectors, called a stack, with a thin-film spacer as shown in Figure 2.3. The conventional air gap is replaced by a dielectric material having an optical thickness equivalent to an integral half-wavelength of the principal wavelength, labeled the absentee layer in Figure 2.3. Light of longer or shorter wavelength than the principal wavelength acquires a phase difference that maximizes reflections and minimized transmission. This combination of interference produces an operative bandpass filter.

The properties of this filter such as passband, blocking range outside spectral region are determined by the number of layers and their arrangement.

The defining feature of a narrow-bandpass interference filter is the transmission profile (or equivalently the optical density). Figure 2.4 shows an exammple of the optical density and transmission values as a function of wavelength for several theoretical filters constructed with different numbers of cavities. With the increase in the number of cavities, the degree of light attenuation outside the passband is greater at wavelengths farther away from the principal wavelength (in this case 450 nm) [15]. The left-hand axis of Figure 2.4 is a representative optical density for a range of Fabry-Perot filter designs. It is defined by the amount of energy blocked by the filter and is also sometimes called "neutral density". A high optical density value indicates very low transmission and a low optical density value indicates very high transmission. The optical density (OD) of a filter is given by the following equation, $OD = -\log\left(\frac{T}{100}\right)$, where T is the transmission fraction, given by $= \frac{I_{OUT}}{I_{IN}}$. I_{OUT} and I_{IN} are the intensity of the light passing through the filter and the incident intensity of light, respectively.

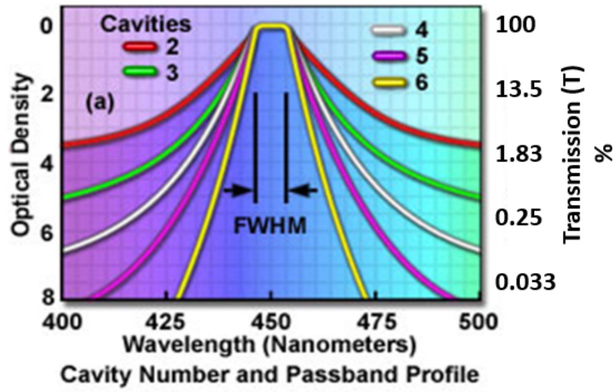


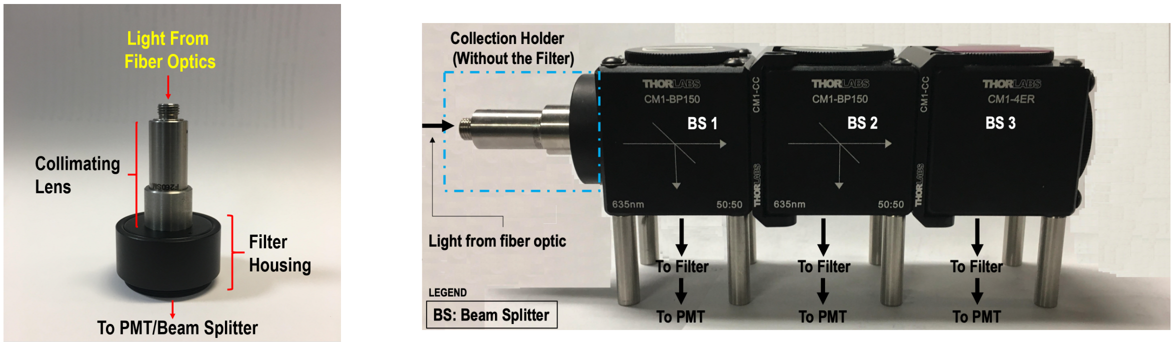
Figure 2.4: *Optical density (left axis) and transmission (right axis) versus wavelength of Fabry-Perot filters over a range of cavity sizes [15].*

2.2.4 Single-Channel vs. Multi-Channel Optics Assembly

As explained before, the light from the plasma source passes through the collection optics and optical fiber towards the collection holder (see Figure 1.1 Label 2). The collection holder is a unit consisting of a fiber optic cable connection, filter housing, and a collimating lens. This unit is used for a direct connection of the light source to the PMTs. Figure 2.5(a) shows the image of a collection holder used in a single channel assembly. As seen in Figure 2.1, beam splitters (BS) can also be used to send light to the filters then to the PMTs. The pellicle type of beam splitters from Thor-labs (CM1-BP150/4ER) (see Figure 2.5(b)) is used in a multi-channel assembly in the filterscope system (see Appendix A: FAQ A.Q.7). However, the last beam splitter (BS3 in Figure 2.5 (b)) can also be changed to a collimating mirror from Thor Labs (CCM1-4ER) to avoid light leaks.

2.2.5 Photo-Multiplier Tube

A critical component of the filterscope is the photodetector, which is the Photo-Multiplier Tube (PMT). The PMTs have been chosen because of their higher gain, higher sensitivity, and faster response time compared to other detector types such as silicon photo-diodes and avalanche photo-diodes. Specifically, a PMT is a photo emissive photodetector that emits an electron when a photon is absorbed. It works on the principle of amplifying the electrons generated by a photocathode when exposed to a photon flux (see Figure 2.6).



(a) *(b)*

Figure 2.5: *Single-channel vs multi-channel assembly as seen in Figure 1.1 (Label 2). a) A Thorlabs-based collection holder used for a single channel assembly. b) A Thorlabs-based pellicle beam-splitter used for a multi-channel assembly.*

2.2.5.1 Brief Background of PMTs

Figure 2.6 shows a schematic representation of a single PMT and labels the major parts of the photodetector. Going from left to right within Figure 2.6, the PMT acquires a photon through a quartz window that covers the photocathode. Next, the photocathode absorbs the photons and releases electrons that are multiplied by a series of metal channel dynodes. Last, the electrons are collected at the anode as a current. The anode current is directly proportional to the photoelectron flux generated by the photocathode.

2.2.5.2 Quick Anatomy of a PMT

The two main components of a PMT are the photocathode and the dynode chains. Most photocathodes are made of compound semiconductors, which consist of alkali metals. Some of the materials used commonly to employ as a photocathode material are Cs-I, Cs-Te, Sb-Cs, Bialkali (Sb-Rb-Cs, Sb-K-Cs), high temperature, low noise bialkali (Sb-Na-K), Multi-alkali (Sb-Na-K-Cs), Ag-O-Cs, GaAsP (Cs), GaAs (Cs), InGaAs(Cs), In/InGaAsP(Cs), and InP/InGaAs(Cs). The window material, however, varies from the photocathode material. Most common window materials employed in the PMT are MgF_2 crystals, Sapphire, Synthetic Silica, UV glass, and Borosilicate glass [10].

There are a variety of dynode types that exhibit different gain, time response, uniformity, and secondary collection efficiency depending upon the structure and the number of stages [10]. The different types of PMTs are described in Table 1 along with its collection efficiency and some features.

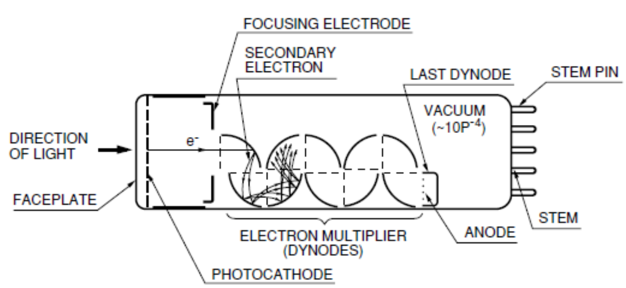


Figure 2.6: *Schematic of a PMT illustrating the conversion of light into photo-electrons [10].*

Table 1: Typical types of PMT dynodes and their features. Adapted from [10].

Dynode Type	Collection Efficiency	Features
Box-and-Grid	Very Good	• High Collection Efficiency
Linear-Focused	Good	• High Speed • High Linearity
Venetian Blind	Poor	• Suited for Large Diameter
Fine Mesh	Poor	• High Magnetic Field Immunity • High Linearity
Micro-Channel Plate (MCP)	Poor	• High Speed
Metal Channel	Good	• Compact • High Speed
Electron Bombardment	Very Good	• High Electron Resolution

2.2.6 PMT Used in Filterscope

The PMTs in Table 1 describe just the tube itself. The filterscope system uses a compact PMT module. A PMT module consists of the PMT and an inbuilt high voltage generator (see Figure 2.7 and 2.8). PMT module types used in the filterscope systems to-date are: the Hamamatsu H5783 Series [16]; the Hamamatsu H10721 Series [17]; and the Hamamatsu H11901 Series. These PMT model types are comprised of a metal package with a metal channel type dynode structure in the PMT and a Cockcroft Walton high voltage supply [18]. These PMT modules are low power consuming devices that are highly sensitive (3 x 10^{-5} A/nW) with fast time response of 0.78 ns and spectral response of 300 to 800 nm depending on the window and photo-cathode material. Different module sub-types are made to have a range of different spectral ranges. For example, The H10721-210 PMT has a spectral response range of 230 nm to 700 nm. The most common PMT module sub-types used are the H10721-01, H10721-20, H5783-00, and the H5783-01 — see the spec-sheet [16, 17] for details on the PMT models used. The photo-cathode in all these sub-types are made up of Ultra-Bi-alkali and the window material is made up of borosilicate glass [17]. An image of the Hamamatsu H10721-20 used in a filterscope system is shown in Figure 2.7.

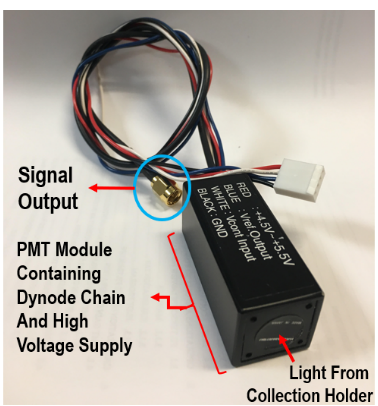


Figure 2.7: A filterscope PMT module (H10721-20) as seen in Figure 1.1 (Label 4).

The compact size of these PMTs allow 12-channel analog signal conditioning in a single electronics housing (Module) as seen in Figure 2.1. Additionally, two electronics modules can fit in the chassis giving a single chassis capability to house 24 PMT channels. The PMT gain and dynode bias in each PMT is controlled by an internal high voltage DC-DC converter and is set externally by a reference control voltage, labelled V_{CONT} in Figure 2.8. The signal-noise ratio characteristics and dynamic range of each of the 24 channels can be optimized simultaneously and automatically through the control voltage V_{CONT} in the DAQC as described in the next section.

Dynode coating damage may occur due to over-current in the PMT. This is prevented by rapid shutoff of the dynode bias if the output current exceeds 100 μA for a few μs. Normal operations can be restored manually or automatically when the condition causing over-current has been resolved [11].

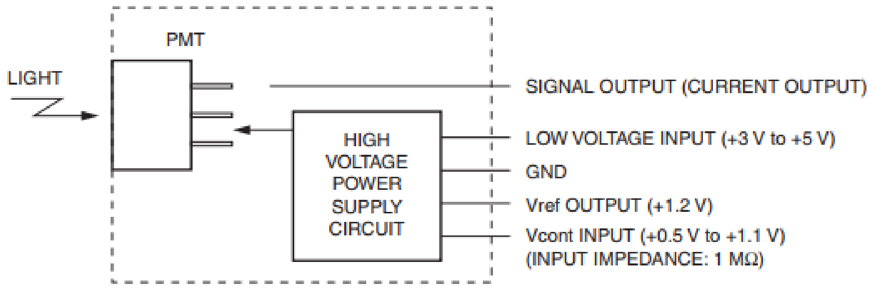


Figure 2.8: *Block diagram of a Hammamatsu PMT module showing the input/output connections [17].*

2.3 Brief Overview of the Filterscope Electronics

The light from the collection holder(s), beam splitter assembly, and the filter(s) with a transmission $'T' = 10^{-OD}$ and Optical Density 'OD' - is transmitted directly to the PMT (left half of Figure 2.9), which on interacting with the first PMT dynode converts the light into photo-electrons in turn producing a photo-electric signal (V_{in}). The photo-electric signal amplified over the dynode chain is then sent to a trans-impedance amplifier which outputs the voltage signal of the PMT (V_{out}). This voltage is then sent out to an non-inverting amplifier and a buffer amplifier to produce a total tube output voltage (V_{PMT}) that is in phase with V_{out}. The buffer amplifier ensures that a robust signal is sent to the ADC as well as prevents the DAQC from loading and interfering with the other electronics of the filterscope. The total tube output voltage is related to the photo-electric signal through a PMT gain (see Appendix A: FAQ for details). The gain of this amp can be directly controlled in the filterscope.vi main tab (see section 4.1). The total tube output is then sent to the DAQ of the DAQC system and V_{PMT} is displayed by the DAQC system, which is detailed in the next section.

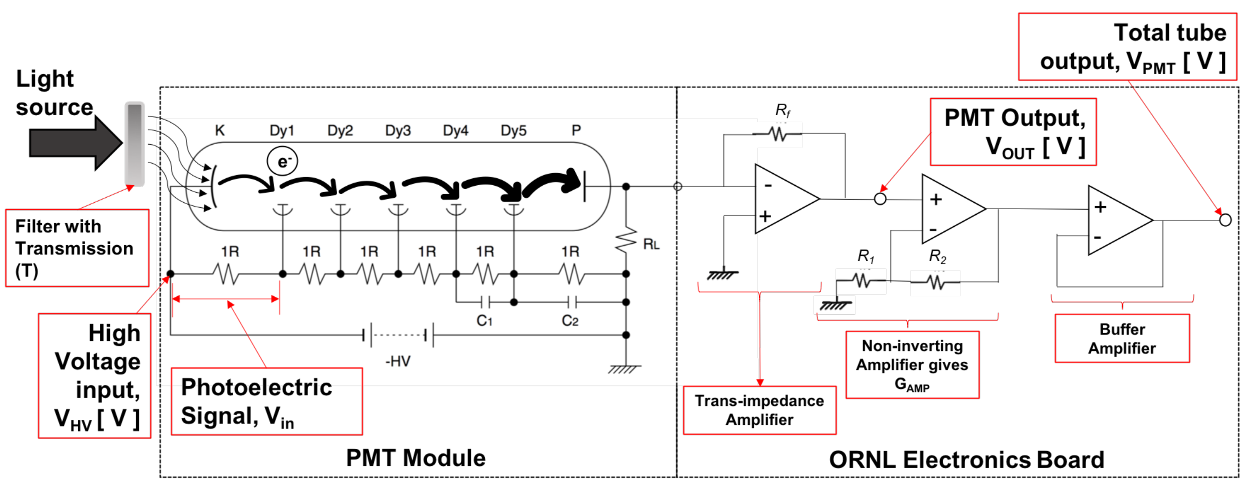


Figure 2.9: *A schematic of the filterscope system as seen in Figure 1.1 detailing the electronics adopted in Label 4 and Label 5.*

2.4 Data Acquisition and Control (DAQC)

The PXI based DAQ system drives the digital control lines to the digital housing interface (Figure 2.1), which sends the control command codes to the analog electronics within the chassis. The digital interface uses geographic addressing to identify which chassis and to which tube in the chassis the control command code applies. There are three major systems that are controlled: 1. the PMT dynode bias voltage for each tube via the PMT module input control voltage (V_{CONT}), 2. the gain amplifier setting for each tube, and 3. reset for the over-current shutoff circuit [11].

The control command code is broadcast over the chassis by attaching the PXI digital output to each chassis in a daisy chain ribbon cable or by using the buffered DIO connectors on the digital housing module (section 2.5). The four-position switch on the front panel of the digital housing interface controls the order in which the tubes are addressed by the DIO and care must be taken in setting the chassis switch number and configuration file for the system (Figure 2.1).

Figure 2.10 shows the PXI based DAQ system used in the filterscope diagnostic. As seen, the PXI chassis contains a PXI control module, PXI multifunction input/output module, additional slot space for needed extension. The Filterscope DAQ consists of a PXI chassis (NI PXIe-1082), a PXI controller module (NI PXI-8119), and at least three PXI multifunction I/O modules consisting of one digital I/O module (DIO NI PXI-6509) along with analog-to-digital converter modules (ADCs) both from National Instruments (NI).

The embedded controller is custom based on the needs of each filterscope deployment. It is usually used for processor-intense, modular instrumentation and DAQ systems. The NI 6509 is a 96-bit, high drive DIO device that features 96 TTL/CMOS-compatible digital I/O lines, 24 mA high-drive output, digital filtering, programmable power-up states, change detection, and a watchdog timer [19]. Typically, the ADC is an PXI 6250, which is a high-speed multifunction DAQ board. This module has an aggregated sampling rate of 1 MS/s (Mega-Samples per second) [20]. Each ADC can be used to get channel sampling up to 100 kS/s using the PXI-6250 or in special cases 1 MS/s per channel using the PXIe-6358 module.

The PXI controller module runs any program, application, or virtual instrument (vi) installed onto the PXI chassis for Filterscope use i.e. the filterscope "vi" and plot "vi". Each DIO can only be associated to one program, application, or "vi". This denotes that if the user needs a new "vi" to deliver/accept commands

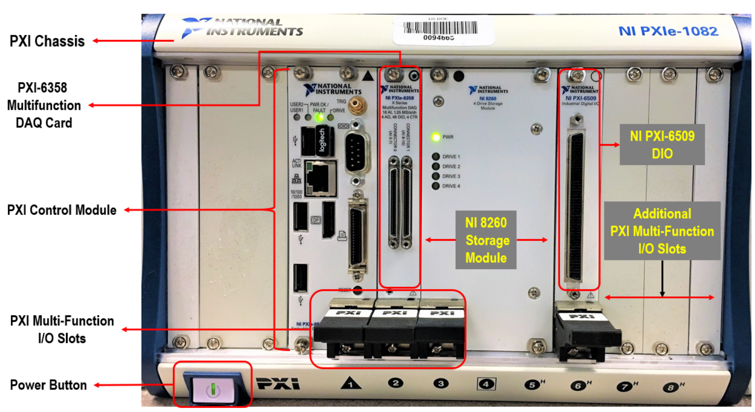


Figure 2.10: *A figure highlighting various ports in the NI PXI-based filterscope DAQC chassis as seen in Figure 1.1 Label 6.*

from a new system then the user must purchase a new DIO. However, the user can have several programs, applications, and “vi” on the PXI chassis. The details of the various “vi” used by the filterscope system are given in chapter 4.

2.5 Cable Connections

There are three main cable-ages needed for correct operation of the filterscope, 1) RG-58 (or -59) 50 ohm coaxial cables with BNC ends for the triggers, 2) Conventional Ribbon cables for the DIO interfaces, and 3) NI shielded twisted-pair cable bundles for analog data and trigger logic transfer. More info on each are given below and a labeled photo containing each connector type is given in Figure 2.11. USB-B connectors are needed for keyboard and mouse interfacing. Most standard monitor connectors are acceptable for local human interfacing i.e. VGA, DVI, Display port, HDMI, etc. One can also setup VNC for remote access to the computer, which is convenient when frequently working from control room to diagnostic hall, as shown schematically in Fig. 1.1. Conventional 3-prong instrumentation power cables (i.e. grounded) are also needed. Input power can be interchangeable between 120V(60Hz) or 240V(50Hz), single-phase AC power.

