The European Optical Module
for DUMAND II
A TECHNICAL DESCRIPTION

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1 Introduction

Central part of the DUMAND II experiment are the 216 optical modules (OMs). They detect the Čerenkov–light originating from charged secondary particles produced in neutrino interactions in the deep ocean [1].

Basically the OMs consist of a large area photomultiplier (PMT) embedded in a glass pressure housing designed for deep ocean applications. They have a highly sensitive photocathode and good collection efficiency enabling them to detect light from muons at distances up to tens of meters. Furthermore good timing characteristics are necessary for an accurate reconstruction of the muon track and thus the origin of the incoming neutrino. A good energy resolution, i.e. the possibility to separate one, two, ... photoelectron signals, is desirable for the suppression of backgrounds and for triggering purposes.

To enable long term operation in the deep ocean, as planned for DUMAND II, all components of the OMs have to fulfill high reliability standards.

In order to achieve maximum variability and the possibility to recognize internal emergency conditions, the OMs are equipped with a ROM-based computer, which has the ability to set and monitor internal parameters via DAC's and ADC's. Attached to the phototube is a fast charge integrating electronic circuit. It outputs a rectangular pulse. The leading edge gives the initial timing of the PMT signal and its width the integrated charge. These signals are transmitted via an optical fiber to a string controller module (SC), which digitizes the data from all optical modules of one detector string. For more details on the specifications of the optical modules and their integration into the DUMAND II system refer to [2, 3].

Two types of OMs are going to be used. One was developed in Japan, called Japanese Optical Module (JOM), the other has been developed and built in Germany, Netherlands and Sweden, called European Optical Module (EOM).

The EOM uses the Philips XP2600 phototube, which is a special development for DUMAND like experiments. Because of its unconventional design, providing good characteristics, it is often called "Smart PMT" [4].

The initial design of a prototype EOM, which was delivered in January 1992 to Hawaii Dumand Center, was developed by the former Aachen group (now: Vijlen Institute for Physics) [5]. It was refined in collaboration with Stockholm University [6, 7] and approved during a review held in Kiel (September 1992).

With major support by the University of Kiel, 12 EOMs have been built in close cooperation between Vijlen and Kiel. The optical penetrators through the pressure housing have been contributed by the University of Bern, Switzerland, the electrical by the University Hawaii, USA.

2 The Philips "Smart PMT" XP2600

This photomultiplier consists of the combination of an electro-optical preamplifier with a conventional small phototube. Photoelectrons, emitted from a large area hemispherical photocathode, (3π sr, 35 cm diameter) are accelerated with a high voltage ($25kV$) to a aluminium coated scintillator placed near the center of the glass–bulb. This scintillator is read out by a small fast 11–stage phototube (Philips XP2982), placed in a recess at the back of the photo tube. A sketch is drawn in figure 1.

The result of the high acceleration voltage is a high gain in the first stage and essentially 100% collection efficiency over the whole cathode area. In this way one photoelectron from the large cathode gives rise to about 30 photoelectrons in the cathode of the small photomultiplier. Due to the good statistics in the first stage, the tube provides an excellent timing and energy

$$\underbrace{\boxed{\text{cathode } \emptyset 35cm} \xrightarrow[25kV]{e^-} \boxed{\text{scintillator}}}_{\text{optical preamplifier}} \longrightarrow \boxed{\text{conventional fast photomultiplier}}$$

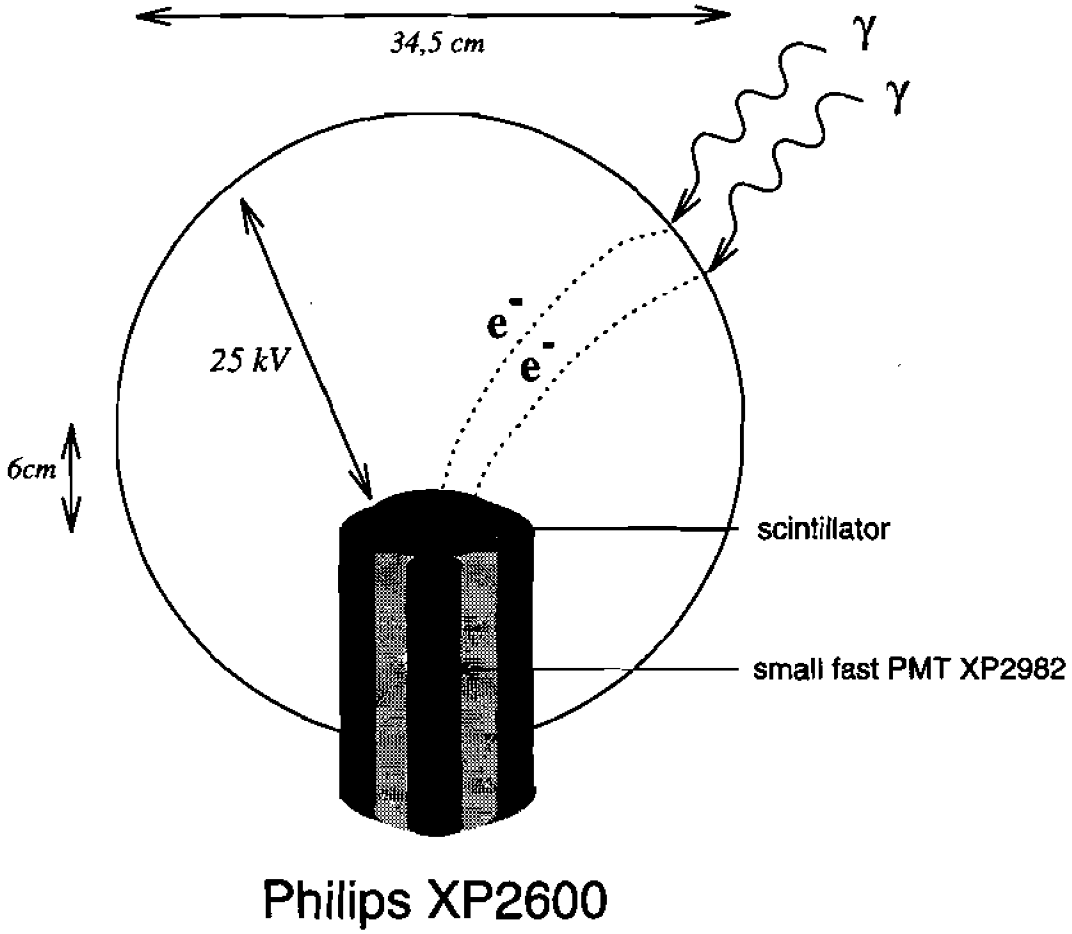

Figure 1: Sketch of the "smart" PMT Philips XP2600

resolution at low photoelectron level[1].

The energy–resolution on the 1PE–level is better than 50% FWHM, resulting in the possibility of a clear separation between the one, two and more PE.

The time–jitter is better than $\sim 5ns(FWHM)$ for 1PE and decreases as $1/\sqrt{n}$ with n, the number of PE.

Another advantage occurs due to the isotropic behavior of the scintillator, which avoids a complicated dynode structure[2]. Thus the tube has a uniform collection efficiency (and therefore gain) and shows only minor magnetic field influences.

The photocathode is bialkaline type SbKCs with a high spectral sensitivity for blue–light but low thermionic emission. The tube is sensitive over a solid angle of at least $3\pi sr$.

An accurate gain calibration of this photomultiplier can be done in situ any time using the dark-current signal originating from thermal emission of photoelectrons from the cathode ("smartness"). For more information see references [4, 8, 9, 10, 11].

