

ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL

**DESIGN OF A SI-PIN BASED GAMMA DETECTOR
USED FOR THE ASSESSMENT OF ENVIRONMENTAL RADIOACTIVITY**

M.Sc. THESIS

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Department of Physics Engineering

Physics Engineering Programme

JUNE 2024

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ LİSANSÜSTÜ EĞİTİM ENSTİTÜSÜ

**ÇEVRESEL RADYASYON SEVİYESİNİN ÖLÇÜMÜ
İÇİN KULLANILABİLECEK SI-PIN BAZLI BİR
GAMA DEDEKTÖRÜNÜN TASARIMI**

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Date of Submission : **24 May 2024**

Date of Defense : **24 June 2024**





Dedicated to those who never give up on their dreams



FOREWORD

I would like to express my respects and appreciations to my adviser Prof. Dr. Cenap Şahabettin ÖZBEN, who encouraged me to make the best of my thesis work. He has shared his knowledge and experience in every step when I encountered problems. I would also like to thank Dr. Mehmet Erhan Emirhan for his helps and guidance.

This work is partially supported by Tubitak 1001 project (121F215).

June 2024

Gökçen TATAROĞLU



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ABBREVIATIONS

UNSCEAR	: United Nations Scientific Committee on the Effects of Atomic Radiation
NCRP	: National Council on Radiation Protection and Measurement
PET	: Positron Emission Tomography
RBE	: Relative Biological Effectiveness
QF	: Quantity Factor
PIN	: P-Intrinsic-N
OPAMP	: Operational Amplifier
JFET	: Junction Field Effect Transistor
CSA	: Charge Sensitive Preamplifier
AC	: Alternative Current
SMD	: Surface-Mount Device
SNR	: Signal to Noise Ratio
MCA	: Multichannel Analyzer
DC	: Direct Current
Lion	: Lithium-ion
Wi-Fi	: Wireless Local Area Network
LoRaWAN	: Long Range Wide Area Network
IoT	: Internet of Things
SPI	: Serial Peripheral Interface
OLED	: Organic Light-Emitting Diode
I²c	: Inter-Integrated Circuit
SD Card	: Secure Digital Memory Card
SCK	: Serial Clock
MISO	: Master In Slave Out
MOSI	: Master Out Slave In
CS	: Chip Select
RTC	: Real Time Clock
LED	: Light-Emitting Diode
CSV	: Comma Separated Value
PCB	: Printed Circuit Board
FFT	: Fast Fourier Transform
DFT	: Discrete Fourier Transform
IDFT	: Inverse Discrete Fourier Transform



SYMBOLS

C	: Carbon
Na	: Sodium
K	: Potassium
Pb	: Lead
I	: Iodine
Tc	: Technetium
Co	: Cobalt
Ir	: Iridium
Cs	: Cesium
He	: Helium
α	: Alpha Particle
c	: Speed of Light
eV	: Electron-volt
u	: Standard Atomic Mass Unit
Ra	: Radium
Rn	: Radon
β	: Beta Particle
N	: Nitrogen
γ	: Gamma Particle
B	: Boron
Ci	: Curie (Unit of Activity)
Gy	: Gray (Absorbed Dose of Ionizing Radiation)
Sv	: Sievert (Equivalent Dose)
rad	: Absorbed Dose of Ionizing Radiation
Am	: Americium
U	: Uranium
Xe	: Xenon
Ba	: Barium
Pu	: Plutonium
Cm	: Curium
Bk	: Berkelium
Np	: Neptunium
Si	: Silicon
Hz	: Hertz
$^{\circ}\text{C}$	: Celcius



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DESIGN OF A SI-PIN BASED GAMMA DETECTOR USED FOR THE ASSESSMENT OF ENVIRONMENTAL RADIOACTIVITY

SUMMARY

Radiation, that individuals frequently experience in daily life, is classified into two types: ionizing and non-ionizing radiation. Non-ionizing radiation is a type of radiation that we are exposed to in daily life, such as radio waves (RF). This type of radiation does not harm the cell structure. On the contrary, ionizing radiation is a type of radiation that we are less likely to encounter in daily life, and it can cause destruction to our cells. One of the most common examples of these types of radiation is X-rays. Radiation can be exposed in two ways, internally or externally. The human body can be exposed to harmful ionizing radiation, such as inhaling dust or smoke containing radioactive materials, consuming liquids and food contaminated with radioactivity, as well as radon gas and medical sources used for treatment and diagnostic purposes. X-rays with energies ranging from 20keV to 300 keV are used in X-ray devices in hospitals. While the patient is exposed to X-rays, the technician moves to a room where he can protect himself from the radiation exposure. Since radiation workers are trained for possible dangers of the radiation exposure and the radiation protection methods. Radiation workers can keep the external radiation dose they are exposed under control with the help of their personal dosimeters in the institutions they work for. Given the fact that not everyone, like radiation workers, will be able to carry a personal dosimeter, the importance of constantly monitoring the level of spatial and environmental radiation is obvious. Nuclear power plants, research reactors, accelerators, isotope production, irradiation and sterilization facilities are places that must always be kept under control for safety. Examples in history have shown that radiation leaks can occur as a result of errors in these plants, releasing unacceptable amounts of radioactivity into the environment. In the face of such a situation, it is necessary to constantly monitor the level of ionizing radiation in certain areas in order to make the fastest intervention.

