Theoretical Development of a Device Based on a Photomultiplier Tube, for Satellite Measurements of the Solar Lyman - Alpha (Lα) Radiation.

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*A device developed for satellite measurements is proposed for investigation of Solar Lyman - Alpha (Lα) Radiation. The input detector is designed with enhanced characteristics for operation in the severe conditions of the space environment. Its basic part is a photomultiplier tube R6835, for astrophysics and ultraviolet radiation detection. It has spectral response from 115 to 200 nm, maximum response 140 nm, quantum efficiency at 121 nm 26%, gain 1*105, anode dark current 0.03 nA and operating temperature from -30 to + 50o C. When the light intensity becomes so low that the incident photons are separated as discrete output pulses obtained from the anode, this technique is known as the photon counting method. The number of output pulses is directly proportional to the amount of incident light. This pulse counting method has advantages in signal-to-noise ratio and stability over the analog mode in which an average of all the pulses is made. Since the detected pulses undergo binary processing because of the digital counting, the photon counting method is also referred to the digital mode. The detector is supplied by 12 V supply voltage whose source is a board battery. This supply voltage is galvanically disconnected from the instrument power supply by means of a transformer.*

Introduction

A project on measurement and study of direct solar Lα radiation, called ASLAF (Attenuation of the Solar Lyman Alpha Flux) was realized as part of the rocket experiment HotPay I at Andoya Rocket Range, Norway, funded by 6 Framework Program [1]. This project was developed by Solar-Terrestrial Influences Institute (STIL), Bulgarian Academy of Sciences (BAS), Stara Zagora Department and Atmospheric Physics Group of Meteorology department at Stockholm University (MISU). ALAF was manufactured at STIL-BAS and it was designed especially for rocket measurements. The aim of this paper is to present a theoretical development of a new device for satellite measurements of the solar Lα radiation.

A device for measuring the scattered solar Lα radiation

The device contains a collimator, a photomultiplier tube (PMT), which is used as primary converter, an electronic amplifier, a discriminator of impulses, a counter of impulses and a power supply. PMT was selected with a spectral sensitivity in the range around 121 nm and is used for registration of Lα solar radiation. The device is designed to be mounted on board a spacecraft. The satellite will fly at Sun-synchronous orbit at an altitude of 700 to 900 km with a period of 12 hours. It will pass over Bulgaria 2 times daily. The orientation will be maintained by the use of star and sun sensors. The useful mass will be 12 till 15 kg.

PMT is used for the detection of a very low light flux, such as Lα radiation. When the light beam is very weak and single photons fall on the cathode, the PMT output receives impulses that are remote from one another. Then the amount of falling light is directly proportional to the number of impulses generated in the output of PMT. This technique is known as of photon counting method [2]. In this case it is required that the average time between the intervals of the impulses is significantly broader than the resolution of the photomultiplier. The photon counting method significantly surpasses the measurements of analog signals during weak light flow in detecting more efficiently with respect to the signal-to-noise ratio.

One of the most important factors when using the method of counting photons is the quantum efficiency (QE). This is the probability of the number of photoelectrons, which will be emitted when 1 photon falls on the photo cathode. Given that one photon falls on the photo cathode, the number of primary photoelectrons issued can only be 1 or 0. Then the quantum efficiency refers to the ratio of the average number of the emitted photoelectrons from the photocathode per unit time, to the average number of photons falling on the photocathode for the same time. The output signal of the photomultiplier in counting mode of photons is calculated as follows.

In the regime of photons counting, the single photoelectron, which is emitted from the photocathode has charge q = 1.6 * 10-19 C. If the amplification of the electronic photomultiplier is $\mu = 5 * 10^6$, then the anode output charge is given by:

$$Q = q \times \mu = 1.6\times10^{-19} \times 5\times10^{6} = 8\times10^{-13}\ [\mathrm{C}]$$

If the width of the impulse at the output of the electronic photomultiplier is t = 10 ns, then the peak output current IP is obtained:

$$IP = \frac{q\times\mu\times\frac{1}{t} = 8\times10^{-13}}{10\times10^{-9}}$$

$$\mathrm{IP} = 80\,[\mu\mathrm{A}] \qquad (1)$$

If the load resistance or input impedance of the adjacent amplifier is 50 Ω, it has a peak pulse output voltage:

$$\mathrm{Vo} = \mathrm{IP} * 4 = 50\,[\mathrm{mV}] \qquad (2)$$

The amplitude in the output of electronic photomultiplier in photons counting mode is extremely small. This requires amplification of the output source with a special amplifier – impulse amplifier, with high amplification and low own noise. The typical amplification factor of the electronic photomultiplier must be μ (121 nm) = $5*10^6$ or more, the typical ratio of noise ENI (121 nm) = $1*10^{-15}$ W, or less.