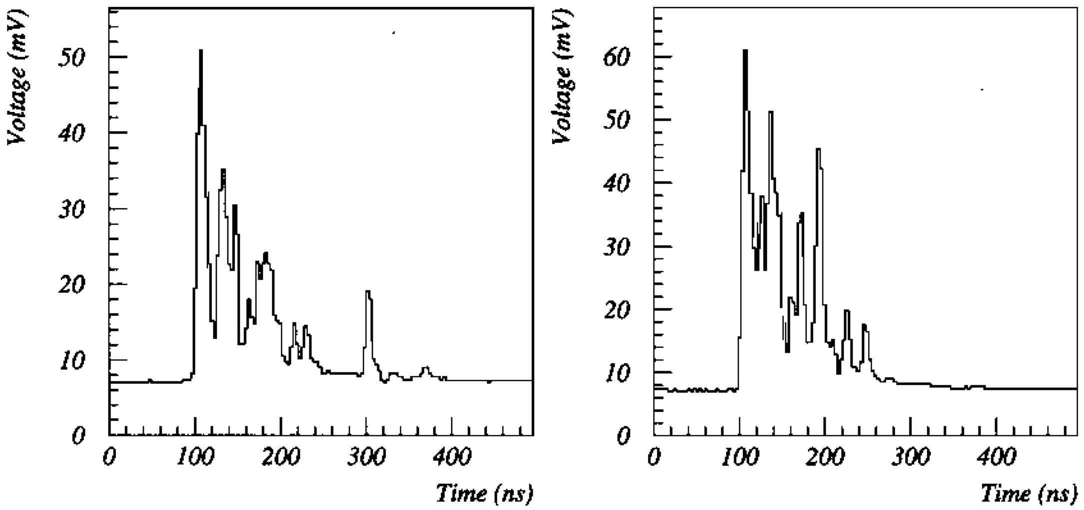

Figure 2: Typical pulses of the Philips PMT with low PE energy. (PMT # 0027)

Typical PMT pulses with low PE energy are shown in figure 2. These pulses were measured with a 200Mhz FADC which has a time resolution of $5ns$ and a vertical resolution of 8bit[3]. One can see, that due to the scintillator decay time, the fast small PMT converts the photons produced in the scintillator as individual pulses. Thus the output is not smooth. The decay

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[1] The unit PE (Photo Electron) will be used in the following for the pulse energy

[2] Such a structure may generate azimuthal and zenithal asymmetry in the pulse-height and timing response.

[3] See K.Trieu, Diploma thesis 1993 RWTH Aachen

time of the scintillator was measured, by superposition of PMT-pulses, to be typically $65ns$. One can see, that there is only a weak correlation between the incoming number of PE and the pulse-height or a TOT (Time Over a Threshold) information.

Thus, to obtain the PE-number, one has to measure the integrated charge of all secondary pulses coming out of the scintillator. This requires at least an integration time of $70ns$. It was measured independently that the full charge information is gathered within $\sim 150ns$ integration time.

3 Electronic hardware

3.1 The fast readout — DMQT

As a result of the pulse characteristics, basic requirements for the EOMs fast readout, named DMQT, are:

- The circuit measures the charge of the PMT signals to obtain the number of initial PE. The output should be strongly correlated with the PMT signal start, the duration has to be proportional to the total charge. The charge measurement cannot be done with a fixed gate time due to long dead-times. These are typically several μs for conventional charge to time converter circuits. The charge conversion is done during the charge collection with variable integration time to achieve a fast conversion, and thus a deadtime of a few hundred ns. The expected ocean noise is around $100kHz$ on $1PE$.
- The DMQT is directly fed from the PMT anode signal without external amplification. Its rectangular ECL output drives directly the LED driver circuit. The leading edge of the output signal has a delay of about 10 ns to the original PMT signal start.
- The circuit has a limited dynamic range for the input amplitude. Therefore it slides over from a linear to a logarithmic charge measurement at higher input amplitudes of PMT signals (typically 5 PE).
- Two thresholds in coincidence control the triggering of the circuit. A high threshold suppresses noise of the small PMT and a low threshold, which is delayed to the high, obtains accurate time information.

The first unit in the fast readout is a fast amplifier(AMP1). PMT pulses are amplified with a gain of approximately 5 before they are fed to two comparators (CMP1, CMP2) which are the two thresholds. The pre-amplification allows an adjustment of the thresholds in the range of 0 to 200 mV. The signal to the second comparator (CMP2) and the further integration is delayed with a $130cm$ coax cable. The actual length of the delay must be longer than the typical rise time of the PMT signal between the two threshold settings.

A wired 'and' between the two comparators starts a monostable multivibrator (in the following named: "timer"), which is set to $\sim 85ns$[4] An output comparator (CMP4), which drives

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[4] Due to timing problems on the latest produced circuit-boards, this number had to be increased from previously $45ns$. (see appendix B)

the LED-driver, is started as well as the controlling of the integration.
The integration control is done the following way [5]:

- In case no PMT signal is applied, two differential amplifiers are both activated in such way that they apply an offset voltage to the positive input of a further amplifier (AMP2 gain 1.7) of the PMT signal (negative input). The output of AMP2 delivers a negative voltage to a voltage controlled bipolar current source. The current source, delivers a positive current to the storage of the integration capacitor, which will force a positive voltage of +0.7 Volts caused by a diode across of the capacitor clamping this point. The integration capacitor is connected to a high impedance voltage follower. Attached to it, a comparator (CMP3) compares its input voltage to a fixed reference voltage. The fixed offset of the amplifier and the resulting voltage at the integration capacitor will hold this comparator in a stable "off" position.
- In case of a negative PMT signal, high enough to fire the input comparators, the timer is triggered. The output of this timer is "ored" with CMP3 and generates an output signal via the output comparator CMP4. The complement output of the timer deactivates the two differential amplifiers stages and the amplifier AMP2 will amplify the PMT signal. The output of AMP2 delivers a positive voltage to the bipolar current source proportional to the PMT output signal. The storage capacitor will be loaded (signal integration) and the comparator CMP3 will go to "on" state. Due to the fact that the outputs of the timer and CMP3 are ored we get an output signal from CMP4 which is correlated to the beginning of the PMT pulse. After 85 ns the timer will switch to its stand-by mode and the first differential amplifier DA1 becomes active. A small negative voltages is fed to the AMP2 (noninverting input) producing a small positive current (conversion current) via the bipolar current source. In case the PMT signal is already over, the negative voltage at the integration capacitor will go in a linear way to zero. The comparator CMP3, and finally CMP4 will stop the output signal. If there is still a PMT signal present, when DA1 is activated to induce the conversion current, integration and conversion currents will be superimposed. The end of the conversion will be delayed correlated to the charge of the PMT signal, still being integrated. Finally the DA2 amplifier is set to its active state to stabilize the clamping of the storage capacitor to +0.7 Volts.

The results of the calibration measurements show a good energy resolution up to 4 PE. The overall dead time of the DMQT is about $200ns$ for 1PE and $320ns$ for 2 PE[5]. The timing accuracy is around $200ps$ the pulse-width resolution arround $1-2\%$.

An I/O-line from the CPU is level adapted and fed to the output comparator CMP4. Thus the CPU can switch the output and thus the LED to ON state.

The inverted output of CMP4 used for the measurement of the PMT's count rates (see chapter 3.4).

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[5] This also had to be increased.(see section B)

3.2 The remote Computer

The computer is based on the Motorola Processor 68301F. The processor possesses three serial interfaces, a 16 bit parallel interface and a 68000 core. It is clocked with a 12.5 MHz Oscillator. The computer has a 16 bit data bus accessing 256 kbyte random access memory and 256 kbyte read only memory (EPROM). The memory is split into even and odd memory banks. The ROM holds the OS-9 operating system and the basic application software.

Input pins		
Pin No.	name	comment
1	ENABLE	+5V
10	WAOUT	Watch dog out
11	RES	Watchdog reset
13	QD2	Clock divided by 128
14	CLK	Clock
23	AS	address strobe

Output pins			
Pin No.	name	boolean equation	comment
15	! BERR.T	! AS & QD2	bus error (bus timeout after n clock tics)
	! BERR.E	ENABLE	
16	! RESET.T	RES	reset
	! RESET.E	RES	(wired by enabling with input signal)
17	! HLT.T	RES	halt
	! HLT.E	RES	
18	INT2.T	–	interrupt 2
19	INT1.T	–	interrupt 1
20	INT0.T	–	interrupt 0
21	! BAS.T	! AS	buffered address strobe
	! BAS.E	ENABLE	
22	! BOOT.T	RES	boot
	! BOOT.E	ENABLE	

Table 1: GAL Programming.

Reset–logic and interrupt–logic is decoded in a GAL 20V8 (see table 1). The proper reset is realized with a watchdog circuit. Address decoding is realized in a PEEL 22CV10, which programming is to be seen in table 2.

3.3 Setting of internal parameters

There are four internal parameters, which can be set remotely.