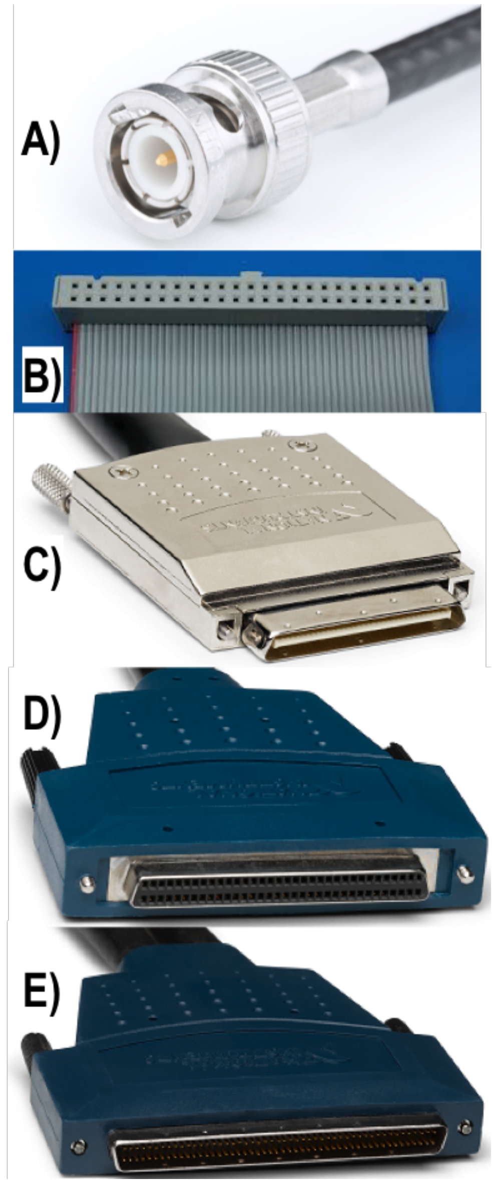


Figure 2.11: *The connectors/plugs used in the filterscope system. A) Standard 50-ohm (RG-58) BNC (male-type); B) 50-pin IDC-50 plug (female-type); C) NI VHDCI-68 plug (male-type); D) NI HPDB-68 plug (female-type) and E) NI HPDB-100 plug (male-type).*

The receptacles for each cable is given in Figures 2.1 and 2.10. Figure 2.11 shows the cable ends needed for connecting receptacle to receptacle. The BNC connector is needed for triggering (explained more below). There are 4 main types of inter-connectors; An IDC-50 connector is needed for the digital I/O on the digital housing labeled in Figure 2.1 and is shown in Figure 2.11-B. This cable is then connected to the DAQC (DIO in Figure 2.10) through a NI-HPDB-100 plug shown in Figure 2.11-E. Connection of the DAC (labeled “output” in Figure 2.1 and DAQ-card in 2.10) are made with NI-HPDB-68 and NI-VHDCI-68 plugs (Figure 2.11-C and -D, respectively).

Arming and triggering of the system is done with active-low, 2-state (binary), 0-5V, logic [21]. The software program and hardware is armed via an active-low digital logic pulse. The logic pulse pulse is typically TTL, which has an acceptable low-state of 0.0-0.5 V and acceptable high-state of 2.7-5.0 V but other active-low digital logic triggers are possible, e.g. CMOS (with an accepted low(high)-state = 0.0-0.05 (4.7-5.0) volts. Acceptable minimum arming (or pre-trigger) pulse widths can be very short (~100 μsec including the rise/fall time) but typically a minimum pulse width of 1-2 msec is used (there is no maximum). Arming the system will lock-out the user from performing any changes to any tab in the vi, reset all active tubes" dynode overcurrent latches, and create a new shot event pulse in the MDSplus tree. Another active-low logic pulse forms a start trigger (t_0). The pre-trigger can occur any time before the t_0 trigger, but has typically been 10–30 sec before t_0. Both triggers are coupled to the system via BNC connectors (see Figure 2.11-A) on the digital housing chassis.

3 COMPUTER SYSTEM & USAGE GUIDANCE

The Filterscope PXI control computer shown in Figure 2.10 is essentially structured like a windows based computer with a **C:** drive containing the operating system and the system files. The ORNL filterscope requires two major components in the Windows configured computer to operate the tool successfully: 1. NI LabVIEW, for the filterscope program, 'filterscope.vi' and 2. MDSplus, for storing the data. The Filterscope.vi (discussed in detail in Chapter 4) uses directories located in the system files of the PXI control computer and MDSplus requires system changes to properly communicate with the Filterscope.vi. Section 3.1 will outline the basic file structure of the Filterscope PXI control computer and the configuration file used to populate the vi. Section 3.2 will transition into the file structure of the MDSplus saved data and introduce the necessary environmental variables.

3.1 The Overall File Structure

The PXI control computer has two operator relevant directories: 1) **C:\MDSplus Data**\ and 2) **C:\Filterscope**\. The **MDSplus Data** directory is where all of the local MDSplus data is stored (see 3.2 for details) and the **Filterscope** directory is where all of the necessary folders for proper operation of the Filterscope.vi exist. The Filterscope.vi relevant folders, located in **C:\Filterscope**\, are named: 1) Executables, 2) config and Config Backup, 3) Cal Backup, and 4) log.

Generally the newest version of the Filterscope.vi will be available on the Desktop of the PXI control computer and the Executable directory will not be as relevant, as the user would be using just the Desktop shortcut . There are also MDSplus related executables that can be used for special circumstances. The absolute location of the Executables folder is **C:\Filterscope\Executables**.

The config and Config Backup folders are the backbone of the Filterscope.vi. When the Filterscope.vi is opened it loads in the configuration file, which is located in the config direcotry. The configuration file, when loaded in by the Filterscope.vi, lets the 'vi' know what tubes are "active" and populates all of the fields described in Figure 4.4. Any changes made in the Filterscope.vi can be saved to the config file for future loading by selecting 'Write to Modules' in the drop down of Figure 4.3. The Config Backup directory is a available for any config files that are high priority or valuable to the Filterscope user. A copy of the config file should be made and stored in the Config Backup folder. An example of a config file is shown in Figure 3.1 and can help guide the user in creating one. The absolute location of the config and Config Backup folders are **C:\Filterscope\config** and **C:\Filterscope\Config Backup**

Cal Backup is used for backing up the calibration values that populate Figure 4.15. An excel file can be created by the Filterscope.vi user and saved to the Cal Backup for importing into Figure 4.15 as well. The absolute location of the Cal Backup folder is **C:\Filterscope\Cal Backup**

The log folder is for debugging. Every process made by the Filterscope.vi from boot up to end of operations is stored in a log-file in the log folder. The log file is created when an issue occurs and is the first file that should be inspected to understand what could be happening to relay necessary information to troubleshoot and fix the issue. If the information is not immediately obvious to the user then the Filterscope administrator should use the log file to understand and fix the problem. The absolute location of the log folder is **C:\Filterscope\log**

Tube #	Status	Voltage	Gain	Tube Name	Tube Descr.	Adj Low Lim	Adj Up Lim	Auto Adj	Contr Name	Contr Desc	Init Volt Ena	Init Volt	Elms Det	Elms Thresh	Elms Width	Elms Occur
1	Active	0.2	1	Tube_1	PMT_Da_6_5N_6	0	0	Auto Off	Control_1	CTL_Da_6_5N_6	ENABLED	0.5	DISABLED	0	0	0
2	Active	0.2	1	Tube_2	PMT_Da_6_5N_2	0	0	Auto Off	Control_2	CTL_Da_6_5N_2	ENABLED	0.3	DISABLED	0	0	0
3	Active	0.2	1	Tube_3		0.25	5	Auto Off	Control_3		ENABLED	0.2	DISABLED	0	0	0
4	Active	0.3	1	Tube_4		0.25	5	Auto Off	Control_4		ENABLED	0.3	DISABLED	0	0	0
5	Active	0.3	1	Tube_5		0.25	5	Auto Off	Control_5		ENABLED	0.3	DISABLED	0	0	0
6	Active	0.3	1	Tube_6		0.25	5	Auto Off	Control_6		ENABLED	0.3	DISABLED	0	0	0
7	Active	0.3	1	Tube_7		0.25	5	Auto Off	Control_7		ENABLED	0.3	DISABLED	0	0	0
8	Active	0.3	1	Tube_8		0.25	5	Auto Off	Control_8		ENABLED	0.3	DISABLED	0	0	0
9	Active	0.3	1	Tube_9		0.25	5	Auto Off	Control_9		ENABLED	0.3	DISABLED	0	0	0
10	Active	0.3	1	Tube_10		0.25	5	Auto Off	Control_10		ENABLED	0.3	DISABLED	0	0	0
11	Active	0.3	1	Tube_11		0.25	5	Auto Off	Control_11		ENABLED	0.3	DISABLED	0	0	0
12	Active	0.3	1	Tube_12		0.25	5	Auto Off	Control_12		ENABLED	0.3	DISABLED	0	0	0

Figure 3.1: *An example showing the details of a configuration file*

3.2 The Local Data Storage via MDSplus and System Environmental Variables

Data archival on the filterscope system is done with MDSplus [22]. Users are encouraged to read through the introduction material on MDSplus at website MDSplus.org [22]. MDSplus uses a method to store all data called **Trees**. A **Tree** is composed of a model tree with shot number equal to -1, a number of shot trees equal to the number of shots taken, and a series of nodes where the data is stored within the tree. When a **Shot** is taken by the facility or local machine a new shot tree is created from the model tree with a facility relevant shot number. Trees are stored on the PXI control computer with the file syntax: **treename_shot number.filetype**. The filterscope local tree, the tree stored on the PXI Control Computer, has a treename equal to *fscope*. Every time a shot is taken a new shot tree is created and stored in the **C:\MDSplus Data** directory as three separate file types: fscope_shot number.characteristics, fscope_shot number.tree, and fscope_shot number.datafile. The shot number changes every time a new shot is taken; for example, if the shot is 900 then the shot tree 900 is created and the shot number is equal to 900. Shot trees are sequential and should be thought of as a historical record of data collected. The **.tree** filetype contains the tree structure, the **.data** filetype contains the tree data, and the **.characteristics** filetype contains the tree node characteristics. A node can be a number of types and are available for viewing and understanding at mdsplus.org\index.org\documentation:users:Datatypes. The later node types are primarily for integrating MDSplus into a full acquisition system. The data storage can also be done on remote networks, if needed.

An example of the filterscope model tree is given in Figure 3.2. As shown, the tree is split into a series of structure nodes and data nodes. The structure nodes (TUBE01 in Figure 3.2) can be expanded to show more structure nodes or data nodes. The data nodes are identified by a small image to the left of the node name. A hash [#] to the left of a data node means that it is a numerical value, a trace means that it is a signal, and small text means that it is a string. Structure nodes can expand to accommodate however many data nodes is necessary and the tree or subtree can accomodate as many structure nodes that are necessary. All this is detailed in Figure 3.2.

Environmental variables are used to describe a programs environment so that it can properly run. Most environmental variables are paths that direct the program to finding a specific variable such as the path to where MDSplus is installed or where the tree is located. Other environmental variables will contain actual variables like the treename of the local or remote tree. For MDSplus there are seven major environment variables for the operating systems and a detailed understanding can be had from the MDSplus website:

1. `DATA_SITE`: This variable tells the software how to handle particular conditions for each diagnostic site. Examples of `DATA_SITE` definitions are *D3D (GA)*, *KSTAR*, *WRITE_ONLY*, *NSTX*, *TEXTOR*, *EAST*, *PEGASUS*, *TEXT*, *MPEX*, *D3D_MDSPLUS*, *W7X*, and *WEST*.

2. `FS_HANDSHAKE`: This variable displays True of False depending on the model of Filterscope.

3. `*_PATH`: This variable defines both local and remote Tree's. (* denotes tree name)

4. `MDS_TREE_PATH`: This variable displays MDSPlus local tree path from top.

5. `MDS_TREE`: This variable shows the MDSplus Local Tree name

6. `MDS_REMOTE_TREE`: This variable displays the MDSplus facility remote tree name.

7. `MDS_REMOTE_TREE_PATH`: This variable depicts the facility MDSPlus path from the top.

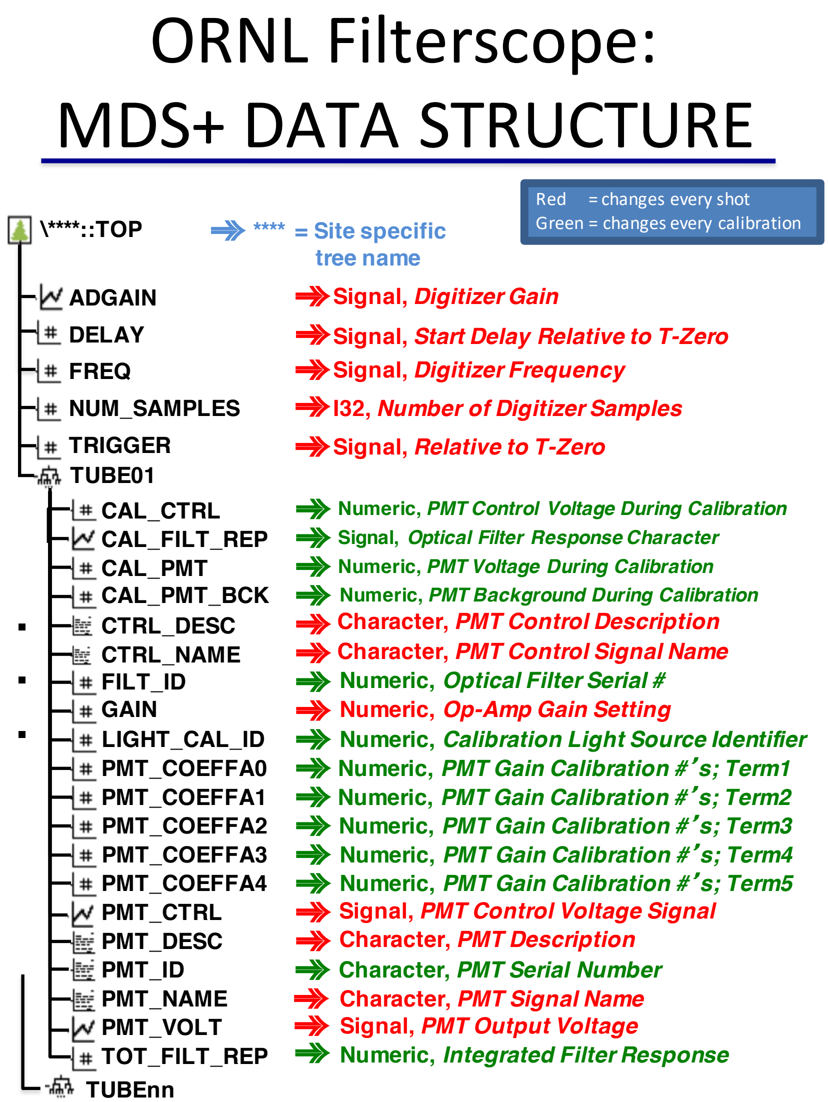


Figure 3.2: *Diagram of the full MDSPlus filterscope Model Tree on the Local Machine*

4 LabVIEW PROGRAMS & USAGE GUIDANCE

The Filterscope face-plate housing is coupled with the optical components (filters and the PMTs) that send the data to the PXI based DAQC system which digitizes the data and sends it to the LabVIEW program, which then locally stores the data in a MDSplus database (see Section 3.2). This chapter will enable the user to understand the basic operation of the LabVIEW program used to perform the aforementioned steps.

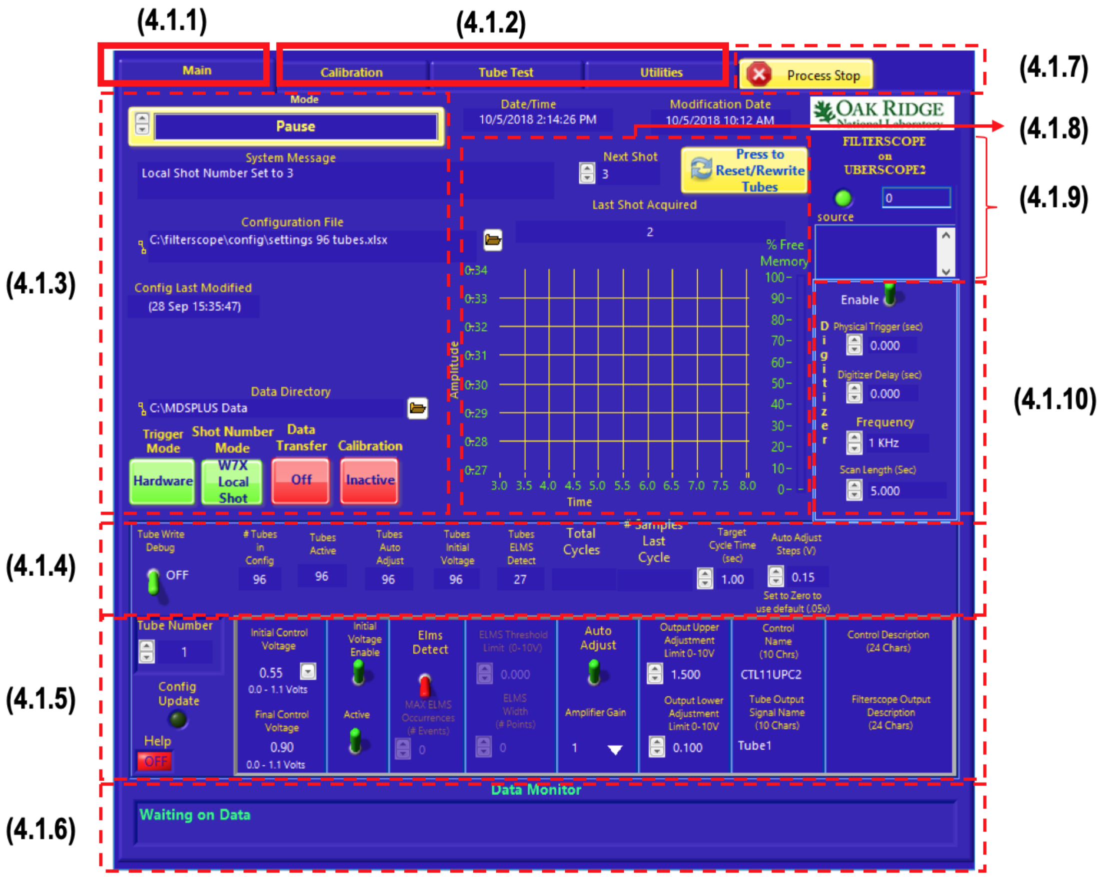


Figure 4.1: *Screen shot of "Main tab" of the LabVIEW program "Filterscope.vi" showing ten major sections of the GUI.*

The NI LabVIEW program is used to operate and control the filterscope system. The primary 'vi' is called the filterscope.vi. As seen in Figure 4.1, this 'vi' is divided into four tabs: Main tab (Section 4.1), Tube Test tab (Section 4.2.1), Utilities Tab (Section 4.2.2), and Calibration tab (Section 4.2.3). The utilities tab is further subdivided into five sub-tabs: USB Light Source (Section 4.2.2.1), Shot Server Test (Section 4.2.2.2), Plot MDSPlus Data (Section 4.2.2.3), Overwrite Previous Calibration Data (Section 4.2.2.4), and Copy Shot Data to Remote Server (Section 4.2.2.5).