Fig. 1 shows a block diagram for measuring the light flow using the method of counting pulses.

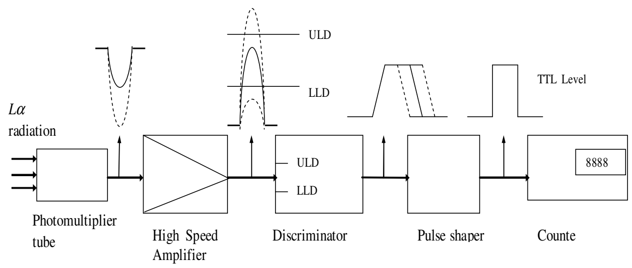

Fig.1 Block diagram for measurement of low light flux by the method of counting photons.

At the end of each block in Fig.1 its outcome signals are given. The signal from the PMT is amplified by an impulse amplifier. Thus the amplified impulse is fed to the Discriminator. The discriminator compares the input impulses with two bearing voltages and distributes them into two groups. One group of impulses is with lower amplitude than the bearing voltages and the other one - with higher amplitude. Impulses with lower amplitudes are eliminated by the lower reference level discriminator (LLD) and in most cases impulses with higher amplitudes are eliminated by the higher reference level discriminator (ULD). The impulses lower than the level (LLD) must be removed, because they were incurred as a result of noise. This noise arises from radioactive decay in the glass balloon, adventitious ions, cosmic rays, thermally generated electrons, and light from a crown discharge and electroluminance. The impulses higher than the level (ULD) must be removed for statistical reasons. The number of electrons in the anode impulse is random variable. It appears as a result of successive random events, which start from the grip of electrons from the first dynode and includes statistical fluctuations in the process of secondary multiplication. The largest contribution to this change of amplitude occurs on the first dynode. This problem is solved by maintaining exact voltage between the first dynode and the photocathode. Studies show that in well manufactured electronic photomultiplier only a fraction of the signal consists of impulses with amplitude 2 times greater than the average. These impulses should also be removed [2].

From the comparator located in the output of the discriminator emerge impulses level TTL. These signals are further converted by the impulse former into rectangular impulses that can be properly read by the meter.

PMT requirements for measuring weak light flows using the photon counting method.

Spectral response and quantum efficiency

PMT spectral response must be consistent with the maximum wavelength of the light beam in the case of 121.6 nm. Quantum efficiency should be as high as possible, especially for weaker signals. Moreover quantum efficiency should be high enough for corresponding wave of light, since its magnitude depends on the wavelength of the measured luminous flux.

The material used for manufacturing the window of the electronic photomultiplier

For wavelengths below 300 nm the spectral response is highly dependent on the material, from which the window of the electronic photomultiplier is made.

Sensitivity of the cathode emission

The sensitivity of the cathode emission influences the quantum efficiency according to the formula:

$$\text{QE} = \frac{S \times 1240}{\lambda} \qquad (3)$$

where:

S – sensitivity of the cathode emission [A / W]

λ - wavelength [nm]

Collection efficiency (CE)

CE represents the percentage probability with which one photoelectron emitted from the photocathode could successfully become a source of anode impulse through the multiplying process of the dynode system. Collection efficiency is expressed in percentage and is usually from 50% to 90%. This characteristic is very important when using the method of counting photons. As the magnitude is greater, this means less loss of signal. The collection efficiency depends on the form of the photocathode, the dynode structure and the distribution of voltage between the dynodes themselves.