Input pins		
Pin No.	name	comment
1	enable	+5V
2	bootdone	boot delay is over
3	as	address strobe
4	! cs0	cpu pin
5	! cs1	"
6	uds	"
7	rw	"
8	lds	"
9	a23	"
10	a22	"
11	a21	"
13	a20	"
14	a19	"
23	a18	"

Output pins			
Pin No.	name	boolean equation	comment
15	RAMSEL	!as & !a23 & !a22 & !a21 & !a20 & !a19 & !a18 & bootdone	ram select
16	WEEVEN	!even & !rw & !ramsel	write even (RAM)
17	EVEN	!uds	select even RAM and ROM
18	WEODD	!odd & !rw & !ramsel	write odd (RAM)
19	ROMSEL	(!as & !a23 & !a22 & !a21 & !a20 & !a19 & a18 & bootdone) — (!as & !a23 & !a22 & !a21 & !a20 & !a19 & !a18 & !bootdone)	rom select
20	WDI	!dtack	watchdog input
21	ODD	!lds	select odd RAM and ROM
22	DTACK	(!as & !ramsel) — (!as & !romsel)	Data acknowledge

Table 2: PEEL Programming.

- The high voltage supply for the first PMT stage ($25kV$) is switched ON and OFF by a relay in the powerline to the 25kV supply unit (chapter 3.6.1).
- The high voltage of the small PMT is controlled with a control line to MPS 1600 supply unit (chapter 3.6.2).
- The internal high and low threshold of the DMQT circuit are set in the range from 0 to $-200mV$.

These parameters are set with an 8 bit DAC. It is programmed with the parallel bus of the processor. The control lines to the high voltage supplies are connected by an additional electronic switch to ensure power OFF during startup. The electronic switch is activated by an I/O line.

The DAC output for setting the thresholds is inverted and level adapted in the DMQT circuit to an appropriate range.

The output–LED can be switched on for a certain amount of time with one CPU–I/O-line. After a level adaption is performed, the LED driver circuit is turned on with the output discriminator CMP4 of the DMQT circuit (see chapter 3.1).

3.4 Controlling of internal parameters

Besides the setting of parameters, monitoring of these and others is provided. They are:

- The thresholds and the high voltages as described above (chapter 3.3).
- The supply voltages and their currents respectively (chapter 3.6.3).
- Temperatures at three different locations.
    1. Cathode temperature (measured in the silicone gel)
    2. Temperature above the DMQT circuit
    3. Temperature above the $+5V$ DC/DC converter
- The emergency case of water inside the module (leak condition)
- The countrate of the fast circuit.

These parameters are monitored with the combination of a multiplexer (16 inputs) and a 10 bit serial ADC (8 inputs), which are connected to the I/O lines of the processor. The output values of the measurements are scaled to ranges from 0 to 5 Volts according to the specifications of the ADC inputs.

For monitoring the high voltage of the small PMT, the voltage given onto the control line to the MPS 1600 is measured as well as the voltage on a monitor line from the MPS 1600, which is proportional to the actual high voltage (see chapter 3.6.2).

All supply voltages ($+5V, -5V, +12V$) are monitored. The corresponding currents are measured by a proportional voltage drop over a small resistor.

The three standard temperature sensors (AD592) provide voltages which are proportional the measured temperature. They are conected with wires to the electronic boards.

The leak sensor consists of two wires which circle around the equatorial zone of the PMT. The isolation of both wires is alternately removed. One wire is on $+5V$, the other is pulled to ground by a resistor. If water comes in, the $+5V$ will pull the other to a higher potential than ground and the corresponding ADC–channel will show a higher value than 0.

The countrate of the PMT is measured by counting the number of pulses fed to the LED-driver (CMP4) within a certain amount of time (see 3.1). The ECL output is converted to TTL, prescaled by a factor 64 and fed to the timer input of the CPU.

3.5 The interfaces to the world

Two interfaces connect the EOM with the string controller. These are a power line for the power supply with the superimposed modem communication and an optical link for the direct transmission of the PMT data.

3.5.1 The power line

The EOM receives $48VDC$ power from the String–controller through a bipolar penetrator in the pressure sphere, which is specified by HDC[6]. The $48V$ input drives the DC–DC converter to generate all used voltages. The DC/DC converters are supplied from the 48 Volt input via a transformer, which extracts the modem signal, superimposed onto the powerline. The communication is done with a 300 baud modem using the frequency shifting method. The transformer amplifies the signal by a factor of 7. Two diodes protect the modem from spikes, which e.g. can occur during power on. A third diode protects the OM from wrong polarity of the input voltage.

3.5.2 The optical link

The DMQT circuit directly transmits its data via a multimode optical fiber to the string controller. To transform the electrical pulses into optical pulses, a diode HFBR 1424 from Hewlett Packard, driven by a LED-driver IC, is used. This was designed by HDC matching to the optical receiver in the String Controller.

The optical penetrator in the pressure sphere was designed by Bern University and Diamond S.A.[12].

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[6] Hawaii Dumand Center

3.6 Power–supply

3.6.1 25 kV power supply for the first PMT stage

The 25 kV for the first PMT stage is provided by a supply-unit, produced by Philips. It allows an input voltage between $24V$ and $48V$ and has an output, which can be regulated with a small potentiometer and is set to $\sim 25kV$.

Electromagnetic fields from the power supply, which influence the electronics, are shielded by a carbon-layer and additional copper foil. As a result of the shielding, the internal current in the supply-unit rises. To protect its internal electronics, the supplied voltage ($48V$) is reduced outside by a voltage divider, which resistor is adapted to the internal resistance of the HV-supply and the capacity of the Philips PMT.

The HV–supply can be turned on and off by software using a relay (see chapter 3.3), but the voltage of $25kV$ is not remotly variable.

3.6.2 Power supply for the small PMT

The high voltage for the small PMT is produced by a separate unit (EMI MPS 1600). This device can produce high voltages from 0V to more than 1600 V. The unit is supplied with 12 Volts.

The high voltage is controlled with a voltage from 5V to 0V on a control line. The high voltage can be monitored on a monitor line. This monitor line gives the high voltage divided by a factor of 1000.

Due to mechanical space inside the EOM, the original housing was replaced by a smaller one, which also provides electro-magnetic shielding.

3.6.3 Power supply for the electronic circuits

The power supply for the electronics is generated by 3 DC/DC converters. They convert the 48 Volts input from the powerline into ±5 and +12 Volt. The DC/DC converters have an efficiency near 83 %.

4 Mechanical layout

4.1 General design

The whole mechanical design is oriented on the geometry and the space avaliable inside spherical glass pressure housings for deep ocean applications. A sketch of the mechanical assembly is drawn in figure 3.

As mentioned above, the large PMT is glued with tranparent silicone gel into the lower half of the pressure housing. The bottom distance is about $2mm$. The avaliable space its top is a limiting factor and dictates the design of all other part. The top distance varies between $0.5cm$ and $1.5cm$ depending on the actual shape of the used PMT.