The overall operating logic in controlling the filterscope system is shown schematically in Figure 4.2. This work-flow is carried out in the Main Tab of the filterscope.vi (found in control computer's directory — see section 3.1). The step-wise flow of operations is carried out as follows:

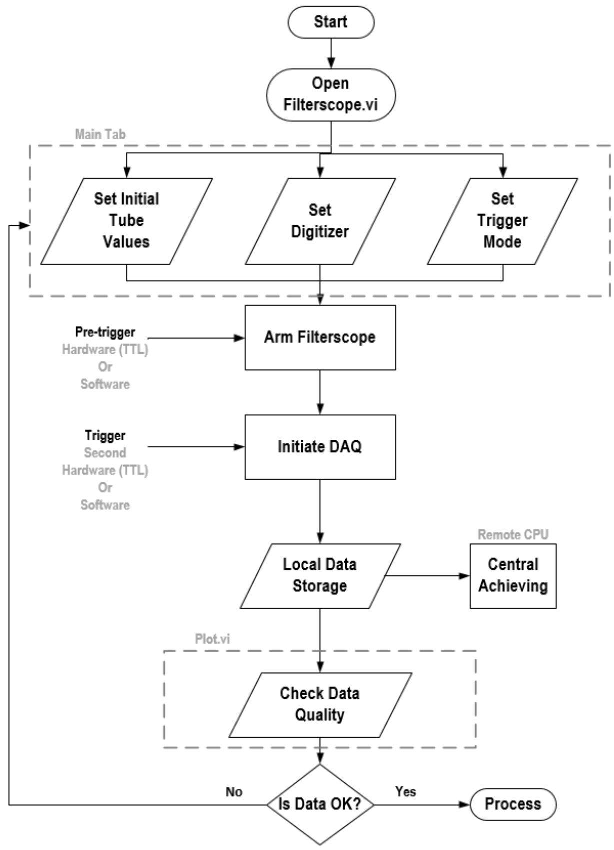


Figure 4.2: *Logic Flow Diagram of the Main Tab in the Filterscope.vi.*

1. The user sets the base operating parameters in the main tab — more details on this are in section 4.1
2. With the help of a hardware pre-trigger or a software pre-trigger, the Filterscope is armed and ready to obtain a trigger to collect data.
3. Once a hardware or a software trigger is received, the filterscope initiates the DAQ card for data acquisition (Note: the vi will be "locked out" during acquisition)
4. Once the digitization is complete (see digitizer parameters in section 4.1.3) and data is acquired, a suite of filterscope system settings and data are transferred to two places: a local computer storage and MDSplus archive (see Section 3.2 for details)
5. After data archival, the suite of information can be plotted via "Plot MDSplus Data" located in the utility tab (Section 4.2.2.3) to check the data quality
6. The user can then repeat the steps above if changes are needed in the data and/or parameters

4.1 Filterscope LabVIEW Program - Main Tab

Figure 4.1 shows the screen-captured image of the Main Tab in the "filterscope.vi". The complete image is divided into ten parts for better understanding of each section in the program. The program opens up with the main tab as default when it is run. The program has two major tab categories: Main Tab (**Label 4.1.1**) and Auxiliary Tabs (**Label 4.1.2**) which consists of Tube Test tab (Section 4.2.1), Utilities Tab (Section 4.2.2), and Calibration tab (Section 4.2.3). The user can toggle between the tabs to use different functionality of the program.

The user operating the program will utilize the "Configuration and Mode Control (CMC)" unit for majority of the time of use. The CMC unit is labelled as **Label 4.1.3** in Figure 4.1 and will be described in detail in Section 4.1.1. Before running the program, the user can configure and control filterscope parameters through the CMC unit. Once the program in general is configured, each tube parameters could be changed and be set up as per the need from the "Tube Control (TC)" unit which is shown in Figure 4.1 as **Label 4.1.5**. The TC unit is elaborated in Section 4.1.2. The user can also change the program digitization rate through the "Digitizer" unit. The Digitizer unit can be found as **Label 4.1.10** in Figure 4.1 and is described in Section 4.1.3. During the operation, the user can get the tube feedback through the "Tube Feedback (TF)" unit which is labelled as **Label 4.1.4** in Figure 4.1. The TF unit will be described in detail in Section 4.1.4. During the diagnostic operation (see Section 4.1.1) of the program, the “Data Monitor” (**Label 4.1.6**) shows the status of the parallel data storage process which is obtained in parallel with the data collection. The **Label 4.1.8** displays the information about the next shot number that will be acquired by the filterscope and also displays the previous shot number that was acquired by it. The “Press Reset/Rewrite Tubes” button in the Label 4.1.8 helps in resetting the tubes with current configurations which are loaded in from the CMC unit. This button is to be used when the tubes saturate and when the user changes the tube parameters from the TP unit. The plot displays each data segment being stored by the data monitor in the parallel program. Information on the name of the filterscope hardware and the hardware or software error is shown in **Label 4.1.9**. To terminate the program the user can press the “Process Stop” button as seen as **Label 4.1.7** in Figure 4.1.

4.1.1 Configuration and Mode Control (CMC) Unit

The CMC unit is used to configure and control different modes of the DAQC. The CMC unit is represented in Figure 4.3. As seen, the CMC unit is sub-divided in to six parts. **Label 4.3.1** in the CMC unit describes the mode of the filterscope.vi. There are four different modes in which the filterscope.vi can operate: 1. *“Pause Mode”*: pauses the program which could be helpful to the user for changing parameters. 2. *“Write New Configuration File Mode”*: helps the user by writing the current configuration to a new Excel file. 3. *“Write to Modules Mode”*: resets and writes current configuration to the tubes, and 4. *“Diagnostic Operation Mode”*: activates the diagnostic mode in the vi and awaits triggering.

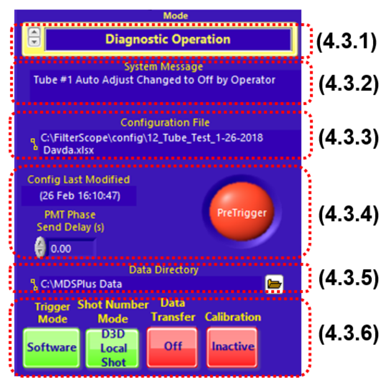


Figure 4.3: *A figure labelling various functions of the CMC unit.*

Once the user selects a mode of operation for the program, the user can appoint a location of MDSplus data storage directory from **Label 4.3.5**. The location of the configuration Excel file that is loaded (see Section 3.1) can be seen in **Label 4.3.3** along with a system showing a message regarding the program in **Label 4.3.2**. The date of last modification to the configuration file can be seen in **Label 4.3.4** along with a software trigger button when in diagnostic operation mode. The interface buttons that control the trigger, shot number, data transfer and calibration are found in **Label 4.3.6**. Label 4.3.6 is sub-divided in to 4 parts: 1. *Trigger Mode:* used to swap between the hardware trigger (Facility trigger) and software trigger (manual trigger). When the “Software” mode is selected, a red button appears near the “Config Last Modified” banner (label 4.3.4). The red button will have a label of “Pre-trigger” written on it and once clicked, the status of the label will change to “waiting on a trigger”. and, the red button will now read “trigger”. The user must click it to trigger the ’vi’ to collect data. 2. *Shot Number Mode:* used to control the shot number that is to be obtained. To make the shot number the same as the machine shot number (e.g. for a run day), change the shot number mode to “Facility Shot”. Similarly, to make the shot number same as the local shot numbers (e.g. to calibrate data), change the shot number mode to “Local Shot” mode. 3. *Data Transfer:* Enables automatic writing of the data to the facility MDSplus tree from the local tree. 4. *Calibration:* When active/on, the ’vi’ uses the calibration parameters to compute each tube’s calibration and stores all relevant parameters for setting the peak normalized radiance (see Section 5.1). When inactive/off, the ’vi’ does not store and use calibration coefficients that set the peak normalized radiance for each tube.

4.1.2 The Tube Control (TC) Unit

Once the program has been configured with the right mode, the user can control individual tubes through the TC unit, see Figure 4.4. For example, the TC unit enables the user to vary the tube control voltage, tube gain, tube name and also enables Edge Localized Modes (ELMs) detection for a specific tube. The TC unit is detailed in Figure 4.4 that represents 13 different parameters of the TC unit.

The user can select the tube that needs its parameters to be edited through **Label 4.4.1**. Once the tube number is selected, the rest of the TC unit displays parameters related to the selected tube. One of the many indicators is the "Active" indicator (**Label 4.4.11**) that shows that the tube is active if the indicator is green whereas the tube is inactive if the indicator is red. The default initial and final control voltage of the selected tube is seen in **Label 4.4.2**, and the user can set the initial control voltage (V_{CONT} from section 2.3) prior to a trigger while the final control voltage is displayed after each acquisition and cannot be edited. It will only be different before a shot if the initial control voltage was changed or after a shot if 'auto-adjust' is active (Label 4.4.6). The initial voltage is user controlled via a toggle switch that can be turned "on" and "off" (**Label 4.4.3**). When the toggle switch is 'on", the tube will begin every shot with an initial voltage value set in Label 4.4.2. When the toggle switch is 'off", the tube will remain at the final control voltage that is displayed in Label 4.4.2. The user can edit the maximum and minimum voltage settings for the feedback loop used for auto-adjusting the selected tube through **Label 4.4.7**. This can be edited only when the Auto-adjust toggle switch is turned "on" in **Label 4.4.6**. When the toggle switch is on, the control voltage in the following feedback loop will be adjusted: V_{PMT} will be maintained within the upper-lower voltage window by changing V_{CONT} every "cycle" (defined in label 4.6.9 in Figure 4.6) by averaging V_{PMT} and comparing the the upper/lower voltage settings. The V_{CONT} steps are defined in label 4.6.10. The TC unit has some

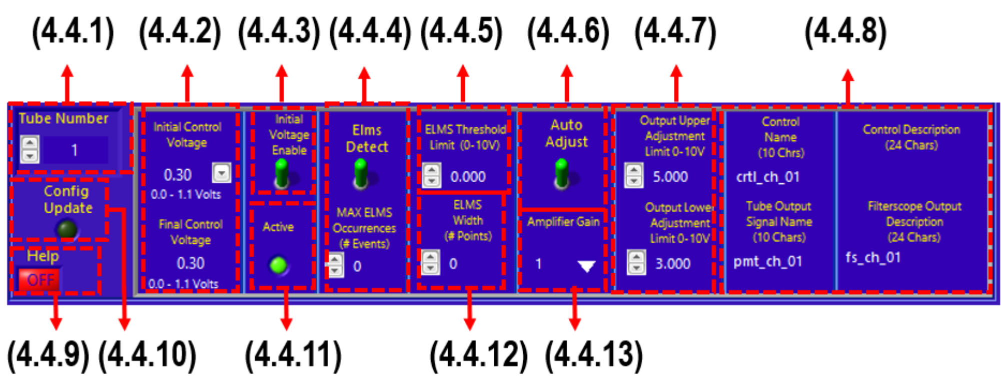


Figure 4.4: *An image labelling and highlighting various components of the TC unit*

additional features that could be of use to the user. One such feature is the ELMs detect (**Label 4.4.4**). To activate this feature, the user can toggle on the ELMs detect feature which would allow the user to access the features from Label 4.4.4, **Label 4.4.5**, and from **Label 4.4.12**. The Label 4.4.4 feature is used in conjunction with the auto-adjust feature (which should also be set to "on") and is used to "skip" transient features (like ELMs) that appear in V_{PMT} for the auto-adjust cycle. Once the feature is "on", the bottom half displays the maximum number of ELM occurrences. The ELM occurrences can be set through Label 4.4.5, which ranges from 0 - 10 V and through Label 4.4.12 that helps the user set a particular width of an ELM that is to be ignored by the auto-adjust feedback loop. The TC unit also provides an option to name a tube along with its parameters while storing it in MDSplus which could be useful while referencing, logistics and post-processing. This feature can be accessed through **Label 4.4.8**. The "Control name" is the tube V_{CONT}

name, and is aligned to the tube; e.g: "CTRL(01)" aligned with "TUBE(01)". "Tube Output" is V_{PMT} and is aligned with "Control name" that is related to the channel's setup, e.g: for a D_α filter in tube one, this would have a setting of "$CTRL(01)_{DA}$". "Filterscope Output" is also related to the channel setup matching to V_{PMT}, e.g. for D_α in tube 1,"$FSCP(01)_{DA}$". As the parameters are being changed, the initial values of the tube are updated in a configuration file that can be seen in **Label 4.4.10** when this alert indicator turns green from red. If additional help is needed regarding the TC unit, the user can click on the Help Button (**Label 4.4.9**) which when clicked displays information in a bubble format for buttons that are hovered over.

Note: The amplifier gain for a tube is normally kept at 1, but can be adjusted, if needed through **Label 4.4.13**.

4.1.3 The Digitizer Unit

The user can vary the digitization parameters through the Digitizer unit (Figure 4.5). The digitizer unit has been divided in to five parts for the better understanding of the user. To use the digitizer block, the user can switch on the unit through the "enable" button, as seen in **Label 4.5.1**. Once the unit is enabled, the user can vary several of its parameters. "Physical Trigger" is one such parameter (**Label 4.5.2**), that displays the start time where the physical trigger of the positive Transistor Transistor Logic (TTL) pulse with respect to the facility time (t_0). The "Digitizer delay" parameter (**label 4.5.3**) shows the amount of time (in seconds) until the data collection begins, once the hardware trigger was initiated. For example, if the external trigger is set to zero seconds, and the "digitization delay" is set at six seconds, then the filterscope will trigger six seconds later and all the signals will begin at t_0 plus the six-seconds offset. The user can change the digitization frequency through **Label 4.5.4** where the number of samples collected per second can be varied via user inputs. Those number of samples collected can be collected over a particular time duration, called "Scan Length" (**label 4.5.5**). The first data point that is noted by the digitizer unit is the culmination of the physical trigger, the digitizer delay, and the digitizer frequency.

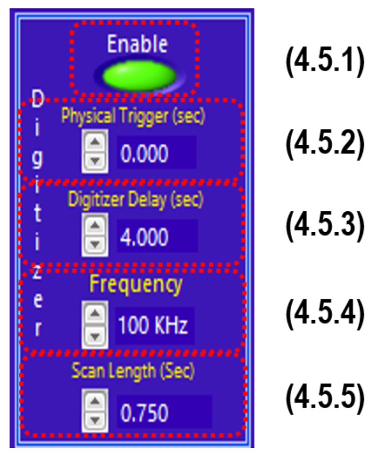


Figure 4.5: *A figure labelling various functions of the Digitizer unit.*

4.1.4 The Tube Feedback (TF) Unit

During acquisition, the feedback unit (Figure 4.6) helps user understand the changes done on the tube. For better understanding of the TF unit, the unit has been divided into ten parts. The number of tubes in the current configuration file can be seen in **Label 4.6.2**. The number of tubes that are active and have taken data at t_0 trigger are displayed in **Label 4.6.3**. One can see the number of tubes that have be auto-adjusted from **Label 4.6.4** where as the number of tubes that have their initial voltage initiated are displayed in **Label 4.6.5**. The number of tubes which were initiated for the ELM detection feature are displayed in **Label 4.6.6**. While the total number of auto-adjusted cycles performed during the last t_0 trigger are displayed in **Label 4.6.7**, the number of samples that were collected in each acquisition cycle is displayed in **Label 4.6.8**. This label (Label 4.6.8) will have the number displayed turn red when the acquisition cycle does not

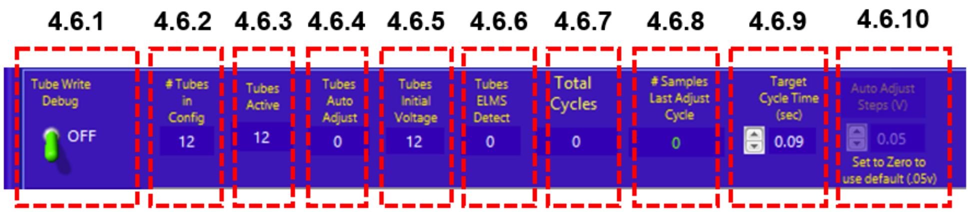


Figure 4.6: *A figure labelling and highlighting various parameters of the TF unit.*

meet the requested minimum cycle time parameter. The aforementioned minimum cycle time parameter can be found in **Label 4.6.9**, which shows the minimum time for tube auto-adjusting the control voltage and can be adjusted as part of the auto-adjust feedback. Common values are 0.02 seconds for PMTs with slower response time, and 1 second for PMTs with faster response time. **Label 4.6.10** displays the voltage increment for each auto-adjust cycle. If this increment is set to zero, the default value of 0.05 V is used. To manually debug the tube writing process, the user can toggle on the "Tube Write Debug" on from **Label 4.6.1**. To know more about Label 4.6.1, see Appendix A, Question 7.

4.2 Auxiliary Tabs

The auxiliary tabs help the user to perform sub-tasks that are needed for the execution of the Main tab. This section will detail the Calibration tab, Tube Test Tab, and the Utilities Tab to explain how these tabs are utilized by the main tab in the filterscope vi.

4.2.1 Tube Test Tab

The "Tube Test" tab (Label 4.2.2 in Figure 4.1) is used for initial testing of the tube output. It basically examines individual PMT by displaying a real-time feedback from the tube without storing the data on the computer and/or MDSplus tree. Figure 4.7 shows the LabVIEW program of the Tube Test Tab and is divided into ten parts for better understanding.

The left half of the tube test tab has input parameters that can be set by the user to carry out the testing of the tube. Each tube is tested separately by selecting the tube number (**Label 4.7.1**). Once the desired tube is selected to test, V_{CONT} of the tube can be set from **Label 4.7.2**. Time between samples can be varied according to the need in **Label 4.7.4** and the number of samples to be acquired can be set from **Label 4.7.5**. The gain for the selected tube also can be varied through **Label 4.7.3**. Once all the parameters are set, a "Tube Test Signal" will be displayed in the right side of Figure 4.7 in **Label 4.7.9**. The user can clear the chart plotted by "clear chart" button, found on top of the graph in **Label 4.7.8**. This label (**Label 4.7.8**) displays the current reading from the graph (**Label 4.7.9**), along with the chart mean and the module of the tube from which the tube is selected. If an error occurs due to hardware, the "Tube Test Error" block will display the error (**Label 4.7.7**).To correct the error, the user can try restrating filterscope program, see if the light source is functioning properly, and/or check if all the connections are correct. The complete tube test can be restarted by clicking "Reset Tubes", which is found at **Label 4.7.6**. Each tube test can follow the above procedure to successfully conduct a tube test and the process can be paused at any time through **Label 4.7.10**.