In this study, a gamma detector that can monitor both spatial and environmental radiation was designed and prototype production of this system was carried out. During the construction of this detector, its simplicity, low power consumption, ability to be built with readily available materials, ability to detect radiation with as low energies as possible, which is one of the requirements in the measurement of environmental radiation, and ability to operate in rural areas as self-sufficient in terms of power were highlighted. The device basically consists of a transmitting station where all the measurements are performed in the field and transmitted to the base-station and a receiver unit where the data is received and stored by the receiving station. The sender unit consists of ten main elements. These are microprocessor

(ATmega328P), solar panels, step up and down converters, power filtering circuitry, batteries, real time clock (RTC), atmospheric sensor, LoRa and a gamma detector. The step-up and step down converters are used for the power management. Since both step up and step down converters run in switching mode, the ripple noise is eliminated by the power filtering circuit to prevent the fake counts in the detector. The atmospheric sensor in the sender circuit is Bosch BME280. This sensor is capable of measuring humidity with an accuracy of $\pm 3\%$, barometric pressure with an absolute accuracy of ± 1 hPa, and temperature with an accuracy of $\pm 1.0^\circ\text{C}$. The collected data is combined with the date and time information received from a real-time clock module (RTC) and sent to the receiver station using a LoRa module. LoRa modules provide relatively long-range (3-5 km in open field) wireless communication, and they are used for the transferring and receiving the data between the two stations. The sender circuit is energized from rechargeable Lion batteries, and two solar panels of 5W each are used for charging the batteries in daytime. The data format of the sender circuit contains comma separated station number, data number, day, month, year, hour, minutes, seconds, temperature, humidity, pressure, battery voltage and gamma counts. The frequency of the data taking can be adjusted based on the desired statistics for the gamma counts.

The receiver station has mainly four components: AT-MEGA 2560 microprocessor module, OLED screen, SD card writer and LoRa module. The microprocessor is used in this part has larger memory compared to the one in the sender circuit for overcoming the memory problem and driving the OLED display. The OLED display provides real time data display for the user, and the data is stored to an SD card continuously in ASCII text format for later analysis.

The most important component of the project is the gamma detector. A BPW34 Si-PIN photodiode with a sensitive area of 7.5 mm^2 is used in the detector. Silicon PIN photodiodes are actually specialized semiconductors used for converting the visible photons into the electric current. Photodiodes are generally operated under reverse bias to increase their efficiency. In this operating mode, the width of the depletion-region is increased by keeping the P side of the photodiode at slightly more positive voltage than the one in N side. This procedure increases the photon absorption probability of the photodiode. The photon absorbed in the photodiode causes charge formation in the depletion region. With the reverse polarization voltage, these charges contribute to the net current. The current created by the gamma rays in the photodiode is quite small. Amplifying this current by separating it from the thermal noise is a challenge encountered especially in gamma detectors. Therefore, it is necessary to use a low-noise charge-sensitive amplifiers (CSA) in the first stage of the amplification. The CSA circuit used was taken from a work in a paper and some modifications were performed on the circuit. LT spice software was used for simulating the circuit. To receive a better noise performance from the circuit we use, BF862 N-channel field-effect transistor (JFET) with an equivalent noise input voltage of 0.8 nV/Hz . This contributed significantly to the reduction of noise. At the same time, the parasitic capacitance method was used for the feedback and the driver transistors were replaced with the low-noise BC560 transistors. In addition, the driver transistors are surrounded by two individual guard-rings. An OPAMP-based amplifying circuit is added to the output of the CSA circuit to filter, amplify and shape the resulting signal. The obtained

analog signal is passed through a comparator and the signals with an amplitude above a certain threshold value are digitized to be properly counted by the microprocessor. Test measurements show that the ^{241}Am gamma line of 59 keV can be successfully detected. There are some measurements and experiments were performed with the prototype device to test its limits and reproducibility of the measurements.