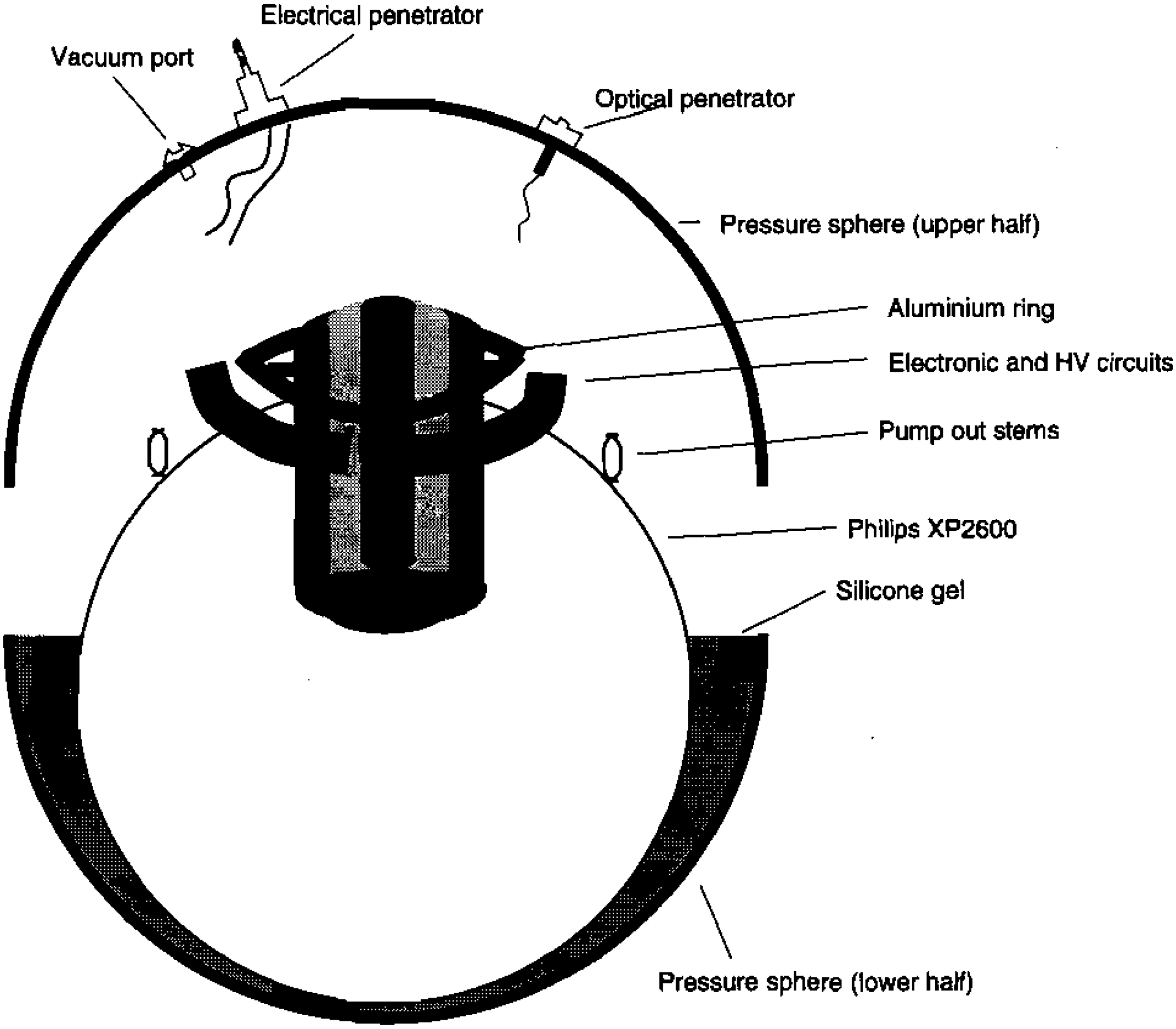

Figure 3: Sketch of the mechanical assembly

The small PMT is glued into the recess in the back of the big sphere, to achieve a better optical coupling between the scintillator and its photocathode.

Due to the spherical geometry of the Philips PMT, the pump–out–stems and the large (quartermoon shaped) $25kV$–HV–supply unit, it was impossible to produce a single ring electronic board fitting into the pressure sphere.

The electronics is divided into two ring segments plus a HV supply unit for the small PMT.

The HV supplies and one electronic board are mounted on an aluminium ring, which is itself fixed to the neck of the PMT at three locations. The second electronic board is fixed below the $25kV$ supply.

4.2 Components

The following sections highlight several important mechanical parts. A fully detailed description would go beyond the scope of this document.

4.2.1 The "Nautilus" pressure spheres

The biggest spheres avaliable are 17 inch diameter glass spheres. They are produced either by Benthos or by Nautilus. For the EOM the Nautilus spheres were chosen. They guarantee a reliable operation up to pressures of $600 bar$. It is possible to combine different halves and no care has to be taken on the orientation of the upper to the lower half.

They consist out of borosilicate glass with a high optical transmission up to $320 nm$. They show no sign of phosphorescence and fluorescence [13].

The Nautilus–spheres have been used in the Baikal experiment as has the silicone gel [14].

4.2.2 The optical Gel

The previously used optical Gel *Wacker 604* ([5]) was changed to *Wacker Semicosil 912*, due to its better mechanical properties. It is a solvent free addition–curing RTV–2 silicone rubber with the same excellent transmission properties as the previous used [14]. The rubber is a two component gel which vulcanises within several hours (room temperature) to a low viscosity (depending on the mixture ratio) gel with distinct tackiness. For the EOM a ratio in the range of 10 : 10 and 9 : 10 of the two components was used. The gel must be flexible, as the housing compresses several mm due to the pressure in the deep ocean. On the other hand it must not "flow" to keep the PMT mechanically in its position.

4.2.3 Penetrators

Two penetrators connect the OM to the outer world. The electrical "E0'–style by "Crouse Hinds" presented some reliability problems and are to be changed. An optical penetrator suitable for multimode optical fibre was designed by Bern University and manufactured by Diamond SA [12]. A titanium vacuum port allows to control the inside pressure.

Three holes for the penetrators have been drilled into the top half pressure sphere. The positions are given on the one hand by the allowed range due to the "hart-hat", which fixes the OM into a detector string, and on the other hand by inside space avaliable. The hart hat allows only positions along one line up to angles of 28 degrees. This maximum angle was chosen for the optical and the vacuum port (due to the inside space), which are positioned at opposite locations. The electrical penetrator is on the side of the vacuum port at a zenith angle of 20 degrees (see figure 3).

The pressure–spheres have been cycle pressure tested up to 600 bar ($6 km$ equivalent depth).

4.2.4 The circuit boards

The internal electronics is realized in two 7 layer circuit boards, called EOM/A and EOM/B. The boards used in the EOM are EOM/A Ver.1 and EOM/B Ver.2.

EOM/A, the so called "power board" contains the DC/DC converter, the modem, DAC and ADC units. EOM/B (the '"computer-board") contains the fast circuit DMQT, the LED, and the computer unit. Connections between the boards are realised with wire-rap cables which are wrapped to EOM/A and soldered to terminal posts on EOM/B.

Connections between the two boards are:
11 IO/lines between CPU and DAC/ADC etc,
6 supply voltage and ground wires,
2 wires RXD and TXD between Modem and CPU and
4 wires for setting and re-reading the thresholds.
For more information, please consult [7] and [6].

EOM/B is connected to the PMT via a coax cable soldered into the board. It also has a 130*cm* coax delay cable. The optical fibre is attached to the LED on EOM/B.

EOM/A is connected to the $48V$ input power. The temperature sensors and the "Leak Condition" are wire wrapped to it. Four cables connect the HV-supply to the small PMT (Supply voltage, ground, control and monitor line). The 48V to the $25kV$ unit is not supplied directly. $0V$ is put to the common ground (all grounds of shieldings etc refer to this point), whereas the $+48V$ is connected to a resistor attached to the holding bow of the small PMT. The voltage is reduced and fed to the $25kV$ supply unit (see chapter 3.6.1).

4.2.5 Mechanical retainers

All devices are fixed to an aluminium ring (itself fixed at the neck of the PMT). It has a gap for the optical penetrator which is positioned in between the two close pump-out-stems.

A new holding bow was designed to fix the small PMT to the alu-ring. The small PMT is also glued into the big PMT, as mentioned above. A Mu-metal shielding around the small PMT protects against magnetic fields.

The circuit boards are equipped with PVC holdings on both ends. EOM/A is fixed to the alu-ring. EOM/B is mounted under the 25 kV supply using tie wraps.

Three IC's on EOM/B and the DC/DC-converters on EOM/A have to be cooled. An optimal solution would be an direct contact to the outer surface, which is not easily possible. In the present version stripes of self-gluing copper-foil are used for mechanical connection between the circuits and the alu-ring.

The PMT surface is conducting. Therefore all blank (or possible) electrical connections have been isolated.

5 The operating system

The operating system chosen for the optical modules is called OS-9. It is a fully "romable" operating system, arranged strongly hierarchically. Thus only small parts, the so called device drivers, are allowed to access direct the hardware. The configuration for the EOM has a ramdisk with 64 kbyte size and a serial I/O. For this purpose a serial I/O device driver had to be adapted onto the present hardware. For the EOM this consists out of a CPU 68301F from Toshiba. Toshiba claims a processor bug in the serial interface, which causes trouble when reseting the serial interface. As a remedy Toshiba uses some code which puts a dummy character in the output register before reseting. Including this code the serial device driver was adapted from a SC68681 example device driver and works correctly on the 68301F CPU. The OS/9 system specifies a rigid organisation and syntax of a device driver. This can be found in documentation on OS/9 systems (e.g.[15])

An internal countregister is used for producing interrupts every 0.01 seconds. These interrupts run a software clock, which is needed amongst other things for counting pulse rates.

The complete OS-9 system is burned in EPROMs including some additional program modules, which simplify the work under the OS-9 system. Table 3 enumerates the modules, implemented in the EOM, and their functions.

During system startup the program *go* is executed. It sets the time and starts the user program *eom0*. Upon exit from the user program it starts the shell. If all processes return to the *go* program, it restarts itself.

The serial port is set to 300 baud, 8 bit data, 1 stop bit and no parity.

Upon Startup, the EOM displays log information on the (successfull) boot of the OS and its time. After the start of the User program, an OM-identification and a version number is displayed.