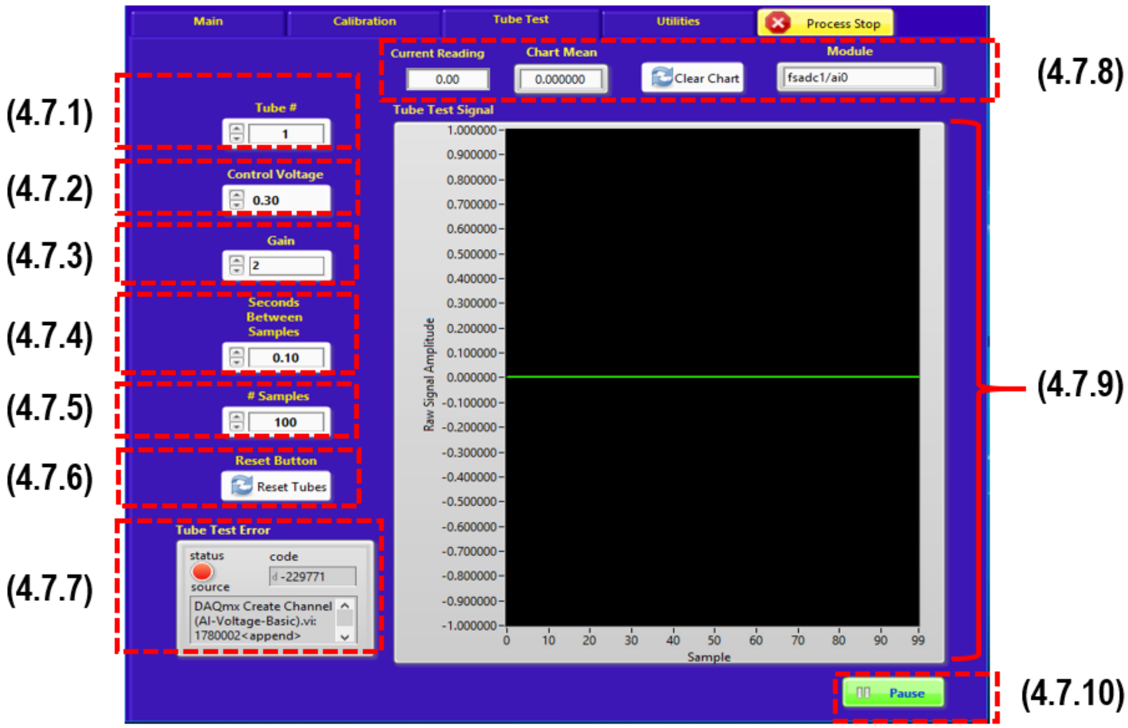


Figure 4.7: *Tube Test Tab*

Figure 4.8: *Utilities Tab*

4.2.2 Utilities Tab

The Utilities tab is used specifically for adding utilities to the filterscope vi. This tab (see Figure 4.8) adds five additional programs that facilitate the use of filterscope.vi. The four different sub-programs embedded into utilities tab are 1. USB Light Source, 2. Shot Server Test, 3. Plot MDSPlus Data, 4. Overwrite Previous Calibration Data, and 5. Copy shot Data to Remote Server. Each of the sub-programs will be detailed in the following sections.

4.2.2.1 USB Light Source Function

This function is used to turn on a USB light source (Figure 4.9). The light source can be used to carry out the tube test in the Tube Test Tab. The program looks for a NI USB-6210 DAQ device which has an embedded light source. If a NI USB-6210 based light source is not found, this program would not execute. Read more about the NI USB-6210 DAQ at http://www.ni.com/pdf/manuals/375194d.pdf.

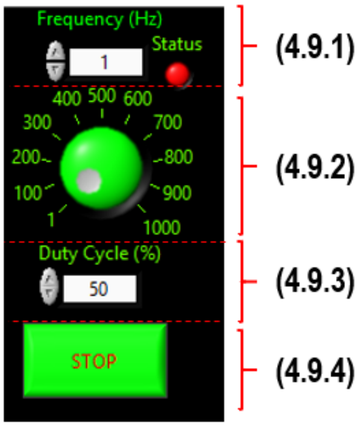


Figure 4.9: *USB Light Source Function Block*

Once the light source is attached to carry out Tube Test, the user can vary the frequency of the light by changing the frequency in the "Frequency" block (**Label 4.9.1**) or by rotating the virtual knob in **Label 4.9.2** from 1Hz up to 1000Hz. Once the frequency is set to a desired value, the user can vary the duty cycle from **Label 4.9.3**. This then would show a "green" light in the "Status" symbol found in Label 4.9.1 suggesting that the light source is turned on. If the status symbol depicts a red light, that would mean the light source is not turned on. Once the Tube Test is done, one can stop the light source by pressing the "Stop" button in **Label 4.9.4**.

4.2.2.2 Shot Server Test

The shot server testing function (see Figure 4.10) is used to change/get local shot parameters and get remote server information. Once the manual set shot is in process, any changes in the "Set Shot" section changes the Next Shot number (**Label 4.1.8** from Figure 4.1).

To carry out a shot server test, the user must select a remote tree in **Label 4.10.1**, where the data could be stored. Once a remote tree is selected, one can click on the "Get Tree Items" button from **Label 4.10.4** to read the selected tree model structure (from Section 3.2). One can also create a pulse to store data by clicking on "create pulse" from **Label 4.10.3**. Once the pulse is created, the user can set shot numbers by clicking on "Set shot #" in **Label 4.10.6**. Finally, one can verify the shot from **Label 4.10.2** by clicking on "Get shot #" button. **Label 4.10.5** shows the "process stop" button that can be clicked to stop the complete process.

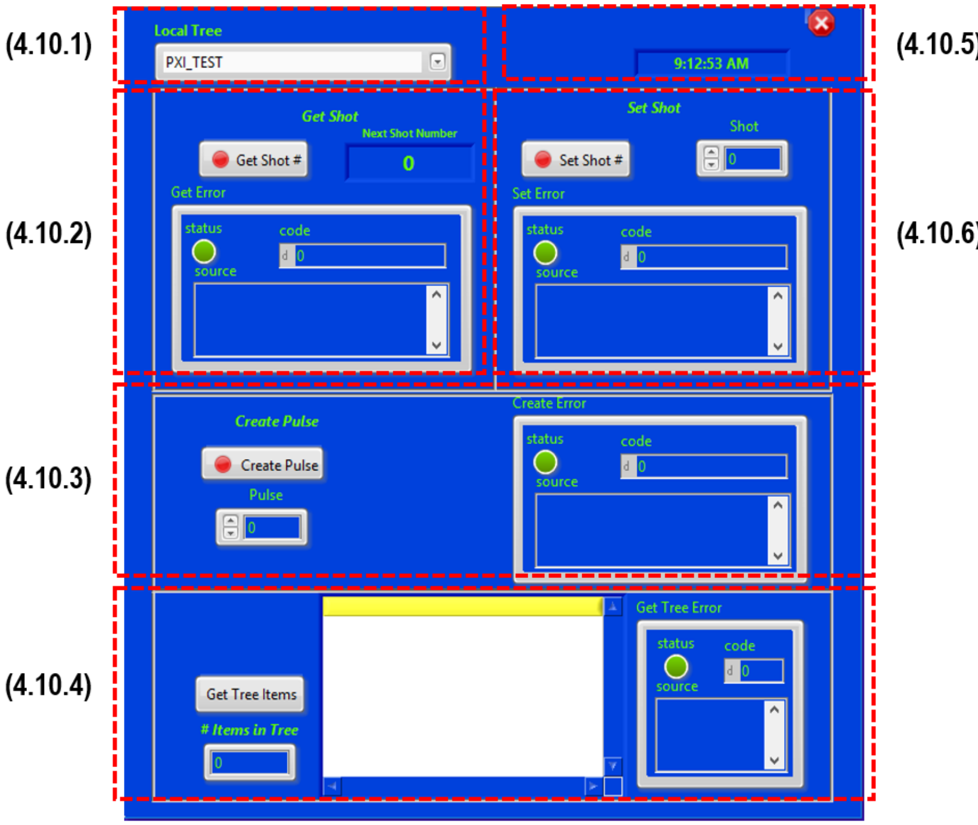


Figure 4.10: *Shot Server Test Tab*

4.2.2.3 Plot MDSplus Data

This program is a part of the utilities tab. From the flow chart diagram in Figure 4.2 it can be seen that eventually all the data is displayed in the plot program.

Figure 4.11 shows the plot program that is used to display the MDSPlus data. The user can select whether the shots displayed in the directory table are updated manually or automatically by switching between the two options from **Label 4.11.1**. Once the directory update procedure is selected, the number of the shot to be displayed in the directory table can be set by selecting a number in “number of shots in directory table” section (**Label 4.11.2**). Shots displayed will be referenced up to the shot number in the ’stop’ control box in the shot range block (**Label 4.11.5**).

The directory table (**Label 4.11.3**) will display the shots. The tree information of a particular shot is listed in **Label 4.11.9** once a shot is selected in the directory table (Label 4.8.3). Once a particular tree node is selected, **Label 4.11.4** will display the data from that node. The signal plot type can be varied from **Label 4.11.6** and the user can clear the plot, if needed, by clicking the “clear plot” button (**Label 4.11.8**). If a remote shot is taken, the user can view the remote shot list by flipping the “Use Local Shot #?” (**Label 4.11.7**) switch to ’Yes’. Local shot number button selects whether the directory update will use the local/remote shot during directory table update. If NO is selected, the “stop” control in the local/remote shot range block

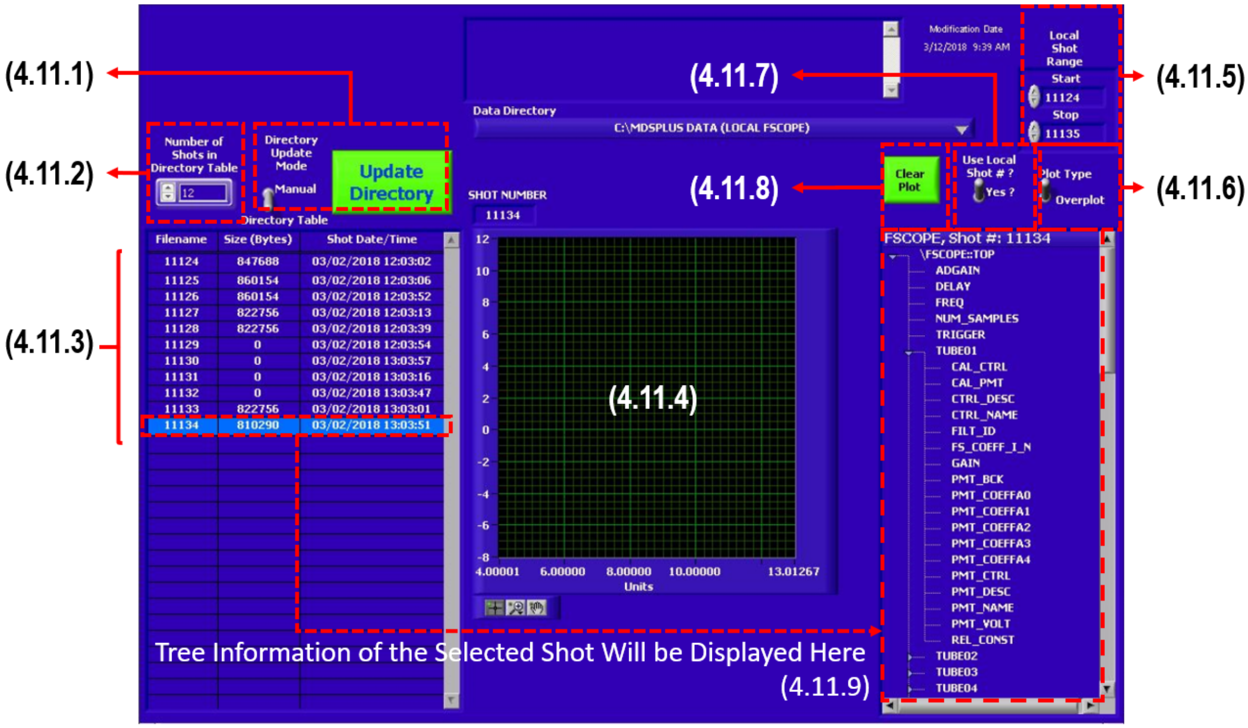


Figure 4.11: *Plot Program Tab Panel*

will turn yellow and the user can set the ending shot to be displayed in the directory table when updated and the start limit will be automatically adjusted to the range listed in Label 4.11.2.

4.2.2.4 Overwrite Previous Calibration Data

This function is used if and when the user wants to overwrite previous calibration data in case the calibrated data is inaccurate. When the "Overwrite Previous Calibration Data" function is opened, the number of tubes attached to the filterscope are shown on the left side of the function window. (see Figure 4.12 **Label 4.12.3**).

To overwrite the previous calibration data, press "Import Calibration Settings From Excel File" button in **Label 4.12.4**, which will automatically fill calibration parameters. The detailed description of the calibration parameters can be seen in Chapter 5 of this manual. Once the calibration parameters are imported, the user must set the start and end shot, found at upper left corner of the function window (**Label 4.12.1**). Once the start and end shot are set, the user must select which tree (local or remote) to alter and once selected, the data tree updates automatically in **Label 4.12.7**. Once the tree has been updated, select the tube that needs the calibration overwrite, if all tubes are to be overwritten, press "select all" button in **Label 4.12.2**. Once the desired tube is selected, press "Overwrite Local Tree Cal" in **Label 4.12.6**, which will overwrite the previous calibration data locally. This process can be done for a remote tree by pressing "Overwrite Remote Tree Cal" button, found next to "Overwrite Local Tree Cal" button in **Label 4.12.6**. An error/warning message is displayed near the "process stop" button that can be found in the top upper right window (**Label 4.12.5**), which helps the user to visualize an error/warning.

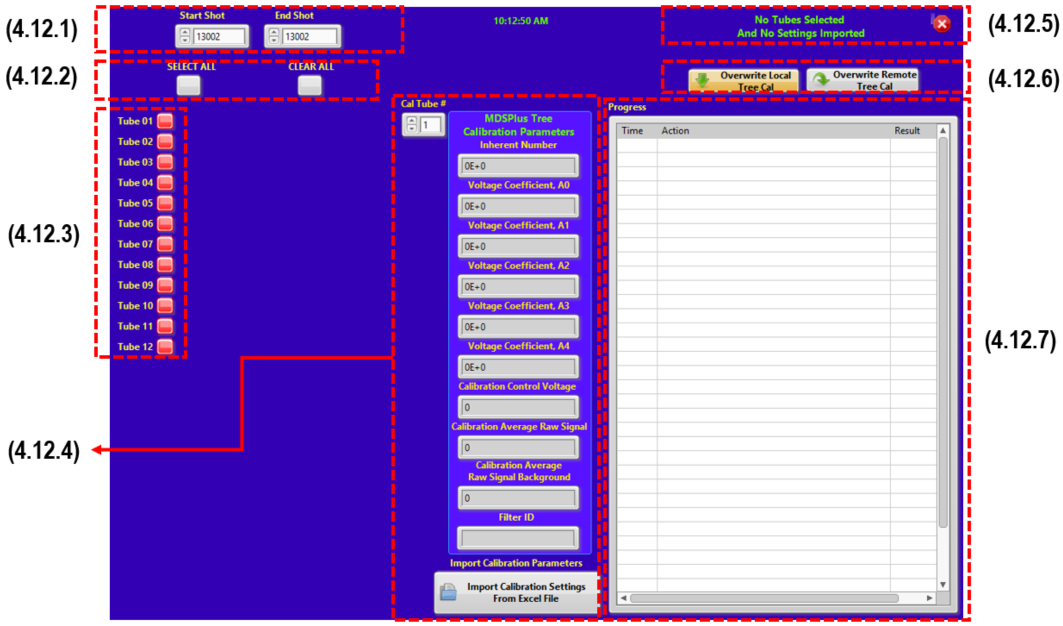


Figure 4.12: *Overwrite Previous Tube Calibration Data Panel*

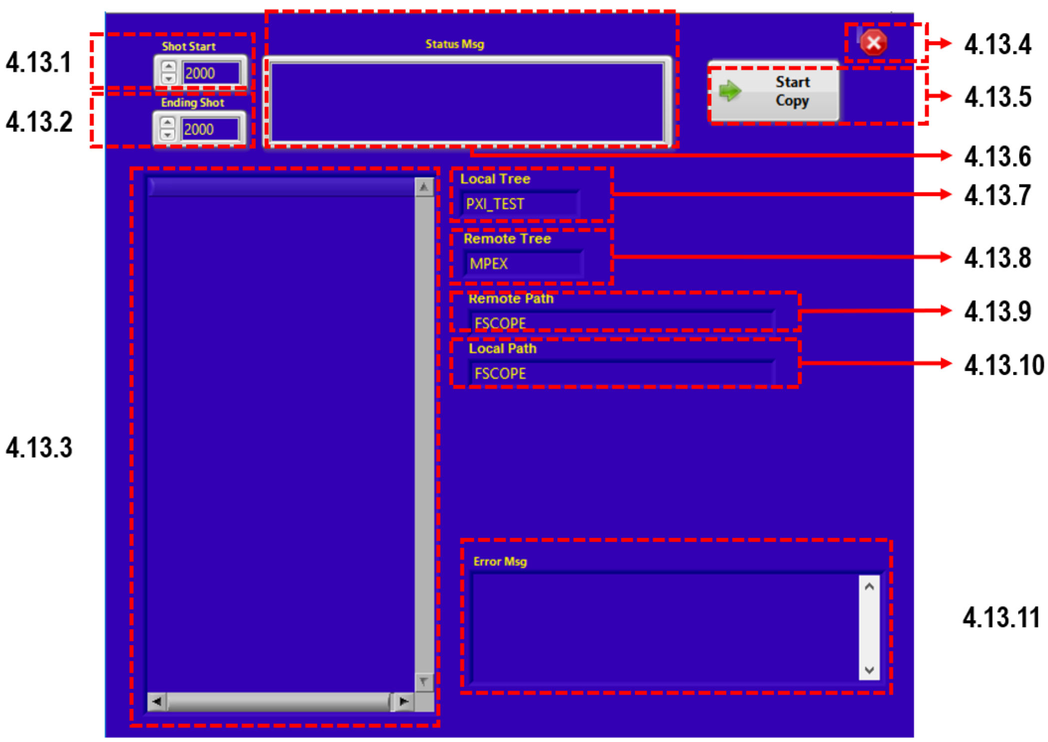


Figure 4.13: *Copy Shot Data to Remote Server Panel*

4.2.2.5 Copy Shot Data to Remote Server

This subprogram (Figure 4.13) allows the user to copy and store the shot data to a remote server. For better understanding, the program is divided into 11 parts. To initiate the copy of shot data, the user must first select the number of shots that needs to be copied through the blocks “Shot Start” (**Label 4.13.1**) and “Ending Shot” (**Label 4.13.2**). Once the number of shots has been selected, the user must select the remote tree that the user desires the shot data to be copied. This can be done from **Label 4.13.8**. The local tree (**Label 4.13.7**) must be displayed already, if not, one can select the local tree. This would initiate the display of the tree in **Label 4.13.3**. Once the local tree and the remote tree has been finalized, the user must input the remote and the local path for the data transfer to occur via **Label 4.13.9** and **Label 4.13.10**. After the completion of the aforementioned steps, the user can start the copy process by clicking the “Start Copy” button in **Label 4.13.5**. Once the start copy button is initiated, the status of the copy is displayed in **Label 4.13.6**. If the program encounters any errors while copying the data, it will show the errors in the “Error Message Block” (**Label 4.13.11**). The user can follow this procedure to copy shot data to remote server and if necessary can stop the execution of the copy anytime by pressing the stop button from **Label 4.13.4**.