ÇEVRESEL RADYASYON SEVİYESİNİN ÖLÇÜMÜ İÇİN KULLANILABİLECEK SI-PIN BAZLI BİR GAMA DEDEKTÖRÜNÜN TASARIMI

ÖZET

Günlük hayatta sıkça karşılaştığımız radyasyon, temelde iyonlaştırıcı ve iyonlaştırıcı olmayan radyasyon olarak iki ana kategoriye ayrılmaktadır. İyonlaştırıcı olmayan radyasyon, radyo dalgaları (RF) gibi günlük hayatta maruz kaldığımız, hücre yapısına zarar vermeyen bir radyasyon türüdür. Öte yandan, iyonlaştırıcı radyasyon günlük hayatta karşılaşma ihtimalimizin daha az olduğu ama hücrelerimiz de yıkıma yol açabilecek bir radyasyon türüdür. İyonlaştırıcı radyasyona verilebilecek en yaygın örneklerden biri olarak X ışınlarıdır. Radyasyona içsel veya dışsal olarak iki şekilde maruz kalınabilir. Radyoaktif madde içeren bir toz veya dumanın solunması, radyoaktivite ile kontamine olmuş sıvıların ve yiyeceklerin tüketilmesi gibi örneklerin yanı sıra radon gazı ve tedavi ve teşhis amaçlı olarak kullanılan tıbbi kaynaklar ile insan vücudu iyonlaştırıcı zararlı radyasyona maruz kalabilir. Hastanelerde bulunan röntgen cihazlarında enerjileri 20 keV-300 keV aralığında değişen X ışınları kullanılmaktadır. Hasta X ışınlarına maruz kalırken teknisyen kendini radyasyondan koruyabileceği bir odaya geçer. Radyasyon çalışanları, radyasyonun zararları ve radyasyondan korunma yöntemleri konusunda eğitilmiş olduklarından dolayı, kendi kontrollerini kendileri yapabilmektedir. Radyasyon çalışanları çalıştıkları kurumlarda kişisel dozimetreler yardımıyla maruz kaldıkları dış radyasyon dozunu kontrol altında tutabilirler. Herkesin, radyasyon çalışanları gibi, kişisel dozimetre taşımasının mümkün olmayacağı gerçeği göz önüne alındığında, mekansal ve çevresel radyasyonun düzeyinin sürekli olarak takip edilmesinin önemi açıktır. Nükleer santraller, araştırma reaktörleri, hızlandırıcılar, izotop üretim, ışınlama ve sterilizasyon tesislerinin içerisi ve çevresi, güvenlik açısından her zaman kontrol altında tutulması gereken yerlerdir. Tarihteki örnekler, bu tesislerde yaşanabilecek kazalar sonucunda radyasyon sızıntılarının olabildiğini ve yüksek miktarda radyoaktivitenin doğaya salınabileceğini göstermiştir. Bu gibi durumların oluşması durumunda en hızlı müdahalenin yapılabilmesi için belirli bölgelerde iyonlaştırıcı radyasyonun seviyesinin dedektörler ile sürekli olarak takip edilmesi gerekmektedir.

Bu çalışmada, hem mekansal hem de çevresel radyasyonu monitöre edebilecek bir gama dedektörünün tasarımı yapılmış ve bu sistemin prototip üretimi gerçekleştirilmiştir. Bu dedektörün yapımı gerçekleştirilirken basit olması, düşük güç tüketimi, kolayca bulunabilen elemanlar ile yapılabilmesi, çevresel radyasyonun ölçümündeki gerekliliklerden biri olan mümkün olduğunca düşük enerjilere inebilmesi, güç bakımından kendine yeterli olarak kırsal alanda çalışabilmesi gibi özellikleri öne çıkarılmıştır. Cihaz temel olarak tüm ölçümleri sahada yaparak bu alınan ölçümleri merkeze ileten bir verici istasyon ve verilerin alınıp daha sonra incelenmesi için saklandığı bir alıcı ünitesinden oluşmaktadır. Verici istasyon 10 temel

elemandan oluşmaktadır. Bunlar mikroişlemci (ATmega328P), güneş panelleri, voltaj yükseltici ve düşürücü regülatörler, güç filtreleme devresi, piller, gerçek zamanlı saat (RTC), atmosferik sensör, LoRa ve gama dedektörüdür. Voltaj yükseltici ve düşürücü regülatörler güç yönetimi için kullanılmaktadır. Voltaj dönüştürücüler anahtarlama modunda çalışırken ortaya çıkan gürültü sayımların hatalı olmasına yol açmaktadır. Bu gürültünün sebep olduğu sahte sayımların engellenmesi için bir filtre devresi kullanılmaktadır. Verici devresinde Bosch BME280 atmosferik sensörü kullanılmaktadır. Bu sensör, nemi $\pm\%3$ doğrulukla, barometrik basıncı ± 1 hPa mutlak doğrulukla ve sıcaklığı $\pm 1,0^{\circ}\text{C}$ doğrulukla ölçebilir. Toplanan veriler, gerçek zamanlı saat modülünden (RTC) alınan tarih ve saat bilgileriyle birleştirilerek LoRa modülü kullanılarak alıcı istasyona gönderilir. İki istasyonun haberleşmesi için rölatif olarak uzun menzilli (açık sahada 3-5 km) kablosuz iletişim kurmayı sağlayan LoRa modülleri kullanılmıştır. Verici devre, şarj edilebilir Lion pillerden gücünü almaktadır ve pillerin gündüz şarj edilebilmesi için her biri 5W'lık iki adet güneş paneli kullanılmaktadır. Verici devre virgülle ayrılmış olarak istasyon numarası, veri numarası, gün, ay, yıl, saat, dakika, saniye, sıcaklık, nem, basınç, pil voltajı ve dedektörden gelen sayımları göndermektedir. Veri alma sıklığı, gama sayımları için istenen istatistiğe göre ayarlanabilir.

Alıcı istasyonunun temel olarak dört bileşeni vardır: AT-MEGA 2560 mikroişlemci modülü, OLED ekran, SD kart yazıcısı ve LoRa modülü. Bu kısımda hafıza problemini ortadan kaldırmak için daha büyük hafızaya sahip olan bir mikroişlemci kullanılmaktadır. Veri gerçek zamanlı olarak OLED ekranda gösterilir ve daha sonra bu verileri analiz etmek için ASCII metin formatında bir SD kartta saklanmaktadır.