6 User Software

Besides the above mentioned *go* program, a user program *eom0* is started. It implements all features that have to be performed by the EOM, which is especially the communication to the SC (String Controller).

6.1 Comunication protocol

To guarantee an easy and error free communication between the string controller and the optical module a protocol was defined in [16].

In principle there are 4 different kind of messages, which are being transmitted with a special protocol.

1. Commands, sent from the SC to the OM (and echoed back). They start with a '$' character followed by one or two command characters and in some cases by parameters separated by a comma (e.g.'$D0,20') .

Module	Function
basic utilities	
attr	examine or change file security attributes
date	displays system date and time
copy	copies files
del	delete a file from disk
dir	displays directories on devices
free	displays free space on a device (ramdisk)
list	displays text-file
mfree	displays free memory
procs	displays running processes
setime	sets system time and date
shell	creates a user shell
programmer utilities	
dump	file-dump
load	load module into memory
save	writes memory modules on disk
tmode	display or change terminal parameters
system management utilities	
deiniz	unmounts a device
devs	displays system devices
fixmod	fixes module header (since version 2.013)
ident	displays module header info (since version 2.013)
iniz	mounts a device
irqs	display system irq polling table
link	links previous loaded module into memory
mdir	displays module names in the system module dir
unlink	unlink a memory module
user software	
eom0	User program for EOM operation (chapter6.3)
go (sysgo)	startup program (init shell, start eom0, init various stuff)
kermit	communication program for serial data transmission

Table 3: Summary of implemented OS/9 system utilies and programs

error code	error description
command parameter errors	
*20	wrong parameter number
*21	wrong parameter length
*22	first parameter not allowed
*23	second parameter not allowed
*24	wrong length for first parameter
*25	wrong length for second parameter
*26	error decoding first hex parameter
*27	error decoding second hex parameter
*28	first parameter out of range
*29	second parameter out of range
*2A	no first parameter
*2B	no second parameter
command input errors	
*40	unknown command
*41	ok received but no command in buffer
*42	nonsens input
*44	no valid command received within 10 min after power on (since version 2.015)
special range errors	
*50	HV value out of range
*51	HV value bigger than allowed
*52	channel for thresh out of range
*53	value for thresh out of range
*54	wrong adc channel ($R,D,F)
*55	wrong emergency report number
*56	can not decode Date/time-string
*57	entry in Date/time string outside bounds
OS9 errors	
*60	error forking kermit
*61	error forking tmode
*62	error forking attr
*63	error chaining ueom
*64	error during getime
*65	error during setime
programming error	
*70	undefined return point

Table 4: Definition of EOM error codes

2. Reports (on commands) sent from the OM to the SC. These start with a '@' character followed by the repeated command characters and the report itself. E.g. '$D523F' or '@Q Do you really want to quit Y/N ?'.
3. Error messages (on commands) sent from the OM to the SC. The EOM error messages are defined in table 4. They start with the character '*' and contain two digits, where the first defines an error class and the second the specific error.
4. Emergency messages (on internal emergency cases) sent from the OM to the SC. Emergency messages start with a '%E' followed by one character indicating the case of emergency.

Each transmitted string is ended by a 'cr' and a 'lf' character.

6.2 Changes and extensions to the standard communication protocol

command	description	OM answer
$\$SN$	Give OM identification	string containing the OMs name
$\$XD <, tt >$	Programs a saw tooth into the DAC's for $< tt >$ seconds (tt=decimal value). The EOMs will not accept inputs during this time. On calling without tt, 10 seconds are taken as default. (Since version 2.013)	nothing
$\$XE <, tt >$	Set time period for emergency reports. $< tt >$ is a decimal number with the unit seconds.	Only when called without 'tt'. The actual set value is responded.
$\$XP, xyz$	Special case of the '$P' command. Automaticly downloads the program 'xyz' (max 20 characters) and executes it.	'READY' like the '$P' command
$\$XT <, tt >$	Sets the time for counting the PMT-pulses and measuring the rate. ($< tt >$ is similar to '$\$XE$')	similar to '$\$XE$'

Table 5: Additional protocol commands for the EOM. '<>' enclose optional parameter.

The EOM performs several extensions and slight changes, mainly caused by EOM-specific hardware, to the standard communication protocol [16]. These are:

- Additional $SN, $XE, $XT, $XP, $XD commands, see table 5.

- On every 'cr' the OM also sends a 'lf' character for easier terminal operation.
- Units for the countrates are always 'kHz'.
- The $M and $N commands receive 3 digit parameters in the unit of kHz (hex). Called without parameter, the actual set value is reported (e.g.'@M010').
- There is no 'G' and 'O' index for the monitor commands and the reports.
- Report index '2' measures the actual set voltage, index '1' measures the input to the *MPS1600* on the input line.
- Report index '3' is the high, '4' the low threshold of the DMQT.
- The temperature sensors correspond to the following report index:

  '5' : cathode temperature,
  '6' : DMQT temperature,
  '7' : $+5V$ DC/DC converter temperature.
- There is no $+15V$, but a $+12V$ supply voltage.
- After a lowering of the HV, caused by a too high count rate (emergency condition '1'), a second automatic lowering is only possible after twice the time of the rate measurement. This is due to a rate mismeasurement caused by the long on mode. Since parameters inside the OM have actually been changed, the long on mode is repeated with the timing of the emergency report, until they are acknowledged. Even if the '%E1' emergency has been acknoledeged ('$A1'), but not resumed (no '$U1'), a new '%E1' report may be generated (until it is acknowledged again) if the HV is changed again automaticly due to too high count rates.
- As a future extension it seems useful to create a Long On mode on every change of a DAC setting, to have a mark on the data stream. This is not implemented yet.

6.3 Description of the user-program

The remote user program is based on the communication protocol discussed in the chapters above. It was written in C using the OS/9 crosscompiler *PCBridge* on the author's PC's [15].

After *initialization*, the *Main* routine repeatly makes sequential calls to three major functions: *Command*, *Trouble* and *Report*, until program exit. A flow chart is shown in figure 4.

During initialization all parameters and variables are set to defaults. The DAC is being programmed with default values (high voltages are Off). The local echo is turned off, and character on the input are not allowed to produce a program termination, which is a protection against noise on the communication line.

If there has been no valid command from the SC within a period of ten minutes after power on, the *Main* routine turns the high voltage to default values. This security mechanism allows

parameter	description	value
MAX_SEKUNDEN	Interval for calculating counting rate	$10s$
TROUBTIME	Repetition interval for trouble reports	$10s$
COUNTDOWN	Time [s] after which OM turns on	$600s$
DEF_HV	Default HV for small PMT	$0x20 \approx 1500V$
DEF_THRESH	Default value high threshold	$0x80 \approx 90mV$
DEF_THRESL	Default value low threshold	$0x30 \approx 35mV$ $0x40 \approx 45mV$ (Vers.2.014)
DEF_BIG	Default for big PMT	$0xFF = ON$
HV_MSET	Maximum allowed HV ($SH)	$0x00 =$ Max.
RATE_MIN	Minimum counting rate	0x000
RATE_MAX	Maximum counting rate	0xFFF
MAX_HV	Maximum HV	0x3FF
MIN_HV	Minimum HV	0x000
MAX_THREH	Maximum high threshold	$0x320 \approx 220mV$
MIN_THREH	Minimum high threshold	$0x06C \approx 30mV$
MAX_THREL	Maximum low threshold	$0x320 \approx 220mV$
MIN_THREL	Minimum low threshold	$0x032 \approx 10mV$
MAX_TEMP1	Maximum temperature Gel	$0x250 \approx 40^\circ C$
MIN_TEMP1	Minimum temperature Gel	$0x0B8 \approx -10^\circ C$
MAX_TEMP2	Maximum temperature DMQT	$0x3B1 \approx 65^\circ C$
MIN_TEMP1	Minimum temperature DMQT	$0x100 \approx 0^\circ C$
MAX_TEMP3	Maximum temperature DC/DC	$0x950 \approx 202^\circ C \equiv -1$
MIN_TEMP1	Minimum temperature DC/DC	$0x100 \approx 0^\circ C$
MAX_VOLP5	Maximum voltage + 5V	$0x3E8 \approx (6V)$
MIN_VOLP5	Minimum voltage + 5V	$0x2DA \approx 4.5V$
MAX_VOLM5	Maximum voltage -5V	$0x3E8 \approx (6V)$
MIN_VOLP12	Minimum voltage -5V	$0x2F8 \approx 4.5V$
MAX_VOLP12	Maximum voltage +12V	$0x3DA \approx (14V)$
MIN_VOLP12	Minimum voltage +12V	$0x2A8 \approx 10V$
MAX_CURP5	Maximum value +5V current	$0x3FF \approx 0.6A$
MIN_CURP12	Minimum value +5V current	$0x0B4 \approx 0.1A$
MAX_CURM5	Maximum value -5V current	$0x384 \approx 0.5A$
MIN_CURP12	Minimum value -5V current	$0x177 \approx 0.2A$
MAX_CURP12	Maximum value +12V current	$0x33E \approx 0.25A$
MIN_CURP12	Minimum value +12V current	$0x04B \approx 0.02A$
MAX_LEAK	Maximum value leak condition	0x040
MIN_LEAK	Minimum value leak condition	-1
MAX_25KV	Maximum setting of 25kV	-1
MIN_25KV	Minimum setting of 25kV	-1