4.2.3 Calibration Tab

The calibration tab is an integral part of the filterscope system as it is used to calibrate each PMT in the filterscope system. The logic flow behind the calibration tab is depicted in Figure 4.14. Like other scientific diagnostic tools, each PMT in the filterscope is to be calibrated before operating.

To start the calibration process, one must carry out the PMT gain calibration procedure (found in Appendix B.3) to obtain the model fitting coefficients (PMT_COEFFA0, PMT _COEFFA1, PMT_COEFFA2, PMT_COEFFA3, and PMT _COEFFA4) that will be inputted in **Label 4.15.2**. The fitted coefficients are representative of the selected tube in the ’Cal Tube #’ box in **Label 4.15.1**. Every tube has separate calibration settings that needs to be tested and saved; therefore, ’Cal Tube #’ allows the calibration settings to be saved for each tube separately. In the Figure 4.15, tube (PMT) 1 is the focus.

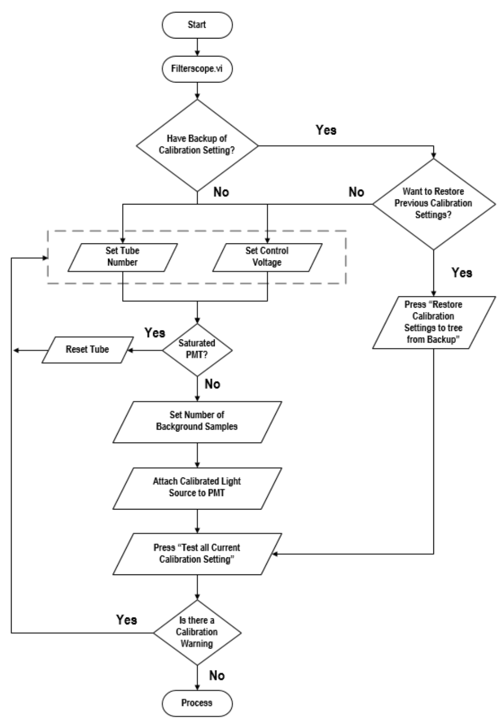


Figure 4.14: *Logic flow chart of the Calibration Tab in the filterscope.vi.*

Label 4.15.1 also displays the “Control Voltage” of the selected PMT. It responds exactly the same way the “Initial Control Voltage” does on the Main Tab (Label 4.4.2 in Figure 4.4). If the “Control Voltage” is increased then the signal will be amplified and if the “Control Voltage” is decreased then the signal will be reduced.

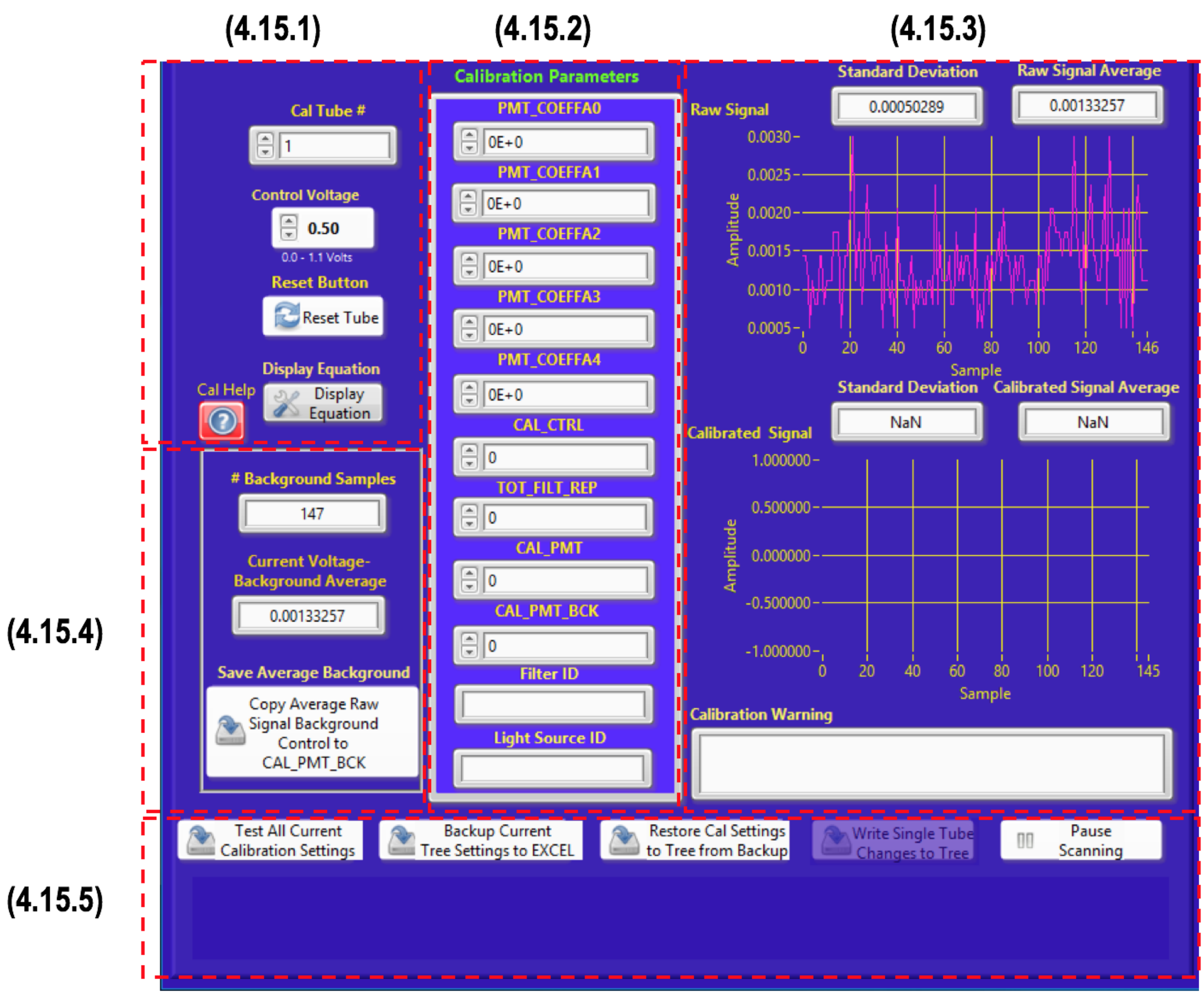


Figure 4.15: *Filterscope.vi - Calibration Tab*

***Note** : Changing the "Control Voltage" on the Calibration Tab **WILL NOT** change the "Control Voltage" on the Main Tab.*

Also in Label 4.15.1, the 'Reset Tube' button resets the tube, for example, if and when the tube saturates, decrease the 'Control Voltage' and then click 'Reset Tube' button to remove saturation. The 'Cal Help' button is there specifically to help the user understand every labeled piece of the Calibration Tab. When clicked, the 'Cal Help' button will turn green and the user can now hover the mouse over any section's title to get a brief description of it. The 'Display Equation' button, once clicked, will open a window that has an interactive calibration logic diagram. The user can use this logic diagram to insure the calibration is being performed correctly.

Label 4.15.2 shows the calibration parameters related to the selected tube. There are 11 parameters that pertain to the calibration of the PMT. First five parameters from the top are the model fitting coefficients as discussed earlier, obtained from the PMT gain calibration procedure. 'CAL_CTRL' is the control voltage at which the user wants the PMT to be calibrated, normally CAL_CTRL is kept at 0.55 V. 'TOT_FILT _REP' is the total filter response for the PMT, normally TOT_FILT _REP is kept at 1. 'CAL_PMT' is the calibrated PMT value found under 'Raw Signal Average' in **Label 4.15.3** at a particular CAL_CTRL value with a light source connected to the filterscope system. 'CAL_PMT_BCK' is the background calibrated PMT value also found under 'Raw Signal Average' in Label 4.15.3 when no lightsource is connected. The calibrated PMT value ranges in the 'Standard Deviation' found in Label 4.15.3. 'Filter ID' stores the description of the filter used while calibrating the PMT. 'Light Source ID' stores the description of the light source used while calibrating the PMT. Label 4.15.3 displays the two plots: the top plot shows the CAL_PMT value in real-time. The bottom plot shows the calibrated plot of the calibrated values displayed in the 'calibration signal average' box along with its standard deviation. This is the visual aid to see the change in Raw signal (top plot), and the calibrated signal (bottom plot).

Label 4.15.4 shows the '# Background Samples' which shows the number of points used in the background average value. In this Figure, 147 background samples are averaged. This average value is the "Current Voltage-Background Average", and this average value can be copied to the calibration setting "Calibration Average Raw Signal Background to CAL_PMT_BCK " (Figure 4.15: Label 4.15.4). This value should be measured when measuring $V_{PMT-cal}$ in Chapter 5; however, the "Background" section can be used as a proxy.

There are five buttons in **Label 4.15.5** that can be used by the user. One can test all current calibration settings that are stored in the vi currently by pressing the "Test all current calibration settings" button. When the user clicks the "Backup current tree settings to Excel" button, the calibration settings stored in the current calibration setting is backed up to a local Excel file. The user has flexibility to transfer all the calibration settings stored in the backup Excel file to the MDSPlus tree by clicking the "Restore Cal settings to tree from Backup" button. The "Write single tube changes to tree" button inputs the current "cal tube #" calibration settings into the MDSPlus tree. To pause the "visual display" in Label 4.15.5, press the "Pause scanning" button.

The PMT is calibrated once the calibrated signal (bottom) plot (in Label 4.15.3) stays steady within ± 5% deviation of the TOT_FILT_REP value over the range of all Control Voltage value (i.e. 0.05 V - 1.00 V).

5 CALIBRATION PHILOSOPHY & METHODOLOGY

Each PMT is separately controlled via the input control voltage, V_{cont}, within the filterscope system, and the reproduciblity and stability of photon detection over time from each PMT is key to quantitative measurements. Equally, to ensure this measurement is independent of instrument settings, the filterscope needs an absolute calibration, i.e. can give an output in units of $photons/sec - m^2 - str$ for example. Calibrating the filterscope system includes two independent steps. Those steps being: 1) calibrating the PMT gain (done only as often as needed for a given PMT), and 2) a normalized radiance calibration (done as often as needed to collect quantitative data from the system — typically paired with an experimental campaign).

The calibrated output of each filterscope channel will give either a line-normalized radiance (in units of $photon/s/cm^2/str$) or peak-normalized radiance (in units of $W/cm^2/str$). Using line-normalized or peak-normalized radiance will depend on the measurement need. The simple expression for a typical use of the filterscope is line-normalized radiance and is given by,

$$L_{A_{i\to k}} = 5.03 \times 10^{24} \cdot \lambda_{i\to k} \cdot \frac{\triangle\lambda_{i\to k}}{\triangle\lambda_{PN}} \cdot L_{PN}\left[\frac{ph}{s - str - cm^2}\right]. \quad (5.1)$$

Here, $A_{i\to k}$ is element A with $i \to k$ transition, e.g. D_α would be $D_{3\to 2}$. $\lambda_{i\to k}$ is the wavelength of the $i \to k$ transition of interest (in nm for this application — using Å units are possible but unnecessary), e.g. $D_\alpha = 656.1nm$. $\triangle\lambda_{i\to k}$ and $\triangle\lambda_{PN}$ are the line-normalized wavelength span and peak-normalized wavelength span, respectively, and are related to the responsivity of the PMT channel, see sections below. Finally, L_{PN} is the peak-normalized radiance for the calibration channel, which is specific to each PMT channel's setup, i.e. filter and calibration light source. The calibrated signal presented in the calibration tab of the filterscope.vi (figure 4.15) is the peak normalized radiance for each channel.

The line-normalized radiance defined in Eq. 5.1 is directly related to that given in Eq. (4) of reference [6]. The exact definition of each term in Eq. 5.1 will be given in the sections below as will the relationship of line-noramlized to peak-normalized radiance.

5.1 The Normalized Radiance Calibration Step

In general, normalization is the process of reducing measurement results as nearly as possible to a common scale to achieve quantitative inter-comparisons. In radiometry, probably the most frequently employed form of normalization is peak-normalization [23]. Here, when the governing (spectral) parameter is the wavelength, λ, the maximum or peak value of the spectral responsivity, $R(\lambda)$, is arbitrarily chosen as a normalizing responsivity, $R(\lambda_m)$ where λ_m is the wavelength at peak responsivity. The exact definitions and significance of these quantities are defined below.

5.1.1 Quick Definition of Some Radiometric Terms

The basic definitions listed below are helpful in understanding the calibration section using the normalized radiance method and form the backbone of the radiant calibration of the filterscope diagnostic tool.

The important radiometric concepts are:

- Radiant flux, $\Phi_e \equiv \frac{dQ_e}{dt}$ with SI units of $[W]$, is defined as the flow of radiant energy (Q_e) per unit time. It is also called radiant energy.
- Irradiance, $E_e \equiv \frac{d\Phi_e}{dS}$ with SI units of $\left[\frac{W}{m^2}\right]$, is the radiant flux incident per unit area of a surface. It is also called radiant flux density (See Fig. 5.1-a).
- Radiant intensity, $I_e \equiv \frac{d\Phi_e}{d\omega}$ with SI units $\left[\frac{W}{sr}\right]$, is the radiant flux emerging from a point source, divided by the unit solid angle (See Fig. 5.1-b).
- Radiance, $L_e \equiv \frac{dI_e}{dS \cdot \cos\theta}$ with SI units of $\left[\frac{W}{sr \cdot m^2}\right]$, is the radiant intensity emitted in a certain direction from a radiant source, divided by unit area of an orthographically projected surface (See Fig. 5.1-c). In situations, such as in typical filterscope setups, when the detector field of view is much smaller than the source (a far-field geometry) and the source is isotropic, then $L_e = \frac{E_e}{4\pi}$ or, more precisely, $E_{e\infty} = 4\pi \cdot L_{e0}$, i.e. irradiance of the source is directly related to the source radiance [24].

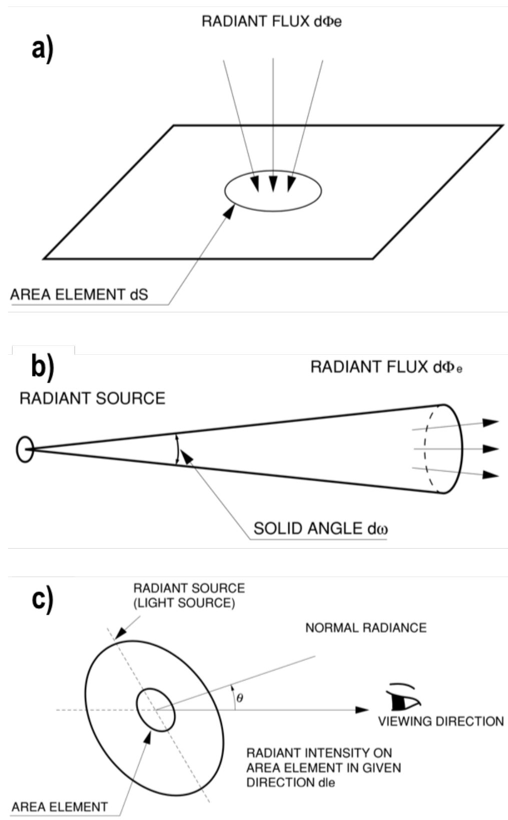


Figure 5.1: *Basic radiometric concepts. Sub-figure a) depicts Irradiance. Sub-figure b) depicts radiant intensity. Sub-figure c) defines radiance. Adapted from ref. [10]*

It is useful to point out that each of these concepts/terms can also be defined as a spectral quantity, e.g. spectral radiant flux or spectral radiance. In such cases, the quantity is a profile with a wavelength dependence and therefore the units of each would then include an addition per wavelength, e.g. the SI units of spectral radiance, L_e, is $\left[\frac{W}{sr \cdot m^2 \cdot nm}\right]$. This terminology is now employed to describe the absolute calibration of each PMT channel of the filterscope system.

5.1.2 Background: Determining Particle Flux via Line-Normalized Radiance

Optical methods allow in-situ measurement of fluxes for boundary measurements in fusion devices and provide the possibility of obtaining information without, or with relatively little, perturbation of the plasma. For fusion research, filterscopes can be used to determine **particle flux** from the wall into the SOL. Particle flux is the rate of transfer of particles per unit time and is denoted by Γ having SI units of $[atoms/sec]$. It is calculated via the following equation at a characteristic wavelength, $\lambda_{i\rightarrow k}$:

$$\Gamma_{A_{i\rightarrow k}} = 4\pi \cdot L_{A_{i\rightarrow k}} \left(\frac{S}{XB}\right)_{i\rightarrow k} \left[\frac{atoms}{sec - m^2}\right], \tag{5.2}$$

where $S \equiv <\sigma_I v_e> \left[\frac{m^3}{s}\right]$ and $X \equiv <\sigma_{Exg} v_e> \left[\frac{m^3}{s}\right]$ are ionization and excitation rate coefficients, respectively and $B \equiv \frac{A_{i\to k}}{\sum_{k\leq i} A_{i\to k}}$ is the branching ratio, which is the ratio of the probability of a transition from a specific upper level to lower level to the total probability of transition from that same upper level to any lower level. The $S/(XB)$ quantities are typically obtained from the ADAS database [25] for a fair number of elements commonly used in fusion — some knowledge of the background plasma (i.e., T_e, n_e) is needed to retrieve values. Open-ADAS has the same information except in a smaller subset of elements and atomic transitions. Using ADAS and Open-ADAS, S and X can be obtained from the ADF11 & 15 databases, respectively. Alternatively, the ratio of $S/(XB)$ can be obtained from the ADF13 directly as a calculated quantity [26].

$\boldsymbol{L_{A_{i\to k}}}$ is the **line-normalized radiance** and is related to the emission coefficient j (see Appendix A.Q.3) and the line-integrated intensity (I), which is calculated along a view within the plasma by $dI = jdr$, where dr is the distance traveled by a particle of speed "v_e" needed to make the given transition $i \to k$. Substituting Equation A.12 into this relationship and integrating it over the transition distance between two states of an atom gives:

$$I = B\frac{hc}{4\pi\lambda_{i\to k}} \int_{r_1}^{r_2} n_A(r) n_e(r) < \sigma_{Exg} v_e >_{i\to k} dr = \frac{\lambda_{i\to k}}{hc} \cdot L_{A_{i\to k}}, \tag{5.3}$$

where r_1 and r_2 are the bounding points for the region where the $i \to k$ transition occurs. As can be seen in the far right-hand-side of this equation, the line-normalized radiance is the photon conversion of intensity for a given transition.