Projenin en önemli bileşeni gama dedektörüdür. Dedektörde 7.5 mm^2 hassas alana sahip olan bir adet BPW34 Si-PIN fotodiyot kullanılmıştır. Silikon PIN fotodiyotlar aslında görünür bölge fotonlarını elektrik akımına dönüştürmek için kullanılan özel yarı iletkenlerdir. Foto diyotlar, verimlerinin artırılması için genelde ters kutuplama (reverse bias) altında çalıştırılmaktadır. Bu çalışma modunda, fotodiyotun P tarafı N tarafına nazaran daha pozitif bir gerilimde tutularak yükten arındırılmış bölgenin (depletion-region) genişliği büyütülür ve bu sayede foto diyotun foton soğurma kabiliyeti artırılır. Fotodiyot içerisinde soğurulan foton yük oluşumuna neden olur. Ters kutuplama gerilimi ile bu yükler akıma katkı sağlar. Gama ışınlarının fotodiyot içerisinde oluşturdukları akım oldukça küçüktür. Bu akımın, termal gürültülerden ayrılarak kuvvetlendirilmesi, bilhassa gama dedektörlerinde karşılaşılan en büyük zorluktur. Bu nedenle düşük gürültülü yüke hassas bir yükselticinin (CSA) kullanılması gerekmektedir. Kullanılan CSA devresi literatürdeki bir çalışmadan alınmış olup, devre üzerinde bazı modifikasyonlar yapılmıştır. Devrenin simülasyonları için LTspice yazılımı kullanılmıştır. 0.8 nV/Hz eşdeğer gürültü giriş voltajına sahip olan BF862 N kanallı eklem alan etkili transistör (JFET) kullanılması gürültünün azalmasına önemli katkıda bulunmuş, geri besleme için parazitik kapasitans yönteminden yararlanılmış, sürücü transistörler düşük gürültülü BC560 transistörleri ile değiştirilmiştir. Ayrıca sürücü transistörlerin kendileri bir zırh halkası (guard-ring) ile çevrelenmiştir. CSA devresinin arkasına oluşan sinyali filtrelemek, büyütme ve şekillendirmek için OPAMP temelli bir yükseltici katı eklenmiştir. Elde edilen analog sinyal bir komparatör üzerinden geçirilerek, genliği belli bir eşik değerinin üzerinde olan sinyaller dijitalize edilmiştir. Yapılan test ölçümleri,

59 keV'lik ^{241}Am gama çizgisinin başarıyla detekte edilebildiğini göstermektedir. Çalışma, prototip ile yapılan bir çok ölçüm ve deney sonucunu içermekte ve üretilen cihazın 40 keV üzerindeki enerjilerde rahatlıkla kullanılabileceğini göstermektedir.





1. INTRODUCTION

Since the very first moments of our existence, all living organisms have been exposed to different types of radiation. The sources of radiation can be categorized into two primary sections; natural and artificial radiation. Natural radiation is the radiation that exists spontaneously in the universe, in the world, that is not human made. Typically, individuals are subject to natural radiation from three main sources; cosmic, terrestrial, internal radiation. The earth is showered by radiation regularly from the outer space named as cosmic radiation. Primary radiation, mostly the energetic protons, enters the atmosphere. As the primary particles interact, the secondary particles generated from these interactions may decay into smaller particles. Depending on the energy and the entrance angles of the primary radiation, the distance of the interaction taking place to the surface of the earth are some of the important parameters for the cosmic rays we exposed on the surface of the earth. Therefore, the dose of cosmic radiation diverges in different places of the earth. In the research of UNSCEAR, the average annually effective dose is around 0,4 mSv as the elevation raise the radiation intake also increase. The people living in high elevations are indeed have higher effective dose than the average. Meanwhile, a plane trip may add some more dose, but it is not noticeable with compared to annual average. On the other hand, neutron and proton come along with cosmic radiation interact with other elements in earth and form some radioisotopes such as tritium, ^{14}C , ^{22}Na . These radioisotopes cause internal radiation exposure. The effect of these to annual effective dose are: tritium $0.01\mu\text{Sv}$, ^{14}C $12\mu\text{Sv}$, ^{22}Na $0.15\mu\text{Sv}$. The Earth contains radioactive elements in addition to the ones being created from the bombarded by radiation from outer space. These are the isotopes arise from the decay series of uranium, thorium, neptunium and actinium. Their decay products can be seen in everywhere. Human can digest these radioactive isotopes by drinking water, eating plant or inhaling the air. Likewise, the radiation intake diverges with the location, depending on the concentration of these isotopes in soil. Finally, to give an example to the internal radiation, all leaving organisms have ^{40}K , ^{14}C and ^{210}Pb

spring in their bodies considered as internal radiation sources. The average annual dose from these is about 40 millirems/year. This dose rate is not significant compared to the one received from the cosmic and terrestrial radiation.