Applied voltage and amplification of the electronic photomultiplier

The height of the impulse in the output of the electronic photomultiplier fluctuates with the applied voltage, even when the light flux is constant. This means that the coefficient of amplification of the electronic photomultiplier is a function of the applied voltage. The secondary emission coefficient is a function of the voltage E between the dynodes and is given as:

$$\delta = A \times E^{\alpha} \qquad (4)$$

where:

A is a constant

α is a value which is determined by the structure and material of the dynodes and usually has a value of 0.7 to 0.8.

If the number of dynodes is n, and δ is a constant measure for the coefficient of amplification we get:

$$\mu = \delta^{n} = (A \times E^{\alpha})^{n} = [A \times (\frac{V}{n+1})^{\alpha}]^{n} = \frac{A^{n} \times V^{\alpha n}}{(n+1)^{\alpha n}}$$

or (5)

$$\mu = K \times V^{\alpha n}$$

The typical PMT has from 9 to 12 diodes, so the alternation of the impulse height ranges from 6 to 10.

Taken into account that α changes from 0.7 to 0.8, we can calculate for 9 dynodes that the amendment will be 9 * 0.7 = 6.3 or the height of the impulse will be about the supply voltage to the 6th degree. For 12 dynodes respectively 12 * 0.8 = 9.6 or the height of the impulse will be about the supply voltage to the 10th degree. In other words, if the applied voltage changes by 5%, the height of the impulse will be changed as follows: from $(1.05)^{6}$ to $(1.05)^{10}$ or from 1.34 to 1.63. In percentages, this means from 34% to 63%.

Noise

In the electronic photomultiplier noises can appear, even when it is in complete darkness. They can be:

– *Thermal emissions from the materials from which are manufactures the dynodes and photocathode.*
– *Scintillation from the glass tube.*
- *Leakage.*
- *Voltage-dependent noise.*
- *External noise.*

These noises can affect the accuracy of counting photons, especially in cases when the signal is weak. Various measures can be taken in order to minimize these noises.

Selection of electronic photomultiplier (PMT)

As primary converter of light impulses, we choose a photomultiplier, R6835, manufactured by Hamamatsu Company. It is used for astronomical measurements of ultraviolet radiation. The electronic photomultiplier R6835 has the following basic characteristics:

- *Spectral Response from 115 to 200 nm,*
- *Maximum Response 140 nm,*
- *Quantum Efficiency at 121 nm 26%,*
- *Amplification $1 * 10^5$,*
- *Anode Dark Current 0.03 nA,*
- *Operating Temperature from -30 to + 50^o ,C*
- *High resistance to shocks, vibrations and accelerations.*

Selecting an amplifier

The amplifier C5594, production of Hamamatsu Company, was developed as the most appropriate device to amplify signals from an electronic photomultiplier, operating in photons counting mode. It is of a non inverting type, has amplification of 36 dB or 63 times, bandwidth i from 50 kHz to 1.5 GHz. These characteristics make it a high speed broadband amplifier, which allows it to reproduce accurately the form of the electronic impulses from the photomultiplier regardless of their high frequency.

Selecting a device for counting photons

The counting photons device S3866, manufactured by Hamamatsu Company is designed to convert single photon impulses from the electronic photomultiplier into 5 V amplitude impulses suitable for use with TTL logic. Its block diagram is shown in Fig. 2.

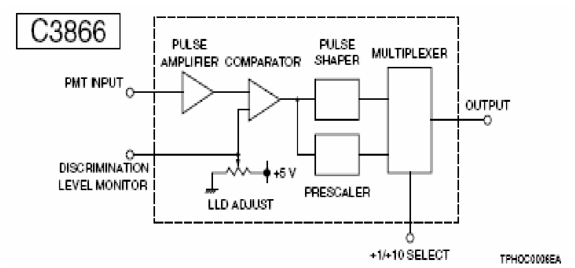

Fig.2. Device for counting photons.

The device itself has a built-in amplifier and discriminator circuits, impulse former and frequency divider. The output of the device for counting photons, which has a high ratio signal/noise, can be directly connected to a standard counter working with TTL logic. S3866 device is filled with high-speed electronic circuits, which enables it to measure with excellent output linearity the frequency of the impulse up to $1*10^7$ s^{-1}.

Power

High voltage supply

The device C4900-51, production of Hamamatsu Company, is a modular high voltage unit designed for powering electronic photomultipliers. The scheme of construction guarantees high stability and low power consumption. Power supply unit provides standard reliable security features.