Table 6: Power on values for the EOM . On '−1', no check is performed

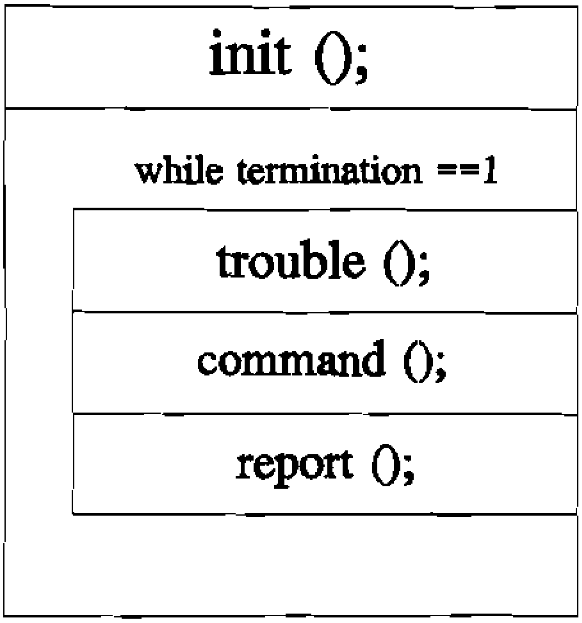

Figure 4: *Main* routine

running the module even if the communication line fails. The initialization values can be found in table 6.

The function *Command* reads commands from the serial interface and checks the syntax. After a correct command was read and also an 'OK' was received the corresponding command is being executed (see figure 5).

The *Trouble* function reads all ADC channels. The values are tested if they are outside the allowed bounds. In this case a flag is set, for the generation of an emergency report (see figure 6).

All emergency reports are done in the function *Report*. One exception is the emergency case of a leak, which is being reported imedeatly. All other reports (e.g. '$R' command) and error messages are created here. The controlling of the timing of the LED Long On and the '$E' command is also done here (see figure 7).

6.4 Calibration of internal values

The DAC calibration was done, using a linear fit for the two thresholds and the HV supply.

$$DAC = INT(0.5 + [a] + [b] \cdot VAL)$$

$[a], [b]$ are the fitted parameter, VAL is the value to be set, DAC the corresponding number to be programmed into the DAC. As an example table 7 gives values for OM #19.

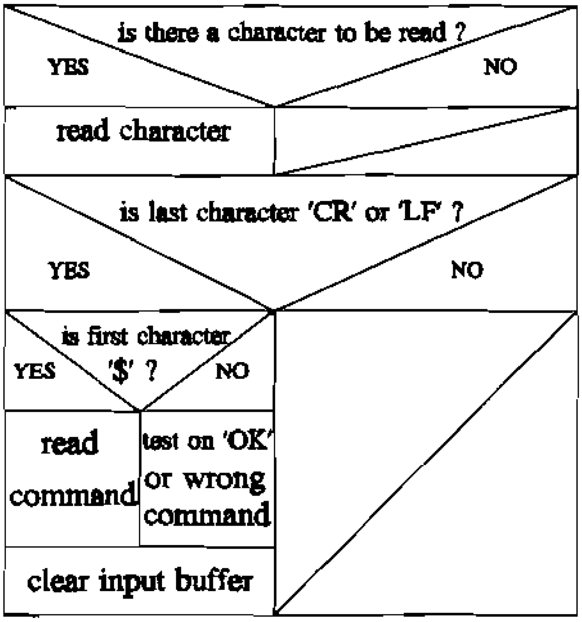

Figure 5: *Command* routine

DAC	[a]	[b]	unit for VAL
HV-set	285.0	-0.169	V
Thr. hi	-3.95	1.432	mV
Thr. lo	-2.17	1.434	mV

Table 7: Example for the DAC calibration. (OM: #19, *4070/Franz Beissel*)

A linear fit was used again for the ADC calibration. This time a value is calculated from a number given by the ADC.

$$VAL = [a] + [b] \cdot ADC$$

Some values have been measured in one point calibrations. Thus there is only one calibration constant. For the 25kV–supply and the Leak–condition there is no unit given. In this cases '1' means ON, '0' means OFF. In case of the the leakage this is very arbitrary, '1' equals the leak-wires dumped in a cup of coffee. Any value different than '0.000' should be taken as a leakage and examined seriously.

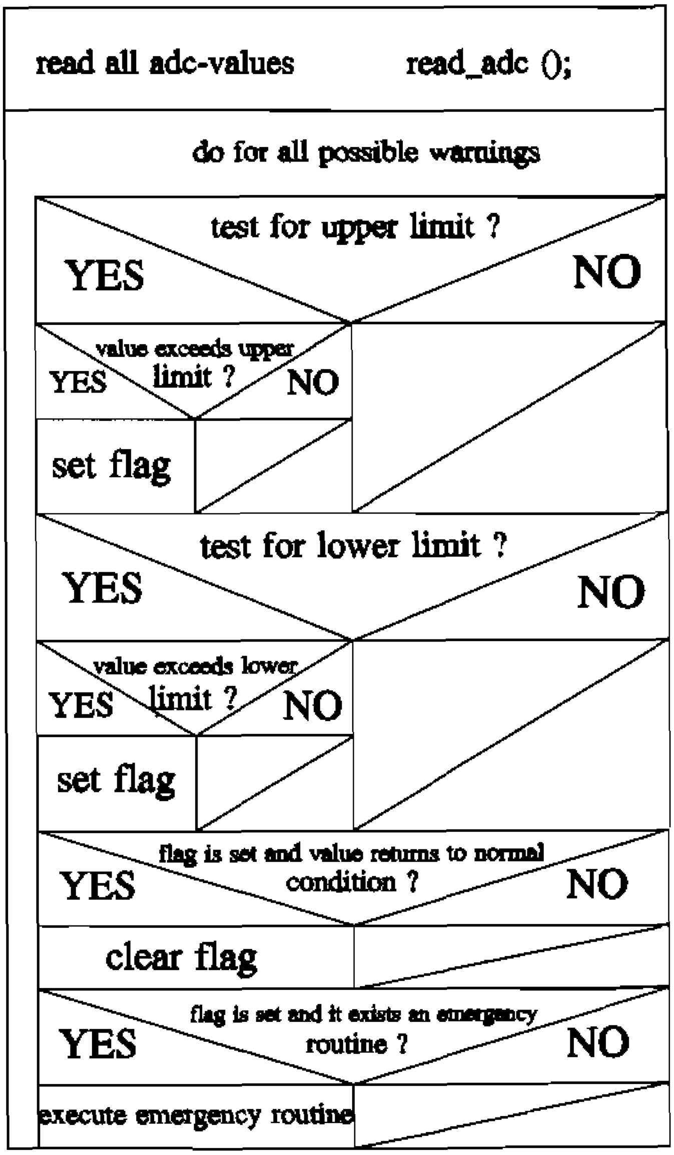

Figure 6: *Trouble* routine

6.5 Further application software

In addition to the inside software, there is a further application program called *SC*. Its purpose is to emulate the communication to a module as if the module is talking to the String–Controller.

The program provides a terminal functionality for the low level communication, but provides also a user command interface between the low level communication and a command structure. The program may read the actual OM calibration from an OM data file, and may keep track automaticly on the OM settings.