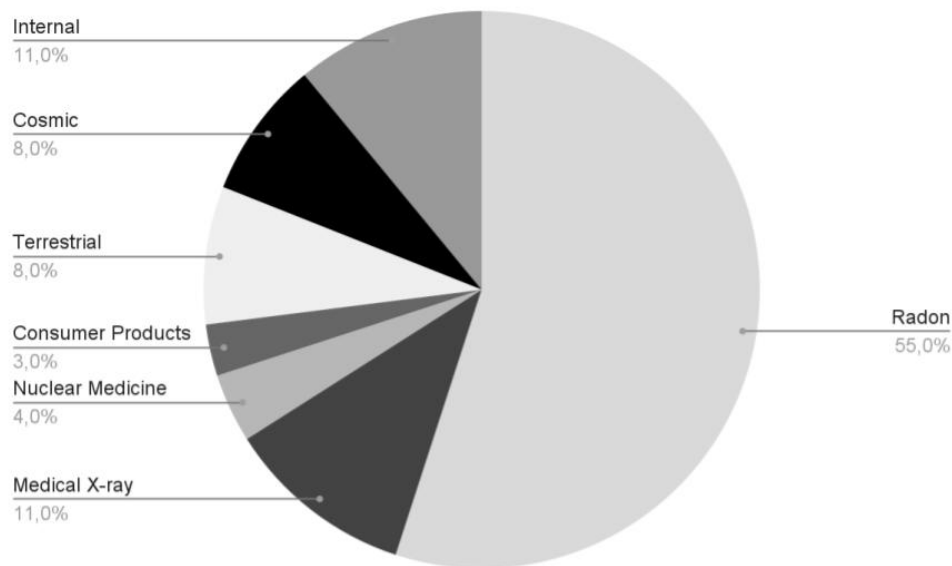


Figure 1.1 : Ionizing Radiation Exposure of the Population of the United States, 1987 [1].

The chart in Figure 1.1 shows the data taken from the National Council on Radiation Protection and Measurements (NCRP) Report No. 93, Ionizing Radiation Exposure of the Population of the United States, 1987 [1]. In the chart it can easily be seen that natural radiation sources dominates the average total dose of about 360 millirems/year. Although the majority of the radiation is due to the natural sources, there is also non-negligible amount of dose comes from the artificial radiation. There are assorted fields that the radiation is used as a tool. The most common applications are medicine, sterilization, diagnostic X-rays, nuclear medicine and radiation therapy. Some of the essential isotopes used for medical purposes are ^{131}I , $^{99}\text{Tc}^*$, ^{60}Co , ^{192}Ir , ^{137}Cs , and several. PET (Positron Emission Tomography) can be a specific example to the medical diagnostics. In this method, the radioactive substance is injected into the body along with a drug that will be absorbed in the organ that is interested in diagnostic purposes. The decay gamma rays emitted from the radioactive source absorbed by the organ are measured with the detectors. This will let the complete visual image of the organ interested in. Depending on the procedure, $^{99}\text{Tc}^*$, ^{137}Cs and ^{131}I isotopes are used.

In addition to the use in medicine, radionuclides are used in various applications from agriculture to material science. For example, in agriculture radionuclides are used for the control of the land slides, and they are also used for thickness determination of the paper production in the industry. Furthermore, ^{14}C is used for determining the age of fossils in archaeology. Additionally, phosphorescent watches, TV sets, X-ray security systems are some of the examples which can be multiplied.

Although the majority of the radiation on earth is originated from the natural sources, the misuse and mishandling of man made radioactivity can cause serious problems. One of the most well-known accidents occurred is the Chernobyl accident in 1986. In this accident the people working in the reactor died instantly while others living nearby became ill and died afterward. Likewise, in the Kyshtym disaster an improperly stored underground tank of high-level radioactive waste exploded. Also, Columbus and Houston radiotherapy accidents caused the death of many patients due to the misuse of nuclear medicine therapy. After all, despite all of its dangers, we use the radioactivity for the proposes that no known techniques can provide the same numerous advantages. However, it becomes apparent that the utilization of this technology requires stringent control measures and a significant level of caution.

Installing a radiation monitor in a risky field can provide an early warning for the abnormal radiation levels. If this monitor stores the data continuously, the algorithms for detecting anomalies can be implemented to the data analysis and for instance, the seasonal changes on the radiation levels can be modeled. Continuous monitoring would be much more useful for determining the dose the workers received compared to the one obtained from the periodical measurements. For that reason, we believe, the low-cost device we designed and produced will be quite handy since many of them can be installed and more reliable data can be collected to protect the population from the harms of the radioactivity.

1.1 Radioactivity and Radiation

Since the formation of the universe, the big bang, heavier elements have emerged, starting with Helium and Hydrogen. Most of the elements formed in this way are radioactive and have been decaying since the time they were formed. Only elements

with half-lives exceeding the age of the earth can be observed on the planet Earth. Radioactivity refers to the spontaneous emission of energy and subatomic particles resulting from the decay of an atomic nucleus. Radioactive decay can occur in a variety of forms, including neutron release, alpha and beta decay, all of which include particle release. The particle (or gamma ray in gamma decay) is the "radiation" linked to radioactivity. Radiation can be classified into two main groups according to the way the energy it carries interacts with the cell; ionizing and non-ionizing radiation. Non-ionizing radiation is a form of radiation that is commonly present in everyday environment. This type of radiation cannot cause ionization in atoms. Therefore, it does not cause cell damage. Light, radio waves and microwaves can be given as examples. Ionizing radiation, on the other hand, is considered harmful because it can detach electrons from the atom in its interaction with the cell. Examples are alpha (helium nucleus), beta (electron, positron), gamma (photon) and x-ray. The spontaneous release of radiation by elements such as uranium and thorium as they pass from unstable to stable is called radioactivity. While some of the unstable radioactive nuclei found in nature is called as natural radioactivity, the nuclei produced in the laboratory environment is called as artificial radioactivity. A radioactive nucleus undergoes decay in three ways; Alpha decay, beta decay and gamma decay. other direct particle releases may also occur, but it is rarely.

The emission of the alpha particle(${}^4_2He$), that is, the positively charged helium nucleus consisting of two protons and two neutrons, during decay is called alpha decay. As a result of the event, the number of protons of the nucleus decreases by 2, the number of neutrons decreases by 2, and the mass number decreases by 4.