Equation 5.3 relates the emitted intensity from the plasma ions to the line-normalized radiance. To obtain the calculated particle flux presented in equation 5.2, one takes the ratio of the line integrated ionization to the line integrated intensity $\Gamma_A = \int_{r_1}^{r_2} n_A(r) n_e(r) < \sigma_I v_e >_{i\to k} dr$, and solving for Γ_A leads to;

$$\Gamma_A = \frac{4\pi L_{A_{i\to k}}}{B} \left(\frac{< \sigma_I v_e >}{< \sigma_{Exg} v_e >} \right)_{i\to k}. \tag{5.4}$$

This analysis assumes $S \equiv < \sigma_I v_e >_{i\to k}$ and $X \equiv < \sigma_{Exg} v_e >_{i\to k}$ have little spatial dependence within the region bounded by r_1 and r_2. This expression is equivalent to equation 5.2.

5.1.3 Determination of Line-normalized Radiance, $L_{A_{i\to k}}$

At this critical step in absolutely calibrating the filterscope system, it is important to remember that the filterscope is a radiometer – meaning it is measuring the total radiant power passing through a fiber over a particular band-pass filter range. This power is related to the spectral information within that band-pass, but is quantitatively different to a spectrum, e.g. from a spectrometer, in that the exact photo-emission from line-radiation is inferred and not directly measured. Nonetheless, this information is useful as the explanation in the last section highlights (see e.g. equations 5.4 or 5.2). That is one can obtain a particle flux from a the line-normalized radiance that is defined explicitly in equation 5.1 and shown here again for convenience;

$$L_{A_{i\to k}} = 5.03 \times 10^{24} \cdot \lambda_{i\to k} \cdot \frac{\triangle\lambda_{i\to k}}{\triangle\lambda_{PN}} \cdot L_{PN} \left[\frac{ph}{s - str - cm^2}\right],$$

where $\lambda_{i\to k}$ is the wavelength value for the line transition of interest; $\triangle\lambda_{i\to k}$ is the band-pass of the line-normalization; $\triangle\lambda_{PN}$ is the band-pass of the peak-normalization; and L_{PN} is the peak-normalized radiance.

The two band-pass quantities are key to making the filterscope a quantitative measurement. A detailed derivation of the normalization technique using a ratio of band-passes is given in more detail in Appendix A.Q.6 . The line-normalized radiance is derived from a basic radiometric equation for radiance, i.e. $L = \frac{V}{R}$, where V is the output voltage of the radiometer, and R is the responsivity of the detector. In the particular case of the filterscope;

$$L_{PN} = \left[\frac{V_{PMT}}{G_{TOT}}\right]_{sig} \cdot \frac{1}{R_{PN}(\lambda_{PN})}. \tag{5.5}$$

Here, the ratio of V_{PMT} (the output voltage of the channel) to G_{TOT} (the channel gain as defined in section 5.2) is the effective photo-electron current and allows the sensitivity to be adjusted; and $R_{PN}(\lambda_{PN})$ is the peak-normalized responsivity. The real-time adjustment of G_{TOT} to allow high signal-to-noise ratios of the effective photo-electron current is one of the great merits of this diagnostic and is unique to a PMT-based detector setup.

Determining a filterscope channel responsivity. The peak-normalized responsivity, $R_{NP}(\lambda)$, of a PMT channel is key to the absolute calibration of filterscope. R_{NP} is related to the spectral radiance and filter transmission by;

$$R_{PN}(\lambda_{PN}) = \left[\frac{V_{PMT}}{G_{TOT}}\right]_{cal} \cdot \frac{1}{L_{filter-TOTAL}}, \tag{5.6}$$

where $V_{PMT-cal}$ is the output voltage of the channel during the calibration – see Appendix B.3; $G_{TOT-cal}$ is the gain setting used during the calibration – also see Appendix B.3; and $L_{filter-TOTAL}$ is the integrated filtered spectral radiance as highlight in the hashed region in the lower sub-panel of Figure 5.2.

The filtered spectral radiance, L_{filter}, is needed for each filterscope channel (i.e., F-P filter and PMT module combination). L_{filter} is related to the spectral radiance of the light source, typically an integrating sphere, and the filter transmission fraction, which is either provided by the manufacturer or measured. An example of a filtered spectral radiance, $L_{filter}(\lambda)$ determination for a D_α filterscope channel is shown in the bottom plot of Figure 5.2, and is based on an integrating sphere light source (left axis of top plot of Figure 5.2) and measured filter transmission fraction (right axis of top plot of Figure 5.2). Integrating $L_{filter}(\lambda)$ over the band-pass range of the F-P filter gives $L_{filter-TOTAL}$ for a channel.

In past explanations of the filterscope calibration [6], the concept of an **inherent number**, $\boldsymbol{I_h}$, was introduced. This is directly related to the line-normalized radiance defined here through;

$$I_h = 5.03 \times 10^{24} \cdot \lambda_{i\to k} \cdot L_{filter-TOTAL} \cdot \frac{\triangle\lambda_{i\to k}}{\triangle\lambda_{PN}}.$$

Here, through the formulation of the line-normalized radiance, the ratio of the line-normalized band-pass to peak-normalized band-pass has been added, i.e., in the past only the first 3 terms in the right-hand-side of the equation were explicitly called out. Similar concepts to this ratio had been added by filterscope users in an ad-hoc fashion over the years. Typically, such efforts were termed a “correction factor” – also sometimes loosely called a “fudge factor.” This has now been formalized with the preceding explanation. Additionally, for simplification of the filterscope.vi. The inherent number is reduced to just $L_{filter-TOTAL}$ to provide the peak normalized radiance in the calibration tab.

As a final note, the ratio of the band-passes is directly related to the magnitudes of the responsivity. Namely;

$$\frac{\triangle\lambda_{i\rightarrow k}}{\triangle\lambda_{PN}} = \frac{R_{PN-MAX}}{R_{PN}(\lambda_{i\rightarrow k})},$$

i.e., the ratio of the magnitudes in the spectral responsivity as opposed to the band-passes.

Given this equality, both ratios can be used interchangeably in defining the line-normalized radiance. The use of the band-pass ratio in this explanation was done as the authors think this is more intuitive when referencing spectrum and photon fluxes (radiances) as is typical with filterscopes. Again, the details of determining all of the quantities are in appendix A.Q.6

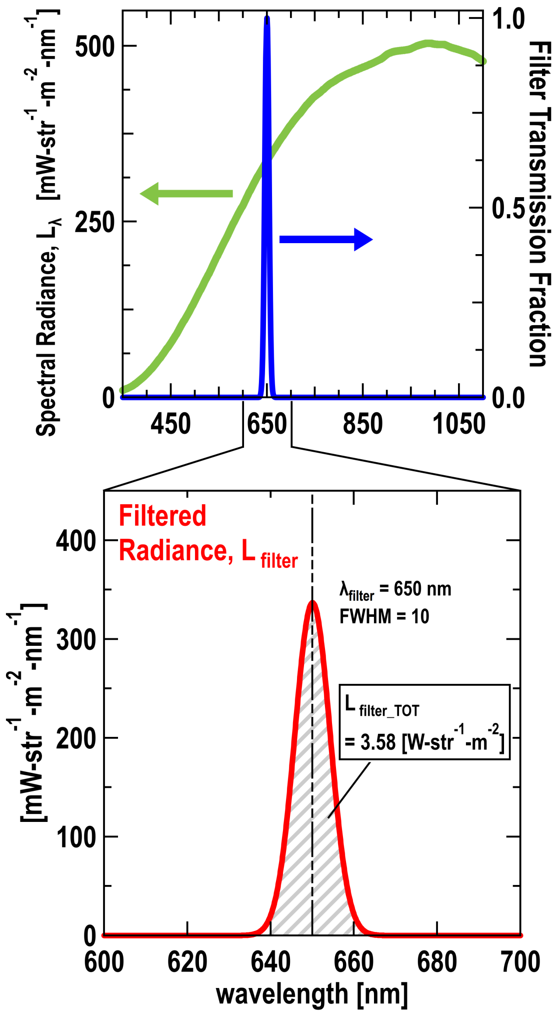


Figure 5.2: *Each component that makes up the filtered spectral radiance, L_{filter} for an example D_α filter (upper). The resultant filtered radiance and $L_{filter-TOTAL}$ (lower).*

5.2 The Gain Calibration Step

The total gain of a PMT in the filterscope system, G_{TOT}, is given by;

$$G_{TOT} = G_{PMT} \cdot G_{AMP}. \tag{5.7}$$

The amplifer gain (G_{AMP}) is set on the main tab GUI of the filterscope (section 4.1). Furthermore, G_{AMP} is assumed to be linear and is not calibrated. In almost all cases, $G_{AMP} = 1$ and it is recommended to keep $G_{AMP} = 1$ for almost all applications.

The PMT Gain (G_{PMT}) is basically the current amplification in the PMT, i.e., the ratio of the anode current (I_a) to the photo-electron current (I_k) as shown in Figure A1. This is non-linearly related to the input control voltage, V_{cont}, and is typically power law dependant (see Appendix A.Q.1). Every PMT module will have specific G_{PMT} characteristics that need to be determined at least once for each PMT used in the filterscope module. Exact measurement of I_k and I_a, to get each PMT gain curve, is very complex and not necessary. Since it is only desired to get a relative gain to the PMT itself, it is sufficent to take the ratios of the PMT output voltage namely, $G_{PMT} = \frac{I_a}{I_k} \propto \frac{V_{PMT}}{V_{PMT-min}}$, where $V_{PMT-min}$ is the output voltage at the lowest V_{cont} setting. This gives, by definition, $G_{PMT} = 1$ at this setting.

This procedure can be thought of as effectively matching the impedance of the filterscope electronics with the PMT and therefore V_{PMT}/G_{TOT} is defined as the effective photo-electron current, I_{k-eff}, of the channel and is therefore directly proportional to the true I_k.

For most applications with the filterscope system to-date, it is found that the G_{PMT} deviates from a power law dependence and is best represented with a polynomial in order to capture the high and low end V_{cont}.

The resultant relationship is given by;

$$G_{PMT} = e^k,$$

where, $k = A_0 + A_1 \cdot V_{cont} + A_2 \cdot V_{cont}^2 + A_3 \cdot V_{cont}^3 + A_4 \cdot V_{cont}^4$, and the fit coefficients (i.e. A_0, A_1, etc.) are determined through the calibration procedure given in Appendix B.3. An example of the output of this procedure is given in Figure 5.3, for a currently used PMT channel at DIII-D. The output from Appendix B.3 gives two different graphs; one with a 3rd order coefficient fitting and 4th order coefficient fitting. Each plot consists of three sub-plots: Top subplot charts the natural log of V_{plot}, the middle subplot plots the V_{plot} and the bottom subplot lays out the Median Percentage Error (MPE) value for each V_{cont} value; where, V_{plot} is defined as V_{PMT}/Transmission(T) (details in Appendix B.3). Once the fit coefficients are determined, $G_{TOT-sig}$ and $G_{TOT-cal}$ are easily determined, where G_{PMT} is related to the V_{cont} and G_{AMP} settings used during the radiance calibration, i.e. $G_{TOT-cal} = G_{PMT-cal} \cdot G_{AMP-cal}$.

Statistically, goodness of fit describes how well the model fit the data. To test the goodness of fit, one can perform and check the chi-squared value, t-test, p-value, look up the Residual sum of squares (RSS), Mean Absolute Percentage Error (MAPE), Bayesian Interference Criteria (BIC), Akaike Interferance Criteria (AIC) and others. But, for PMT gain calibration we use a different goodness of fit measurement called the Median Percentage Error (MPE). MPE follows the same logical thinking as the MAPE but instead of the mean, we find the median of the absolute percentage error of the data. The fit with $\widetilde{MPE} \leq 5\%$ is the fit that is to be selected for calibrating the PMT. (See Appendix B.3 for procedureal method to calibrate the gain of the PMT). The fit coefficients can be chosen between a 3rd order polynomial and a 4th order polynomial based on the MPE value. Mathematically, MPE is defined as the fraction of the difference between the data and the fit of the data over the data, mathematically it can be written as

$$\widetilde{MPE} = \left| \frac{V_{ploti} - e_i^{ln(V_{plot})}}{V_{ploti}} \right| \cdot 100\% \qquad (5.8)$$

where, i corresponds to the V_{cont} value at which the data is being fitted.

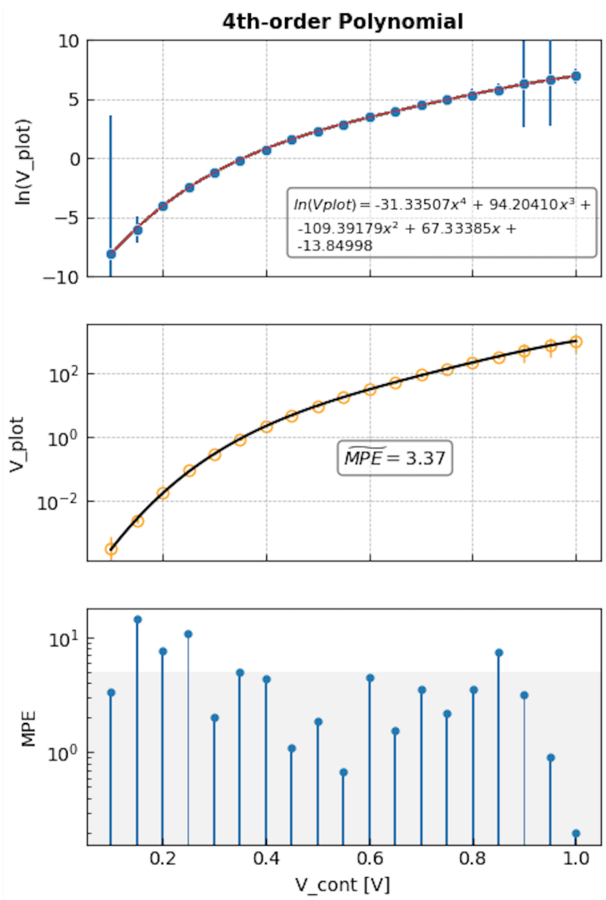


Figure 5.3: 4th Order Polynomial fit for gain calibration data on an example filterscope system single PMT.

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APPENDIX A. FREQUENTLY ASKED QUESTIONS (FAQs)

A.Q.1 How does Filterscope gain relate to the PMT gain?

PMT gain (G_{PMT}) is basically current amplification in the PMT, i.e., anode current (I_a) by photoelectron current (I_k).

It is represented by:

$$G_{PMT} = I_a/I_k = \alpha * \delta_1 * \delta_2 * \delta_3....\delta_n \qquad (A.1)$$

where, "α" is the collection efficiency of the dynodes in the PMT and "δ_n" is the secondary emission ratio, which is a function of the inter-stage voltage of the dynodes. The number in the subscript of the secondary emission ratio indicate the distinct stage of dynodes where emission of photoelectrons happens in the PMT [10]. Ideally, in a case of a PMT with "n" number of dynode stages operated using an equally-distributed divider, the gain "G_{PMT}" changes in relation with voltage "V_{HV}", as follows:

$$G_{PMT} = a^n * \left(\frac{V_{HV}}{n+1}\right)^{\alpha n} = AV_{HV}^{\alpha n} \qquad (A.2)$$

where, "a" is a constant; "A" is equal to $a^n/(n+1)^{kn}$; "α" is determined by the structure and material of the dynode and has a value from 0.7 to 0.8. Figure A1, shows a typical gain vs supply voltage graph. The slope of the logarithmic graph becomes "αn" and the current amplification increases with increase in supply voltage [10].

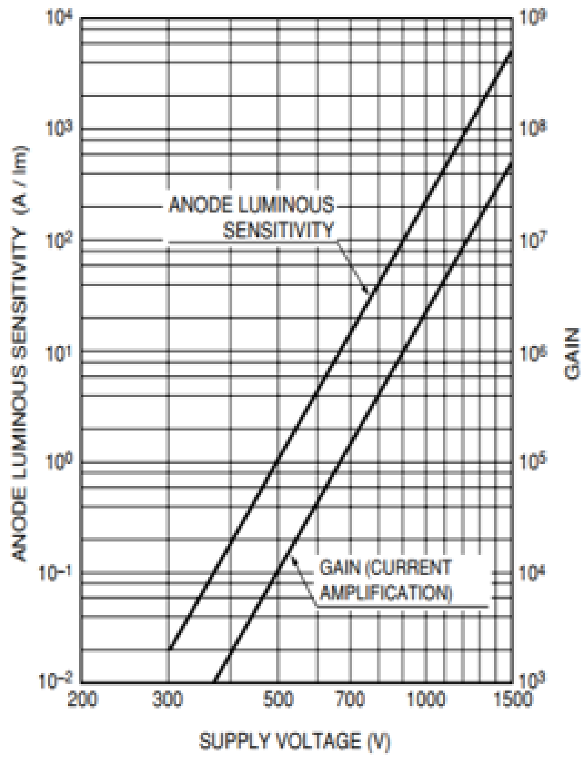


Figure A1: *Gain vs Supply Voltage of a PMT [10]*

A.Q.2 How is the Total Tube output related to Pmt gain?

The total tube output 'V_{PMT}' is a function of the PMT gain 'G_{PMT}' and 'V_{light}' - the signal of the light hitting the first dynode of the PMT through a filter with transmission 'T', as seen in Figure A2. Mathematically it can be written as:

$$G_{PMT} = \frac{1}{V_{light}}.\frac{V_{PMT}}{T} \qquad (A.3)$$

Now to derive the above equation (Equation A.3), let us refer back to Equation A.1 where, the PMT gain (G_{PMT}) is the function of the cathode (I_k) and the anode (I_a) current with respect to Figure A2:

$$G_{PMT} = I_a/I_k \qquad (A.4)$$

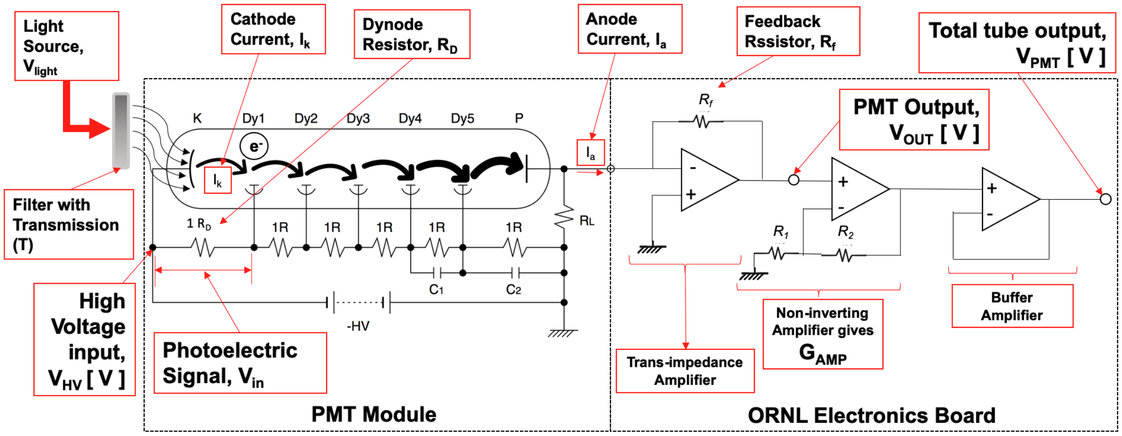


Figure A2: *An electronics schematic of a PMT to understand PMT gain calibration*

Using the Ohm's law, let us define $V_{in} \cong R_D \cdot I_k$ and $V_{out} \cong R_f \cdot I_a$, where R_D is the resistance of the dynodes, R_f is the feedback resistance across the trans impedance amplifier, V_{out} is the PMT output voltage and V_{in} is the input photoelectric signal across the first dynode chain.