Low voltage power supply

The instrument is supplied with 12 V, which source is the onboard battery. Its individual modules require low voltage power supply as follows:

Amplifier - +12 V / 95 mA
Counting device - +5.2 V / 150 mA and-5V / 300 mA
High voltage power supply - +12 V / 95 mA

For the acquisition of these supplies chips type DC/DC made by AIMTEC Company are used. They transform the voltage of 12 V into secondary voltage. AM3TW1207DZ and AM3TW1215DZ chips are chosen. The chips contain in their hull high frequency transformers with high isolation resistance, which untie the input and output voltage. The filtration of the supplied voltage must be especially precise, as the requirements of electronic modules in this regard are very high.

Calculating the electrical circuit of the instrument for measuring the Lα radiation.

The electrical circuit of the instrument is shown in Fig.3.

From the spectrum in the ultraviolet part of the geocorona, we know that at altitude of about 600-1000 km, the Lyman alpha line is very narrow, and furthermore, near it there are other spectral lines with comparable intensities. Therefore, Lyman-alpha radiation enters into the

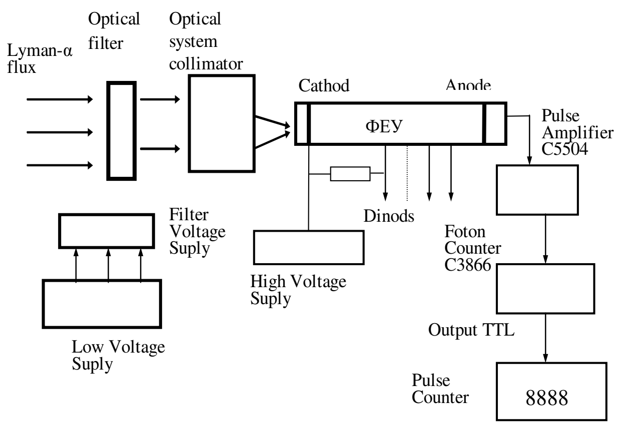

Fig.3.Electrical circuit of the device for measuring Lα

collimator through an optical interference filter with a bandwidth of about 10 nm (FWHM) centered approximately at 120 nm. The collimator is made of blackened aluminum with hexagonal cell material (foam), 2.54 centimeters in length and pitch of the cell 1.53 millimeters, setting off almost a cylindrical visual field. Then the Lyman-alpha radiation is detected by an electronic photomultiplier (PMT) and is amplified by an impulse amplifier [3].

The use of the amplifier is necessary because of the low output from the PMT. In formula (1), we noted that the expected output signal is 80 μA, with amplification factor of 10^6. The voltage supply chosen by us is 1250V and provides an amplification coefficient for the PMT of about 10^4. Then the expected output signal from the PMT will be IP = 0.8 μA.

Calculating the input and output voltages of the amplifier:

$$V_{in} = IP \times R_{in} = -0.8 \times 50 = -40[\mu V]$$

$$V_{out} = V_{out} \times K = -40 \times 63 = -2520[\mu V] = -2.52[mV]$$

where:

V_{in} - *Input voltage of the amplifier*
IP - *Output current of the PMT*
R_{in} - *Input resistance of the amplifier*
V_{out} - *Output voltage of the amplifier*
K - *Amplification coefficient of the amplifier*

The discriminator in the counting device works with levels of discrimination from -0,5 mV to -16 mV. The amplifier output voltage is -2.52 mV, and it is located exactly in the required range. The outcome from the photon counting device represents formed impulses with TTL level suitable as input to any standard meter.

The output frequency of the impulse from the counting devices is proportional to the intensity of the Lyman-alpha radiation and is determined by the meter of digital impulses.

In theory, the expected signal of Lyman-alpha intensity is a few thousand photons falling on the detector, not taking into account the absorption of the interference filter. For better filters that absorption is negligible. This value coincides with the range of counter pulses.

Summary

A modern device for satellite measurements of the scattered solar Lyman-alpha emission has been theoretically developed. A high quality PMT for the use in space instrumentation was chosen. The new equipment was designed on the base of this new sensitive sensor. It ensures the recording and amplification of signals with very small amplitude and processing in digital mode.

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