In alpha decay, the element transforms into another element. In decay, relativistic energy and momentum must be conserved. We can calculate the energy by using the formula $Q = Mc^2$. Q is energy, m is mass, and c is the speed of light.

$$Q = (M_X - M'_X - M_\alpha)c^2 \quad (1.3)$$

For example, in the alpha decay of ^{226}Ra an energy of 4.87 MeV is produced. As a matter of conservation of momentum (assuming the main nucleus is at rest), the alpha particle is much less massive than ^{222}Rn , most of the energy released is that of the alpha particle.

$$\begin{aligned}
 Q &= (M_X - M'_X - M_\alpha)931,494\text{MeV}/u \\
 &= (226,025402u - 222,017571u - 4,002602u)931,494\text{MeV}/u \\
 &= (0,005229u)(931,494\text{MeV}/u) \\
 &= 4,87\text{MeV}
 \end{aligned} \tag{1.4}$$

However, since the alpha particle is heavier than the electron or photon and has a charge value of +2, it causes ionization due to coulomb interactions in the substance it penetrates, and it loses its energy before it can penetrate very deeply. For this reason, a piece of paper is enough to stop the alpha particle.

On the other hand, the emission of beta particle that either electron or positron is called beta decay. During beta decay, an electron with a charge of -1 or its antiparticle with a charge of +1, a positron, is emitted. During beta decay, the number of neutrons remains constant, but the atomic number and mass number change by 1. In the beta minus decay, the electron and electron antineutrino are emitted, so the number of protons increases by one. In beta plus decay, the opposite is true.

$${}^A_Z X_N \longrightarrow {}^A_{Z+1} X'_{N-1} + e^- + \bar{\nu}_e \quad \text{negative } \beta \text{ decay } (\beta^-) \tag{1.5}$$

$${}^A_Z X_N \longrightarrow {}^A_{Z-1} X'_{N+1} + e^+ + \nu_e \quad \text{positive } \beta \text{ decay } (\beta^+) \tag{1.6}$$

$${}^{14}_6 \text{C}_8 \longrightarrow {}^{14}_7 \text{N}_7 + e^- + \bar{\nu}_e \tag{1.7}$$

$${}^{14}_7 \text{N}_6 \longrightarrow {}^{14}_6 \text{C}_7 + e^+ + \nu_e \tag{1.8}$$

The electron released as a result of decay performs ionization due to coulomb interactions in the substance. On the other hand, as a result of its less mass compared to the alpha particle, it can go deeper into the matter but with the help of a thin aluminum plate, it is still possible to stop beta particles.

Lastly, If the radioactive nucleus is in an excited state after decaying, it emits photons with a second decay and goes into the ground state. The electron that replaces the

electron detached from one layer in the same atom emits photons as the energy between the layers, the same procedure is true here. The radioactive element, which passes from the excited state to the ground state, emits photons as much as the energy difference between them, and these photons are called gamma rays. Their energy is relatively high, and it is generally between 1 MeV and 6 MeV.

$$X^* \longrightarrow X + \gamma \quad (1.9)$$

$${}^{12}_5B \longrightarrow {}^{12}_6C^* + e^- + \bar{\nu}_e \quad (1.10)$$

$${}^{12}_6C^* \longrightarrow {}^{12}_6C + \gamma \quad (1.11)$$

A nucleus transforms from the excited energy state into another element by decaying into alpha and beta. The excess energy left in the daughter nuclei can be released, and stable nuclei can be obtained after gamma decay. Due to the high energy of the gamma rays, They penetrate much deeper into the matter, and they are more destructive and harmful compared to the alpha and beta particles if the source is out of the body. A lead plate can be used for stopping the gamma rays.

1.1.1 Activity

The activity of a radioactive source is proportional to the number of radioactive atoms present.

$$\text{Activity} = -\frac{dN}{dt} = \lambda N \quad (1.12)$$

λ is the disintegration constant and $\frac{dN}{dt}$ is the rate of change of number of atoms. The sign is minus because the number of nuclei **decreases** with time. After performing certain mathematical operations, Equation 1.13 can be derived. In this equation N_0 is number of radioactive atoms at time $t=0$.

$$N(t) = N_0 e^{-\lambda t} \quad (1.13)$$

By multiplying Equation 1.13 with the scalar λ , one can derive an expression for activity, where λN represents the measure of activity.

$$A(t) = A_0 e^{-\lambda t} \quad (1.14)$$

In Equation 1.14, A refers the activity at time t and A_0 refers the activity at time $t=0$. The unit for activity is Curie ($1Ci = 3.7 \times 10^{10}$ dis/sec). It is the activity of 1gr radium.

1.1.2 Half-life

The half-life is the amount of time it takes for half of the atoms in a radioactive source to undergo transformation. If A is half of the initial ($A = A_0/2$) for mentioned value, and it is substituted into Equation 1.14.

$$\frac{A(t)}{A_0} = \frac{1}{2} = e^{-\lambda T_{1/2}} \quad (1.15)$$

After some mathematical exercise, the half-life equation can be derived by isolating the variable $T_{1/2}$.

$$T_{1/2} = \frac{\ln 2}{\lambda} \quad (1.16)$$

λ is disintegration constant has unit of reciprocal time (s^{-1}, min^{-1}, h^{-1}). In calculations one generally use the value of half life instead of λ which is not a common quantity. One should notice that the nature of radioactive transformation is exponential.