Substituting the I_k and I_a values in Equation A.4, we get:

$$G_{PMT} \cong \frac{V_{out}}{V_{in}}\left(\frac{R_D}{R_f}\right) \tag{A.5}$$

where R_D/R_f is a constant 'C' and we can assume it to be 1, giving:

$$G_{PMT} \cong \frac{V_{out}}{V_{in}} \tag{A.6}$$

Now, let us define $V_{in} = V_{light}$. T, we would get

$$G_{PMT} \cong \frac{V_{out}}{V_{light}.T} \tag{A.7}$$

Now, Referring back to Equation 5.7, we can write,

$$G_{TOT} = G_{PMT}.G_{AMP} = \frac{V_{out}}{V_{light}.T}G_{AMP} \tag{A.8}$$

When $G_{AMP} = 1$, $V_{out} = V_{PMT}$ and $V_{light} = V_{PMT}$ at [V_{cont}=1, Tuned T]. Where 'Tuned T' means a filter that is tuned at any transmission T. This would give us

$$G_{PMT} = G_{TOT[G_{AMP=1}]} = \frac{1}{V_{light}}.\frac{V_{PMT}}{T} = \frac{1}{V_{PMT}[V_{cont} = 1; TunedT]}.\frac{V_{PMT}}{T} \tag{A.9}$$

A.Q.3 What is the Emission Coefficient?

The **Emission Coefficient** is the amount of energy ($h\nu$) emitted per unit volume, per unit time, per unit frequency, per solid angle (4π). The density of element A at an upper energy state is denoted by n_A and the Einstein's emission coefficient for an electron transitioning from upper state i to lower state k is denoted by $A_{i\rightarrow k}$.

$$j_{i\rightarrow k} = \frac{hc}{4\pi}\lambda_{i\rightarrow k} n_A A_{i\rightarrow k} \left[\frac{W}{sr \cdot m^3}\right] \tag{A.10}$$

The emission coefficient j equation (see equation A.10) is not usually useful as it does not give any information about the number of particles in the ground state [23]. If we assume that there is an equilibrium between electron excitation from the ground state n_A and de-excitation to any lower state through radiation, we obtain the following:

$$n_A \sum_{k\leq i} A_{i\rightarrow k} = n_A n_e < \sigma_{Exg} v_e > \tag{A.11}$$

where n_e is the electron density, σ_{Exg} is the atomic excitation cross-section for the $i \rightarrow k$ transition, and v_e is the electron thermal velocity. From this equation, we can write the emission coefficient in terms of the branching ratio by combining equation A.10 and A.11 as:

$$j = \frac{hc}{4\pi\lambda_{i\rightarrow k}} B n_A n_e < \sigma_{Exg} v_e > \tag{A.12}$$

A.Q.4 What is MDSPlus?

MDSplus is a set of software tools for data acquisition and storage and a methodology for management of complex scientific data. MDSplus allows all data from an experiment or simulation code to be stored into a single, self-descriptive, hierarchical structure. The system was designed to enable users to easily construct complete and coherent data sets. The MDSplus programming interface contains only a few basic commands, simplifying data access even into complex structures. Using the client/server model, data at remote sites can be read or written without file transfers. MDSplus includes x-windows and java tools for viewing data or for modifying or viewing the underlying structures.

Read more about MDSplus on http://www.mdsplus.org/index.php/Introduction.

A.Q.5 What is an Integrating Sphere?

An integration/Ulbricht sphere is an optical component comprising of a hollow spherical cavity with its interior enclosed with a reflective coating with holes for entrances and exit ports. Its pertinent property is its uniform scattering or diffusing effect. The primary radiation source can be located either inside the sphere or in front of the source's entrance port. If the source is in line or in the sphere, the radiance of the light is considered and if the source is outside the sphere and has a diffusion to its radiation, then the irradiance is considered for calibrating the source. Figure A3 depicts a basic working of an integrating sphere with radiance of the source in form of a diagram. The incident beam is inserted into the sphere through an aperture and hit the"first strike spot" or has its "first bounce" and then has multiple radiations throughout the sphere to be detected by a photodetector (in our case the photodetector is a PMT).

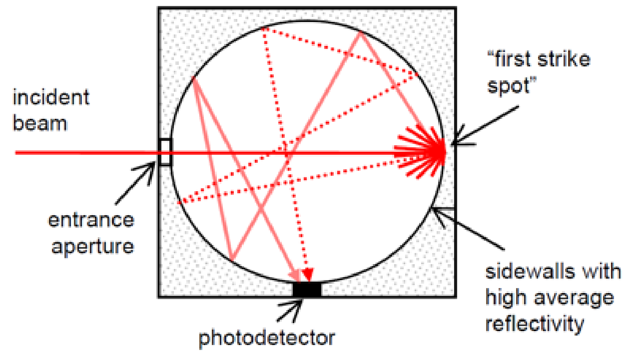


Figure A3: *Basic Operating Principle of an Integrating Sphere*

As mentioned before, an integrating sphere in a nutshell is an enclosure that can contain and diffuse input light so that it evenly spreads out the light over the entire surface of the sphere. This diffusion is completed through two mechanisms: a Lambertian reflectance surface (coating) and a sphere shape. The geometry of the sphere ensures that every point within the sphere receives the same intensity or light as every other part of the sphere at the first bounce. The energy from the first bounce illuminating every other spot on the sphere would simply be the input energy divided by the surface area of the sphere [19]. Since an illuminated surface is also a radiant source, the expression of radiance at each spot on the sphere after the first illumination would be:

$$L_{surface} = \frac{E_{in}\rho}{\pi A_s} \left[\frac{W}{m^2 \cdot sr}\right] \tag{A.13}$$

Where, "E_{in}" is the input energy; "ρ" is reflectivity of the sphere; "π" is the total projected solid angle from the surface and "A_s" is the surface area of the sphere. Now that each spot in the sphere is reflecting and radiating, there are multiple reflections within the sphere. Each radiating spot can be illuminated more than once after the first bounce. The radiance of the sphere wall at any point within the sphere is given by

$$L_{sphere} = \frac{E_{in}}{\pi A_s}\frac{\rho}{(1-\rho(1-f))} = \frac{E_i n_M}{\pi A_s} \left[\frac{W}{m^2 \cdot sr}\right] \tag{A.14}$$

Where, "f" is the port fraction which takes the non-reflective surface areas in to account, such as ports. These non-reflective features subtract from the ideal throughput of an integrating sphere as they represent losses in the enclosure's multiple reflection effects; "M" is the sensitivity factor, which is typically in the range of 10 to 25. As "ρ" approaches 1, "M" increases to infinity "∞". The reflectivity factor increases the sphere throughput in an asymptotic fashion and provides a unit-less gain factor to make the sphere radiance better than the original case of single surface illumination.

Irradiance of the sphere's inner surface is proportional to the total radiant power either emitted by a source inside the sphere or entering the sphere through its entrance port. Geometrical and directional distribution of the primary source's radiation do not influence irradiance levels if direct illumination of the respective location is prevented. This property becomes especially important when an integrating sphere is used as the input optical element of a detector for radiant power. Radiance reflected by a region of the sphere's inner surface shielded from direct illumination is constant in its directional distribution and independent from the specific location where the reflection occurs. Thus, the sphere's exit port can be used as an ideal Lambertian source as optical radiation leaving the sphere is characterized by homogenous radiance and exitance distributions. This property becomes especially important when a sphere is used as a standard calibration source.

A.Q.6 How is Line-normalized and Peak-normalized Responsivities Determined?

The defining feature of the line-noramlization is through defining the line-normalized bandwidth ($\triangle\lambda_{i\to k}$), which is related to the peak-normalized responsivity of the PMT channel, $R_{PN}(\lambda)$, which is again related to the filtered spectral radiance of the PMT channel, $L_{filter}(\lambda)$. An example of $L_{filter}(\lambda)$ is shown in lower sub-panel of Figure 5.2. The defining step in the absolute calibration of the PMT is through determining the maximum peak-normalized responsivity, $R_{PN}(\lambda_{PN})$ or R_{PN-MAX};

$$R_{PN-MAX} = \left(\frac{V}{G}\right)_{cal} \frac{1}{L_{filter-TOTAL}},$$

where $L_{filter-TOTAL}$ is shown in Figure 5.2. From this point a spectral peak-normalized responsivity, $R_{PN}(\lambda)$ is defined, arbitrarily, by setting the filtered spectral radiance of the source, $L_{filter}(\lambda)$ to unity and then multiply this curve by R_{PN-MAX}. $R_{PN}(\lambda)$ typically has SI units of $\frac{V \cdot str \cdot m^2}{W}$. An example of $R_{PN}(\lambda)$ based on the light source and filter given in Figure 5.2 is shown in Figure A4. Here, the blue trace is $R_{PN}(\lambda)$. In this Figure, the integral of the responsivity, $\int R_{PN}(\lambda) \cdot d\lambda$, is also given by the shaded region under the curve. The peak-normalized band-pass is defined based on this curve, given by;

$$\triangle\lambda_{PN} = \frac{\int R_{PN}(\lambda) d\lambda}{R_{PN-MAX}},$$

and for this particular example has a value of 10.6*nm*. Similarly, The line-normalized wavelength span is given by;

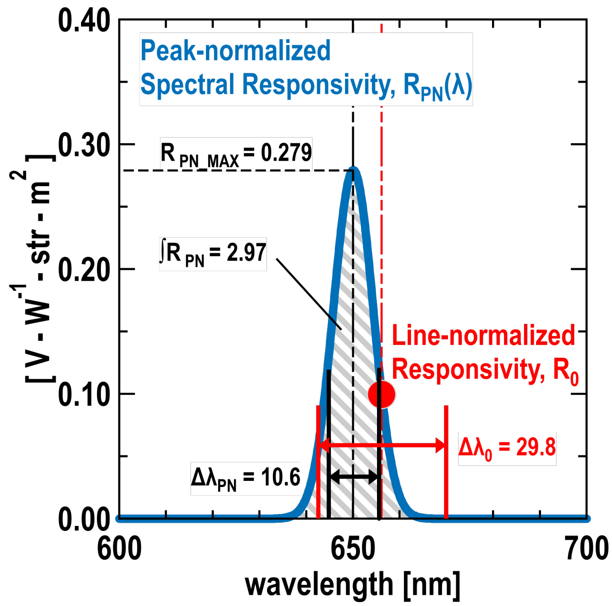


Figure A4: An example of spectral responsivity from a filterscope channel. Both the peak-normalized and line-normalized responsivity values are highlighted as well as the two related band-pass values.

$$\triangle\lambda_{i\to k} = \frac{\int R_{PN}(\lambda) d\lambda}{R_{PN}(\lambda_{i\to k})},$$

where now the responsivity value, $R_{PN}(\lambda_{i\to k})$, is taken at the wavelength of a given transition (the line), i.e. $\lambda_{i\to k}$. This value is highlighted in red in Figure A4, and is also termed the line-normalized responsivity, R_0. This analysis gives $\triangle\lambda_{i\to k} = 29.8nm$ for the example given in the Figure.

As a reminder, the ratios of the two band-pass values, e.g. $\frac{\triangle\lambda_{i\to k}}{\triangle\lambda_{PN}}$, is directly related to the ratios of the responsivity;

$$\frac{\triangle\lambda_{i\to k}}{\triangle\lambda_{PN}} = \frac{R_{PN-MAX}}{R_{PN}(\lambda_{i\to k})}.$$

And as a final note, as mentioned in section 5.1.3, the line-normalized radiance can be expressed in terms of the responsivity ratio instead of the band-pass ratio – explicitly;

$$L_{A_{i\to k}} = 5.03 \times 10^{24} \cdot \lambda_{i\to k} \cdot L_{PN} \cdot \left[\frac{R_{PN-MAX}}{R_{PN}(\lambda_{i\to k})}\right]\left[\frac{ph}{s \cdot m^2 \cdot str}\right].$$

Since this analysis is key to having a fully calibrated filterscope system, it worth explicitly stating that the philosophy of this step is to approximately correct for the potential discrepancy between the overall response of the filterscope and the response "fraction" of where a particular spectral transition of interest lays within the band-pass region. Ideally, there should be no discrepancy, in which case $\frac{\triangle\lambda_{i\to k}}{\triangle\lambda_{PN}} = 1$, but in most cases there is a modest correction needed, i.e. $\frac{\triangle\lambda_{i\to k}}{\triangle\lambda_{PN}} = 3 - 5$.

A.Q.7 What is a Pellicle Beam Splitter?

A pellicle beam splitter is an ultra-thin, ultra-lightweight semi-transparent mirror employed in the light path of an optical instrument, splitting the light beam into two separate beams, both of reduced light intensity. Splitting the beam allows its use for multiple purposes simultaneously.

The filterscope employs Thorlabs cube mounted pellicle beam splitters, which boasts advantages such as no ghosting, no chromatic aberration with focused beams, and threaded entrance and exit ports.

For more information visit: ThorLabs Website

A.Q.8 How to use the filterscope.VI debug feature?

As seen in Figure 4.6, the write debug helps the user to manually access the writing process of each tube. Once the Toggle switch from the Figure 4.6 is turned on, the Figure A5 is popped up to the user. This Figure allows the user to access the writing process manually. As seen in the Figure A5, the user can input the tube number where the debug needs to be started and where the debug should stop through **Label A.4.2** and **Label A.4.3**. Once the array of tubes are set, the user can press "continue" from **Label A.4.4**. Once

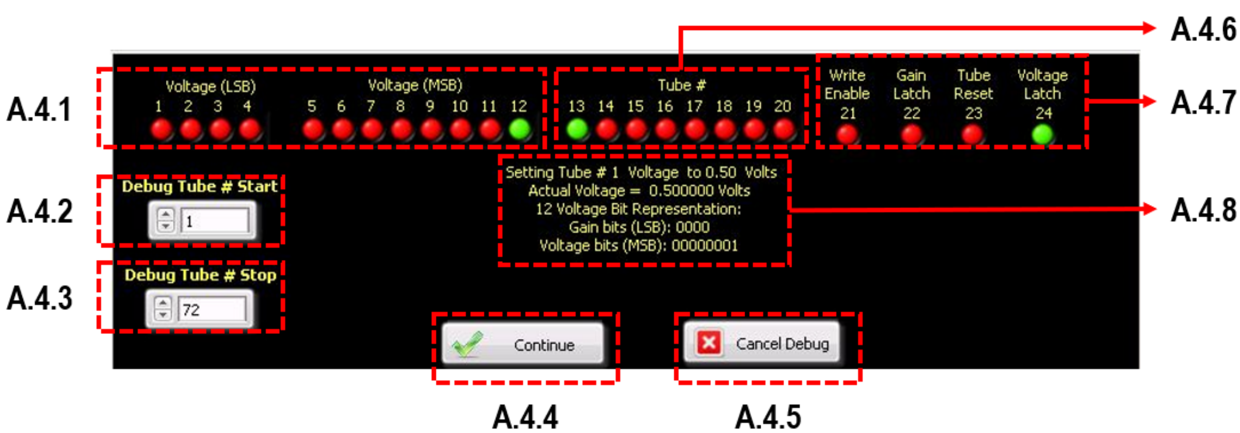


Figure A5: *Debug Menu*

the continue button is pressed, the debug process initiates. This is understood when the voltage indicators at the Least Significant Bit (LSB) and Most Significant Bit (MSB) changes, as seen in **Label A.4.1**. This process is accompanied by the indicators of the Tube that is being debugged, which is shown in **Label A.4.6**. While the debug is in process, the parameters such as “write enable”, “Gain Latch”, “Tube Reset”, and “Voltage Latch” are indicated as utilized in **Label A.4.7**. Along with the above indicators the debug menu has a message board (**Label A.4.8**) that displays the information as the debug process continues. If the user agrees with the information provided in Label A.4.8, one can press the “continue” button, to access the next batch of information and if the user disagrees with the information, one can “cancel Debug” though **Label A.4.5** and change some parameters till one find way to rectify the debug error.

APPENDIX B. Procedures for Startup, Checkout, & Calibration

The following steps are to be followed by the user to start the system. The steps described in this Section are to be carried out in order to help the user run the Filterscope diagnostic tool without any error.

B.1 Steps to Start-up the System

1.0) Remove all the equipment from the boxes and make necessary connections.

2.0) Switch on the power of the PXI Chassis. It is needed to be switched on for proper functioning of the filterscope.

3.0) Switch on the computer and log in. Once logged in, open filterscope.vi on the computer.

4.0) In the filterscope.vi, make sure all the information needed for the experiment is updated correctly. Order to check for details:

  4.1) Load a config file in the filterscope.vi if not pre-loaded.

  4.2) In Figure 4.6, check if all the tubes are on, initial voltage is active, bias voltage is stated as required and so on.

  4.3) In Figure 4.5, check if scan is appropriate for the plasma pulse length, check if shot number depicted correctly and so on.

  4.4) In Figure 4.3 before switching to "Diagnostic operation" in the drop-down menu, check if all the buttons are set correctly, check if the configuration file is uploaded correctly, check for data storage location and so on.

5.0) Select the "Diagnostic operation" from the drop-down menu (see Figure 4.3). This will make the filterscope ready to accept a pre-trigger and a trigger.

6.0) OPTIONAL STEP: In the plot.vi, update the list on the left and then keep the list on auto-update or manual-update. Note: This step is site specific.

7.0) For the first shot, make sure the filterscope is receiving a pre-trigger and a trigger. The status (Figure 4.3) on the filterscope.vi will change to waiting on a "hardware" trigger once it receives the pre-trigger. This will then trigger when an external trigger is applied through a "trigger module" (Figure 4.3). Once the filterscope receives the trigger, it should be triggering correctly.

8.0) Open Plot.vi from the "Utilities tab". Make sure the signals received are not saturated by going through each PMT signal. Check the PMTs before clicking on the "refresh" button that resets the program. (Figure 4.1).

9.0) Although the filterscope has an ability to run autonomously, it is recommended to check the signal after every shot. The signal can be viewed by MDSplus specific jscope or a coding language (such as Python) in a separate room away from the filterscope.

10.0) If the signal seems to be inaccurate, check the physical aspect of the filterscope such as the hardware and inspect the software.

B.2 "Out-of-box" Filterscope System Checkout & Integrity Check-list

This section describes the step-by-step procedure of testing a filterscope System after its setup.

Before starting the procedure to perform the tests, the user should select the **software trigger** in the main tab (see section 4.1) and run the vi in diagnostic operation. Once the user has selected these options, the following steps are to be carried out and recorded in filterscope check-list provided. **Note:** This checkout procedure should be carried out for each module in the filterscope system.