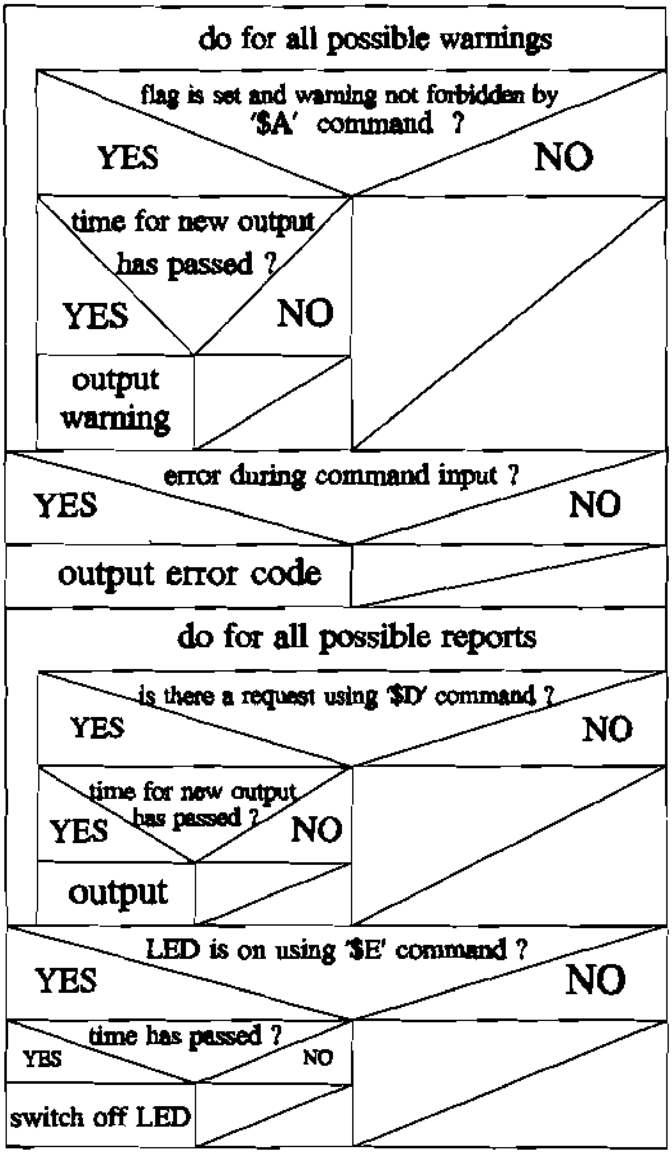

Figure 7: *Report* routine

VAL	[a]	[b]	unit for VAL
HV-ctrl	1692.4	-1.596	V
HV-moni	-8.38	1.845	V
Thr. hi	-0.42	0.268	mV
Thr. lo	-2.28	0.268	mV
Temp 1	-18.61	0.088	$^\circ C$
Temp 2	-20.36	0.089	$^\circ C$
Temp 3	-24.40	0.095	$^\circ C$
U +5	—	$6.12 \cdot 10^{-3}$	V
U -5	—	$5.93 \cdot 10^{-3}$	V
U +12	—	$14.59 \cdot 10^{-3}$	V
I +5	—	0.571	mA
I -5	—	0.582	mA
I +12	—	0.285	mA
Leak	—	$11.11 \cdot 10^{-3}$	—
25kV	1.01	$-1.0 \cdot 10^{-3}$	—

Table 8: Example for the ADC calibration (OM: #19, *4070 / Franz Beissel*)

7 Notes on Operation

7.1 Getting started — Power on

Immediately after power on the OM boots the operating system and starts the user–program. The EOM displays log information on the (successfull) boot of the OS and its time. As an OM-identification a report on the *\$SN* and *\$SV* commands is automaticly generated after the start of the User program,.

For each module the operation values for the HV and the thresholds have to be set individually. Table 9 gives the standard DAC settings for each EOM and the corresponding ADC values. Maximal[7] values for the inside temperatures and corresponding count rates are also given.

The big tube is turned ON with the '\$OFF' command and turned off with the '\$O00' command. After turning on, it takes several seconds until $25kV$ are actually given onto the big tube. Due to the high capacity of the PMT, the high voltage stays on the PMT even after turning off the supply. Thus the dark count rates decreases very slowly over a few hours.

To prevent any damage during operation and handling, care should be taken on the following points:

- The setting of the HV of the small PMT is done with a negative coefficient. Thus '\$V00' corresponds to maximum voltage and '\$VFF' to minimum voltage, respectively. Also the the ADC that monitors the switching of the '25kV'–supply has a negative coefficient.

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[7] These values were measured with the OM operating in a cardbox without external cooling.

No:	Name	HV ($Vxx)		T_{hi} ($T1,xx)		T_{lo} ($T2,xx)		Temp.(ADC)			Max.
		DAC	ADC(2)	DAC	ADC(3)	DAC	ADC(4)	(5)	(6)	(7)	Rate
11	U.Keussen	10	356	C0	1FE	40	0AE	1F0	23A	2A6	01D
12	V.Commichau	42	2B2	90	184	35	095	1DB	269	2B7	051
16	P.Koske	04	382	C0	204	40	0B3	1E4	28D	2A1	018
19	F.Beissel	3C	2CB	B0	1D6	40	0B3	1BA	2B6	27E	01A
22	L.Thollander	1C	343	D0	231	50	0DA	210	2AC	2E5	045
26	ESSO	0D	268	90	183	30	086	1EF	2B2	2D5	03D
33	C.Camps	35	2F4	D0	222	40	0B3	1D3	26E	295	01A
35	U.Berson	45	2BE	60	106	30	085	1F2	2B3	2CA	02A
44	P.Bosetti	05	385	A0	1AA	40	0B1	209	27B	2B2	01E
46	T.Bolln	2E	2FB	D0	226	40	0B3	1FE	28A	2AC	02A
52	C.Wiebusch	05	383	D0	231	40	0B5	1C2	278	29E	02A
53	J.Rathlev	45	2BB	B0	1DC	30	087	1F0	269	2A1	028

Table 9: EOM Settings

- If the OM is being operated with exposure to light, be sure to give a valid command within 10 minutes. If not, the tube will automaticly turn high voltage ON and may be damaged.
- Do not expose the PMT to bright light or flashes (e.g. for photo's). PMT's cathodes have memories like elephants, remembering bright intensities and long integral illuminations long, even if no voltage was applied. Typically times are days, but this may go up to month and irreversible damage.
- Take care to keep the module in an upright position for long-term storage, due to the softness of the gel.
- Check the vacuum before putting the OM into water.
- Mechanical operations like opening or carrying a module require at least 2 persons!

7.2 Smartness? — Tube out of balance

The good energy resolution allows some calibrations and operational checks using the dark noise data of the tube itself. Examinations of these pulses allow adjusting of HV and thresholds as well as the checks, if there as been any change to the PMT's behaviour, like a drift in the gain.

Figure 8 shows a typical distribution of the integrated charge of dark noise pulses. One sees following typical characteristics.

- As expected from the high gain in the first PMT-stage, 1PE pulses resulting from thermal noise, produce an almost gaussian distribution.

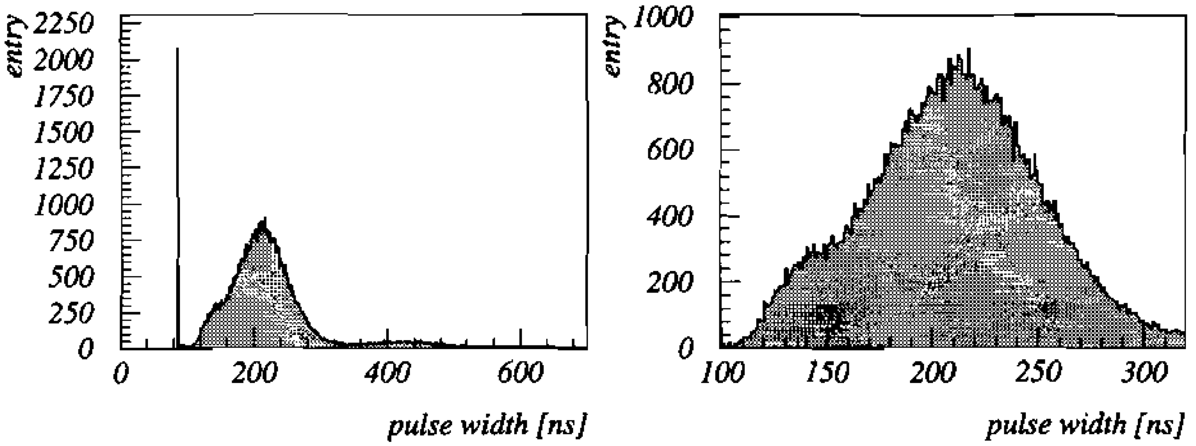

Figure 8: Typical distribution of dark noise at reasonable settings for HV and threshholds (OM: #19 *4070/Franz Beissel*

- A $2PE$ peak is visible in the distribution.
- At pulse widths of $85ns$ a lot of entries can be obseved. This is the time, the internal integration current is started. Thus these entries are pulses with almost 0 PE energy and represent the zero point of the energy scale. The total conversion time for each pulse is given by the integration time plus this pedestrial of $85ns$.
- The 1PE-distribution has a shoulder on the left side. These are entries from scintillator noise, with pulse–heights higher than the trigger thresholds. Below a conversion time of $\sim 160ns$ the DMQT works not linear. Therefore pulses from the whole region $80ns - 160ns$ are moved to the right. This shoulder may occur with equal height as the 1PE for a too low PMT gain. This shoulder should be always visible to make sure, that the PMT-gain is high enough, and the thresholds are not too high.