1.1.3 Radiation doses

Radiation dosimetry is the quantitative description of the effect of radiation on living tissue. The absorbed dose of radiation is defined as the energy delivered to the tissue per unit mass. The SI unit of absorbed dose, the joule per kilogram, is called gray(Gy), another unit is the rad.

$$1rad = 0.01J/Kg = 0.01Gy \quad (1.17)$$

Absorbed dose by itself is not an adequate measure of biological effect because equal energies of different kinds of radiation cause different extents of biological effect. This variation is described by a numerical factor called the relative biological effectiveness (RBE) also called the quantity factor (QF), of each specific radiation. X-rays with 200 keV of energy are defined to have an RBE of unity, and the effects of other radiations can be compared experimentally. In Table 1.1, some approximate values of RBE are shown.

All these values depend somewhat on the kind of tissue in which the radiation is absorbed and the energy of the radiation. The biological effect is described by the product of the observed dose and RBE of radiation; this quantity is called biologically equivalent dose, or simply equivalent dose. The SI unit of equivalent dose for human

Table 1.1 : RBE for Several Types of Radiation.

Radiation	RBE (Sv/Gy or REM/RAD)
X and γ rays	1
Electrons	1.0-1.5
Slow neutrons	3-5
Protons	10
α particles	20

is the Sievert (Sv).

$$\text{Equivalent Dose (Sv)} = \text{RBE} \times \text{Absorbed Dose (Gy)} \quad (1.18)$$

A more common unit, corresponding to the rad, is the rem.

$$\text{Equivalent Dose (REM)} = \text{RBE} \times \text{Absorbed Dose (RAD)} \quad (1.19)$$

1.1.4 Some radioactive sources used for tests

There are many radioactive isotopes (sources) used in the fields. We use some standard sources to test our equipment. The activities of these sources are known, and mostly they are used for detector calibration. The two of them are especially important for us. They are ^{241}Am and ^{137}Cs .

1.1.4.1 Cesium 137

It was discovered in 1941 by Margaret Melhase and Glenn T. Seaborg. Cesium is formed as the fission product of nuclear fission of ^{235}U . ^{137}Cs has 55 protons and 82 neutrons. Its half life is 30 years. The parent isotope is ^{137}Xe , and it decays to $^{137}\text{Ba}^*$, ^{137}Ba . $^{137}\text{Ba}^*$ has half life of 153 second and so decays to ^{137}Ba at that moment they emit gamma rays with 0.662 MeV energy. The decay scheme of ^{137}Cs is shown in Figure 1.2.

The 662 keV gamma is actually produced by $^{137}\text{Ba}^*$, the decay product of ^{137}Cs , which is in secular equilibrium with ^{137}Cs . ^{137}Cs is used in various industry; to calibrate detectors, radiation therapy, radiography.

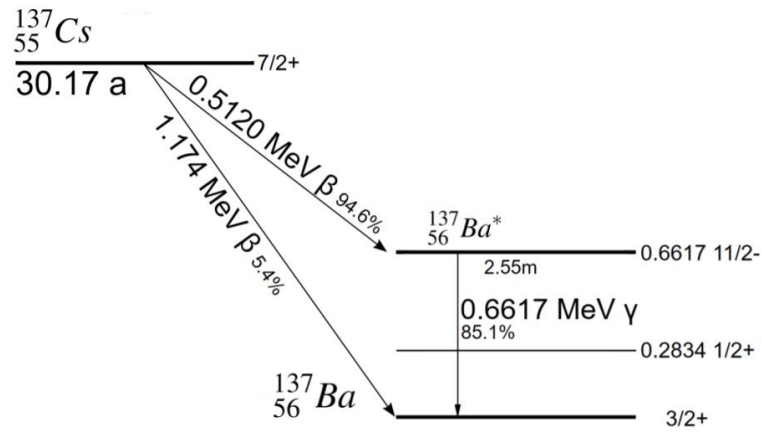


Figure 1.2 : Decay Scheme of ^{137}Cs [2].

1.1.4.2 Americium 241

^{241}Am is a synthetic radioactive product. It is produced by beta decay of ^{241}Pu . ^{241}Am has 95 proton and 146 neutrons. Its half-life is 432.6 year. Its parent isotopes are $^{241}\text{Pu}(\beta^-)$, $^{241}\text{Cm}(\text{EC})$, $^{245}\text{Bk}(\alpha)$ and decay product is ^{237}Np .

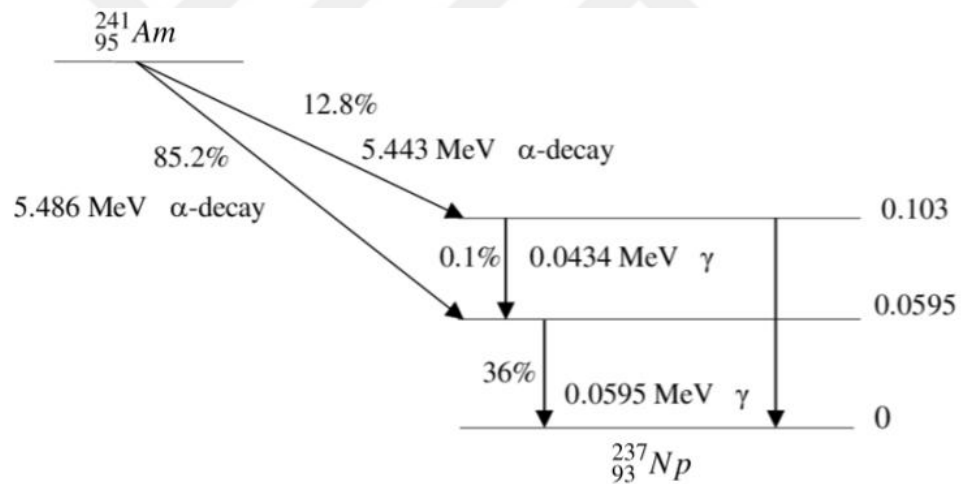


Figure 1.3 : Decay Scheme of ^{241}Am [3].