1.0) Basic Module & Stray-light Tests (To be carried out in "Tube Test" tab of Filterscope.vi)

- 1.1) Main Tab: Set ELM Detect = off, Auto-adjust = off, initial control voltage = 0.35V; press refresh/rewrite to send configuration data.
- 1.2) Check "Control Voltage" sockets on module front panel using multi-meter (should read 0.35V).
- 1.3) Tube Test Tab: Increase control voltage step by step, voltage on the multi-meter should match control voltage setting in Filtercope.vi for each tube for each step.
- 1.4) Set control voltage to 1.0V and verify the change with multi-meter and front panel socket. Record max control voltage whether it is 1 or lower.
- 1.5) Check "dark noise" level (i.e. light off) in tube test interface with and without drop cloth at control voltage 1V. Average value should be below 5 mV. (2–3 mV is a typical value). Record average values for both.
- 1.6) With beam-splitted tubes, check that "dark noise" level for each tube is < 15mV.
- 1.7) If "dark noise" are above these minimum values, search for light leaks around faceplate and beam-splitters.
- 1.8) Repeat all steps for each tube.

2.0) Module Signal Amplification Settings (in Tube Test Tab of Filterscope.vi)

- 2.1) Lightsource.vi: Set 10Hz & 95% duty cycle.
- 2.2) Set "GAIN" to 1
- 2.3) Set "Control Voltage" to 0.3V (adjust as necessary to achieve realistic signal and prevent overload). Record control voltage for both preset and adjusted control voltage.
- 2.4) Take note of signal voltage for both 0.3 V and adjusted control voltage.
- 2.5) Make sure all tubes are < 1V
- 2.6) Set a few "GAINS" to something higher (e.g. 4, 10, 20). Record one of the gains.
- 2.7) Verify signal value is multiplied by the gain value set by the user. Record average signal at gain set above. Please note that the software does not plot >10 V.
- 2.8) Repeat all steps for each tube.

3.0) Basic DAQ tests & PMT Functionality

- 3.1) Tube Test Tab: Set control voltages to 0.5 V and set Gain to 1.

3.2) Tube Test Tab: Verify tube signals > ~1V. Record average signal.

3.3) Tube Test Tab: If the tube signal is not > ~1V increase control voltage and repeat above steps until > ~1 is achieved. Record both the control voltage and the average signal.

3.4) Repeat steps 3.1–3.3 for all tubes.

3.5) Main Tab: Set all “Int Voltage” to the voltages from steps 3.1–3.3 that provides best signal

3.6) Main Tab: Set all “GAINS” to 1

3.7) Lightsource.vi: Set to 10Hz & 50% duty cycle

3.8) Filterscope.vi: Set digitizer to 50 kHz & 1 sec.

3.9) Press pre-trigger and then trigger in the vi.

3.10) Plot.vi: Look in to MDSPlus under Tube and select PMT_Volt plot.

3.11) Plot.vi: Verify noise level with light OFF (trough of signal) < 9 mV [zoom in to lower trough to measure noise]. Record level.

3.12) Plot.vi: Verify noise level with light ON (crest of the signal) <~ ± 0.1V of mean value [zoon in to upper crest to measure noise]. Record Level.

3.13) Repeat steps 3.9–3.12 for all tubes.

4.0) PMT Control Test

4.1) Set to 10Hz & 95% duty cycle

4.2) Main Tab: Set digitizer to 1 kHz & 5 sec

4.3) Main Tab: Set “AUTO ADJUST” to “AUTO ON” for all tubes

4.4) Main Tab: Set all “OUTPUT LOWER ADJUSTMENT” to ~ 3V. If this is adjusted record value.

4.5) Main Tab: Set all “OUTPUT UPPER ADJUSTMENT” to ~ 5V. If this is adjusted record value.

4.6) Main Tab: Set “TARGET MIN ADJUST CYCLE TIME” to 0.2 (or 1.0 if signal oscillates)

4.7) Press pre-trigger and then trigger in the vi.

4.8) Plot.vi: Verify signal voltage avg value in plot.vi is between 3V–5V.

4.9) Repeat steps 4.7 & 4.8 for all tubes.

B.3 Gain Calibration of Filterscope PMTs

Attention: To complete this procedure, you would need to be a member of the 'ORNL-Fusion' team on GitHub.

Note: To understand the gain calibration, one must have read through Question A.Q.2 regarding how the PMT gain is related to the PMT output. As seen in the Section 5.2, the PMT gain has a polynomial form.

Continuing the derivation from A.Q.2,

It is known that the PMT gain is a function of V_{cont}, which in turn means that the PMT output is a function of V_{cont}. This can be written in equation form as

$$G_{PMT}(V_{cont}) = \frac{1}{V_{PMT}[V_{cont} = 1; TunedT]} . \frac{V_{PMT(V_{cont})}}{T} \tag{A.15}$$

but as we know from Section 5.2,

$$G_{PMT}(V_{cont}) = e^{A_4 V_{cont}^4 + A_3 V_{cont}^3 + A_2 V_{cont}^2 + A_1 V_{cont} + A_0} \tag{A.16}$$

Now, taking natural log on both sides,

$$ln\left(\frac{V_{PMT}}{T}\right) = A_4 V_{cont}^4 + A_3 V_{cont}^3 + A_2 V_{cont}^2 + A_1 V_{cont} + A_0 + ln(V_{PMT}[V_{cont} = 1; TunedT]) \tag{A.17}$$

Let $A_0 = A_0$ + ln($V_{PMT}[V_{cont}$=1;Tuned T]. Defining,

$$V_{plot} = \frac{V_{PMT}}{T} \tag{A.18}$$

$$k = ln(V_{plot}) = A_4 V_{cont}^4 + A_3 V_{cont}^3 + A_2 V_{cont}^2 + A_1 V_{cont} + A_0 \tag{A.19}$$

Note: This section details the step-by-step process of gain calibration for each PMT in the Filterscope.

Note: This section is to be carried out after completing the 'out-of-the-box' checkout procedure (Appendix B.2)

1.0) Create an Excel sheet just as seen in Figure B.1 with the columns names as the tube names.

2.0) Main Tab: Select a PMT to be calibrated (for example: Tube 13)

3.0) Attach a light source to the selected PMT through fiber optic cable

4.0) Main Tab: Set the Initial Control Voltage (V_{cont}) to 0.05 V

5.0) Lightsource.vi: Turn on the light source at 1000Hz, 99% Duty cycle

6.0) Main Tab: Set desired values in the Digitizer Unit (Section 4.1.3). For example, set: Physical Trigger: 0.00 second(s), Digitizer Delay: 1 Second, Frequency: 1MHz, Scan Length: 5 second(s)

7.0) Main Tab: Set ELM Detect = Off, Auto-Adjust = Off

8.0) Main Tab: Set desired trigger mode: Hardware/Software; Shot Number mode: Local/Facility; Data Transfer = On (if facility shot mode); Calibration = Inactive (See section 4.1.1 for screen shot of these options in the Main Tab)

9.0) Main Tab: Add the ND filter value in the 'Control Description'. For example: lightsource ND1.5. **Note:** The user must start the gain calibration process with no filter

10.0) Main Tab: Select 'Diagnostic Operation' to take a shot with light on

11.0) Note down the shot number in the excel file corresponding to the control voltage set to the PMT prior to taking the shot

12.0) Lightsource.vi: Turn off the light source

13.0) Main Tab: Select 'Diagnostic Operation' to the take the shot with light off

14.0) Note down the shot number in the excel file corresponding to the control voltage set to PMT prior to taking the shot

15.0) Repeat steps 5 —14 with increments of 0.05V in Vcont until the PMT overloads and trips at a particular Vcont value

16.0) Once the PMT overloads, the user must add an ND filter of choice. For example, if the PMT trips at Vcont = 0.5V, add in a ND filter and repeat steps 5 —14 until the PMT overloads and trips at a particular Vcont value

17.0) Repeat steps 5 —16 till Vcont of 1 V is reached for the PMT

18.0) Make sure the shot numbers are noted down on the Excel sheet (Excel file example shown in Figure B.1)

19.0) Repeat steps 2 —18 for each tube in the Filterscope module

20.0) Once you have the data, plotting the data via python

  20.1) Pull the 'fscope_gain_calibration.py' script from GitHub/ORNL-Fusion/Fscope repository

  20.2) Run the code by executing the "main" function in the python script

  20.3) The main function has the following attributes:

    i. TubeNum: Enter the tube number of the PMT

    ii. ShotFileName: Enter the Excel file name (Step 1) where the shotlist is saved

    iii. SheetName: Enter the sheet name of the Excel File

    iv. NumIter: Number of iterations for the calibration, defaulted to 500

    v. Verbose: If you want a written output (defaulted to False)

    vi. fitPower: to apply test metric such as MPE (defaulted to True)

vii. tstart: used when tube data is loaded (defaulted to 0)

viii. tend: used when the tube data is to be stopped after loading data (defaulted to 2.5)

ix. tstep: used for steps taken for tstart and tend (defaulted to 0.0001)

20.4) Once you run the code, a couple of plots will pop up (see Figure B.2). This figure shows two plots depicting a 3rd order and a 4th order fitting of data.

20.5) This will give the figure of merit (Mean Percentage error [MPE]) for a 3rd order, and 4th order. The coefficients of the fit with MPE ≤ 5 is to be selected for calibration (For example, in Figure B.2, the 4th order has MPE = 3.37 which is ≤ 5, hence a 4th order fit would be selected)

21.0) Calibration Tab: Insert the coefficient from Step 20.5 to the slots available (See Figure 4.15)

22.0) Main Tab: Repeat steps 2 —18 with the coefficient stored in the tree

23.0) Checking the calibration:

23.1) Pull the "fscope_gain_calibration.py" script from GitHub/ORNL-Fusion/Fscope repository

23.2) Run the code by executing the "CalCheckPlot" function in the python script

23.3) The "CalCheckPlot" function has the following attributes:

i. Filename (str): Name and path of excel file containing the shot numbers for one module for the calibration check

ii. Module (str): Name of Sheet in excel file contain said module

iii. Tubes (List): List of Tubes to be plotted

iv. calib (int): May be 1 or 2. If 1 background is calculated from shot. If 2 background is calculated from gain calibration shot with light off.

v. verbose: Prints out V_PMT (normalized and not), V_CTRL, ND switch counter, Index of ND switch, Index of calibration value, and calibration V_cont

vi. Outputs Dictionary with V_cont, V_PMT and normalized V_PMT, V_Error, and calibration V_cont for each tube.

23.4) Once you run the code, a plot will pop that would look like Figure B.3. The plot shows calibrted value of two PMTs (PMT 90 and PMT 94 from the DIII-D system) that were calibrated at TOT_FILT_REP = 1 with ± 5% deviation between control voltage 0.25 - 1.0 V.

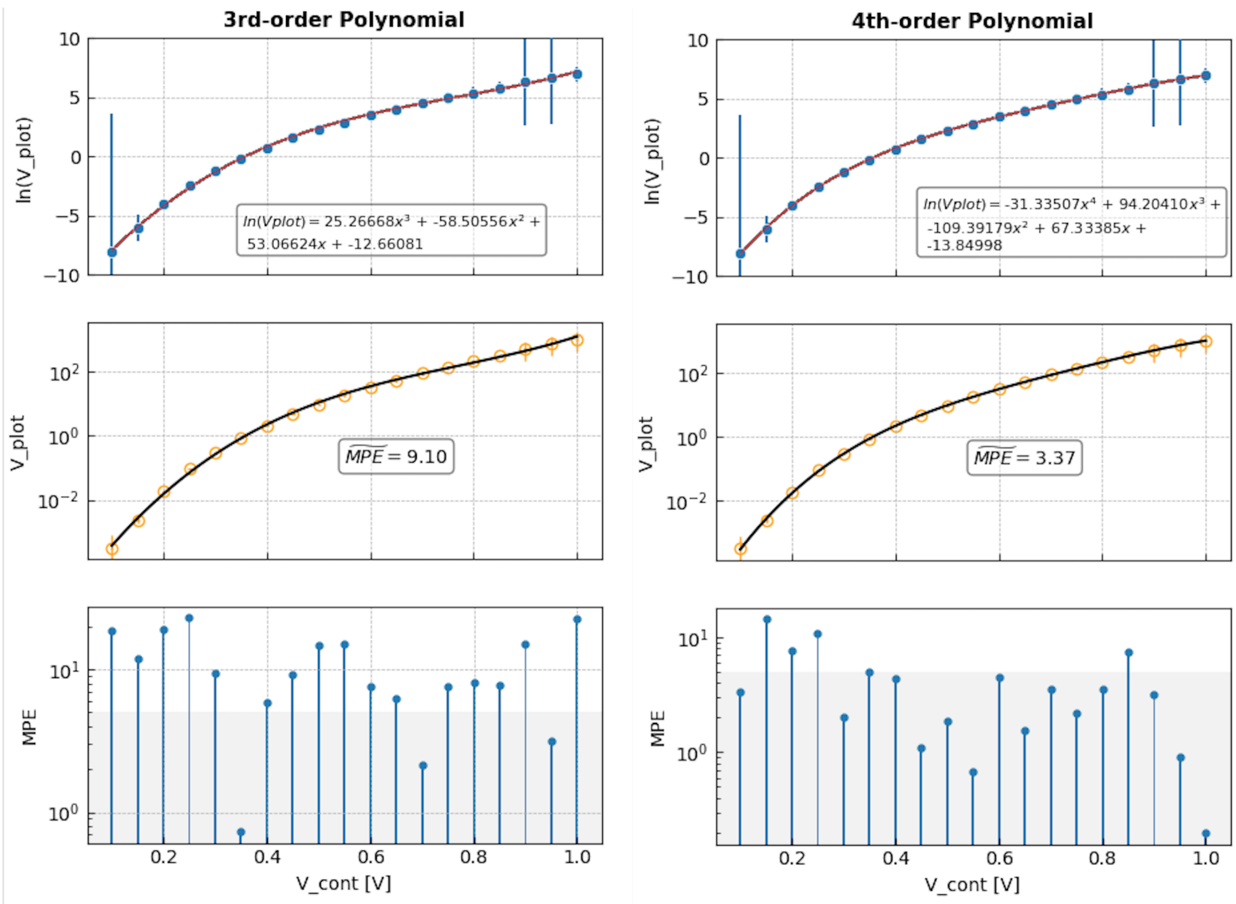
23.5) Make sure the graph is aligned to y-axis = 1 (if the TOT_FILT_REP is set to 1)

24.0) If the plot from Step 23 is aligned closer to 1 (green band on the figure), the PMT has been calibrated

25.0) Repeat all the above steps for all the PMTs to be calibrated

Vcont	TUBE13_On	TUBE13_Off	TUBE14_On	TUBE14_Off	TUBE15_On	TUBE15_Off
0.05	1903140002	1903140003	1903140002	1903140003	1903140002	1903140003
0.1	1903140004	1903140005	1903140004	1903140005	1903140004	1903140005
0.15	1903140006	1903140007	1903140006	1903140007	1903140006	1903140007
0.2	1903140008	1903140009	1903140008	1903140009	1903140008	1903140009
0.25	1903140010	1903140011	1903140010	1903140011	1903140010	1903140011
0.3	1903140012	1903140013	1903140012	1903140013	1903140012	1903140013
0.35	1903140014	1903140015	1903140014	1903140015	1903140014	1903140015
0.4	1903140016	1903140017	1903140016	1903140017	1903140016	1903140017
0.45	1903140018, 190318055	1903140019	1903140018, 190318055	1903140019	1903140018, 190318055	1903140019
0.5	1903140023	1903140021	1903140023	1903140021	1903140023	1903140021
0.55	1903140024	1903140025	1903140024	1903140025	1903140024	1903140025
0.6	1903140026	1903140027	1903140026	1903140027	1903140026	1903140027
0.65	1903140028, 190318056	1903140029	1903140028, 190318056	1903140029	1903140028, 190318056	1903140029
0.7	1903140030, 190318057	1903140031	1903140030, 190318057	1903140031	1903140030, 190318057	1903140031
0.75	1903140034	1903140035	1903140034	1903140035	1903140034	1903140035
0.8	1903140036	1903140037	1903140036	1903140037	1903140036	1903140037
0.85	1903140038	1903140039	1903140038	1903140039	1903140038	1903140039
0.9	1903140040	1903140041	1903140040	1903140041	1903140040	1903140041
0.95	1903140042	1903140043	1903140042	1903140043	1903140042	1903140043
1	1903140045	1903140045	1903140045	1903140045	1903140045	1903140045

Figure B.1: *A table showing the EXCEL sheet during a gain calibration process*



(a) *3rd order polynomial fitting* ***(b)*** *4th order polynomial fitting*

Figure B.2: *Relationship between Gain of the PMT with the V_{cont} for Tube 75 in DIII-D filterscope*

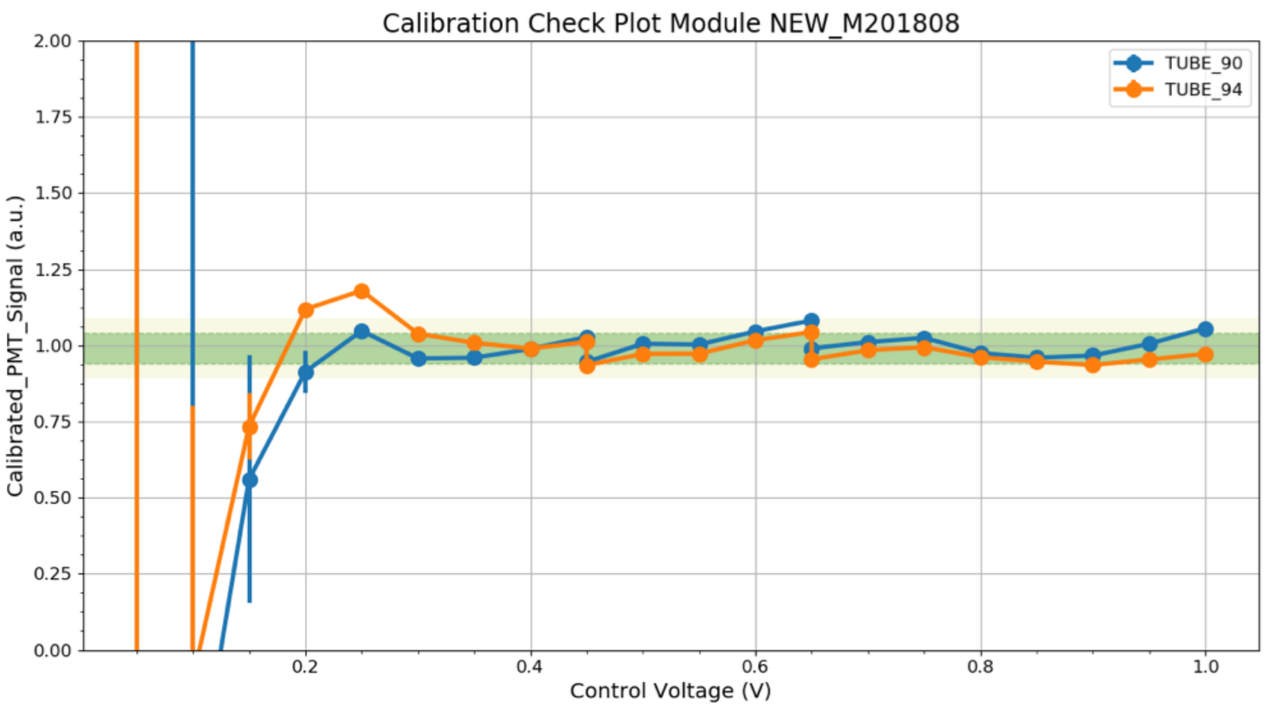


Figure B.3: *Checking the Calibrated fit of data*