Usually a good setting for the HV and the tresholds are such where the peak of the 1PE is around $200ns$ and the left shoulder is visible.

How can it be evaluated, if there is something wrong with a module (e.g. the module is not working in its normal operation mode)? Here are some methods that may help to find out problems down in the ocean.

High threshold to low.

Pulses from the small PMT are not suppressed by the DMQT. In the energy–distribution (e.g. dark current), are a lot of entries with energies smaller 1-PE. Also there is a higher dark–current rate.

High threshold to high.

1-PE–pulses with lower energy are more often cut out than Pulses with higher energy. Also the 1PE-distribution is not gaussian, the 1-PE–peak seems to be at higher conversion times than expected and the energy resolution seems to be better than the calibrated value.

Low threshold too low.

There is no direct influence, except, that there may be some oscillations on the output of the EOM.

Low threshold too high.

Statistics in the pulse–rising influence the time–information. The width of time–distributions increases.

High voltage too high

The PMT-gain and therefore the pulse height and charge respectively become higher. Thus conversion times may become very long. One may not even see the one PE before the logarithmic slide–over.

If there is a high rate, the PMT-base current may even saturate. PMT–pulses do not reach their origin amplitude. Thus the PMT-gain changes, the count–rate decreases and the energy–resolution becomes worse.

High voltage too low

The PMT-gain decreases. The DMQT has to operate outside its operational range. Thresholds can not be adjusted at very low voltages. Therefore 1PE–pulses are lost and the count–rate decreases. The Energy–resolution becomes worse.

A Calibration of the DMQT

A negative (ground-free !) test pulse is applied to the input (ca. -200 mV, 40 ns). The thresholds have to be low enough to fire the input comparators. The input signal will be integrated and produces a negative linear ramp at the integration capacity down from the positive clamping point till the end of the input signal. From this point to the end of the monostable time the voltage has to be adjusted to a flat horizontal line with a potentiometer. This corrects all DC-offsets and makes sure that during the time where there is only charge collection (before the conversion starts) and no input signal, no current flows to or from the storage capacitor. As the conversion starts, there is a positive linear ramp till the end of the conversion.

Any change to the internal amplification must include a re-calibration of the DMQT.

B Changes to EOM/A and EOM/B since November 1992

For the EOM production the initially produced electronic board EOM/A vers.1, made by Lars Thollander, and the newly manufactured board EOM/B vers.2 were used.

Additional to changes reported by Lars Thollander [7] several minor changes to these circuits have become necessary since September 1992. They will be listed in the following:

Changes to EOM/A

1. On the 48V input to the tranformer, the connections to pin 4 and pin 5 have been exchanged. This is almost equivalent to the desired exchange of pin 6 and pin 7. This is necessary to guarantee a proper modulation and de-modulation of the modem signal onto (from) the power line.
2. The diodes D2 and D3 are connected to pin 1 of the tranformer and GND (see [7]).
3. R36 was changed to $20k$ (instead $33k$).
4. pin 12 of IC 12 goes to $-5V$ instead of GND.
5. R 31 should go to $+5V$ instead of GND. This change was not made.

Changes to EOM/B

1. R 73 was changed to 560Ω (instead 680Ω).
2. To allow proper turning on and off of the LED by the CPU the following changes were done:
   - R103 to $18k$ (instead of $10k$). It is connected to $-5V$ (instead of GND).
   - Q10 is a pnp BC 560 (instead of a npn BC 550). Base to R103/R102 collector to R104 and emitter to GND.
   - R104 is 390Ω (instead of 330).
   - R105 is 880Ω (instead of 1k).
   - R106 is 680Ω (previously unpopulated).
3. To improve coupling of the pre-amplifier output. R58 is changed to 50Ω (previously 100) and C59 is changed to $0.47nF$ (instead of $1nF$).
4. The gain of the pre-amplifier is changed to 5 by the change of R52 to 120Ω (instead of 820).
5. To correct the DC-offset of the pre-amplifier R52/R53 are connected to $-5V$ via $180k\Omega$. This guarantees a positive DC-offset and avoids oscillating of the DMQT on too low thresholds.

6. To increase the DMQT's charge gain, the following changes were done
    - R70 is 11Ω (instead of 22).
    - R81 and R85 are 255Ω (instead of 510).
7. To reduce the the jitter of the falling edge $47pF$ are put between pin 8 and pin 4 of IC35 (CMP 3).

C Known bugs

Following problems have occurred or bugs are known until September 17, 1993:

- Due to timing problems in the present version of the DMQT, the integration time had to be elongated compared to previous versions. The HV should be adjusted to a value where the conversion time for one PE is at least $200ns$ to achieve a good energy resolution. In the previous version, a conversion time of $130ns$ was enough.
- Due to a bug in the serial device driver, the module uses a slightly higher baud-rate of ~ 314 *bauds*. This may cause communication problems.
- The $\$RF$ command does <u>not</u> measure if the 25kV is actually ON or OFF. The ADC ($RF) measures if there was an attempt to turn the relay for 25kV ON or OFF. If the relay fails, $RF will NOT see this. The relay was tested with several million switching cycles, which is much more than the expected cycles for the life time of the EOM. There may be differences from circuit board to circuit board, though.
- During power on, the control for the MPS 1600 is not set to $5V$ (as it should for $0V$ HV-output) but to $0V$ (resulting in $\sim 1600V$ output). The User-program, which is immedeately started after power on, turns off the HV.

  Even with HV set to minimum ('$VFF') Since there is even a voltage around $50V$ fed to the voltage divider of the small PMT with
- The countrate cannot be measured if the EOM is in Long–On mode. The $\$R0$ command will produce misleading results. The reason is, that the countrate is measured with the rate of the DMQT-output discriminator CMP4. This comparator is also in Long–On mode, when the LED is put into Long–On.
- The communication protocol differs slightly from the JOM due to a misunderstanding in [16]. If the EOM sends reports to the SC, it echos not only the channel number, but also the command letter that was sent to the EOM.

  (e.g. on the command '$\$R0$, the JOM reports back: '@02Af', whereas the EOM reports: '@R02AF')
- The upper limit of temperature sensor 3 (DC/DC) was taken far too high. Therefore no real checking is performed.

- A large number of electrical penetrators (Crouse hinds version) have failed so far. They seem to be mechanically sensitive especially on upsetting. They all should be replaced, especially since they have not been properly packed during shipping to the pressure tests.

The following parts in the EOM have been working well, but have not been tested for long-terms:

- The connections of the temperature sensors occasionally made problems in the past due to badly removed isolation before wrapping. All cable connections have a probability to fail.
- The cooling of the IC's is a critical task. Cooling in the EOM is uncertain, due to low convection and no direct contact to the outer sphere. The most critical circuits are the DC-DC converters, the comparators and the monostable multivibrator IC on the DMQT.
- The 25kV supply and the scintillator have not been tested for long-terms (years)[8]. There has been no failure so far.
- During booting the modem immediately starts sending characters. If the operation voltages are not stable already, the boot messages may be distorted

Things to check when opening an EOM:

- Some wires on a few EOM/B-boards may not be soldered to their posts (maximum 2 OMs).
- The space on top of the PMT may be critical for some EOMs when the sphere is shrinking under pressure.
- Clean the edges of the pressure spheres before taking vacuum (*Tri Chlor Ethan* works good).
- Check the optical penetrator.
- Remove tape between some EOM/B boards and the 25kV supplys if possible.

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The production of the EOMs is a result of several years development and many helping hands (and brains). We are indebted to all of them and so we'll try not to forget anybody in the following list. Unfortunately we are not perfect, so please forgive us for forgetting somebody.

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[8] Except for the baikal experiment

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