In Figure 1.3 the decay scheme of ^{241}Am is shown. The gamma ray emitted with 0.0595 MeV energy has emission probability of 36% per single decay. ^{241}Am is commonly used in smoke detectors, neutron sources and medicine for medical applications.

1.2 Literature Review

When a light hit a material, it interacts with the surface particles the evidence of that interaction goes through a process in brain and eyes, resulting that material can be seen. In the absence of any effect or if there is a problem with the eye, material may not be able to seen. Similar process can be seen in the detector systems. Nevertheless, particles are not directly observable in most cases; instead, an intermediary element that interacts with the material is used and a specialized apparatus that transforms this interaction into a detectable signal. There are various types of detectors. Since each particle has different charge, mass etc..., their interaction with the detector medium changes. This results the detection methods differ from each other for different types of radiation. The particle detectors are designed depending on which particle is detected and what kind of property need to be observed.

In the scope of this project, a gamma radiation aimed to be measured so that Si-PIN photodiode used as an active element to detect particles. The PIN photodiode was invented by Jun-Ichi Nishizawa and his colleagues in 1950. It is a semiconductor device. In regular diodes, there are P and N regions. P region known as positive it has holes as charge carrier and N side, negative, has electron charge carriers. In addition to P and N regions, PIN photodiode has an intrinsic region. Biasing the photodiode expands the depletion region. Wider intrinsic region helps to convert more photons to current. The Figure 1.4 shows the diagram of PIN photodiode. Typically, the intrinsic area is composed of semiconductors like silicon or germanium that are either weakly doped or undoped. When exposed to photons, the intrinsic layer absorbs light and generates electron-hole pairs. The intrinsic layer creates a depletion region between the P-type and N-type layers. The width of the depletion region is determined by the applied reverse bias voltage across the photodiode. PIN photodiode typically operated in reverse bias voltage, which means P side connected to negative and N side connected to positive voltage. Reverse bias voltage helps the depletion region extent stem from that photodiode light absorption capability increases. When PIN photodiode is reverse biased, an electrical field is created which causes electrons go through the N sides and holes go through the P side, The separated electrons and holes contribute to the flow of current in the external circuit connected to the PIN photodiode, resulting in

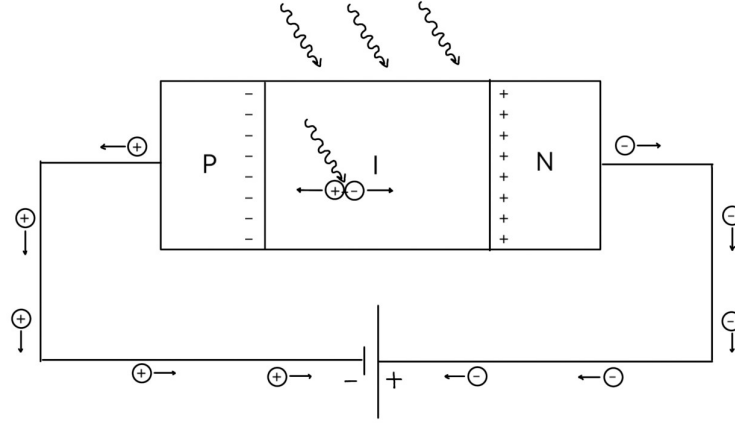


Figure 1.4 : Diagram of Si-PIN Photodiode.

a photocurrent. The photocurrent is proportional to the incident light intensity, the efficiency of the absorption and the charge separation processes. There are various types of PIN photodiodes. Both of their surface areas and the materials they are composed of vary. Depending on the needs of the project, the proper PIN photodiode should be selected. The BPW34 silicon PIN photodiode was chosen for this research because of its affordable price and simplicity of its use.

As explained, Si-PIN photodiodes generate a current in response to the radiation and this current needs to be converted into the voltage. A charge sensitive preamplifier can convert that current to the voltage. With the intention of designing a low noise preamplifier, the components must be chosen carefully. Additionally, the design of the printed circuit board plays an important role. For this reason, research has been carried out for a simple and low-noise design. The CSA designs, using OPAMPs, are found to be not as efficient enough as we desired for. Furthermore, very low noise OPAMPs are pricy and not easy to find in local markets. Hence, a JFET based design is chosen. After a literature review, some circuits found to be having similar aspects. The basic layout, shown in Figure 1.5, consists of a protection circuit at the input, a charge amplifier and a shaper followed by a non-inverting linear amplifier [4]. This circuit is for (large area) high-capacitance silicon detectors. The key point in this circuit is four BF862 loops are used to achieve better performance. Another circuit design is given in the Figure 1.6 this CSA circuit operates without a feedback resistor to enhance signal-to-noise ratio. Also, the JFET at the input is biased by its gate leakage current, which forward

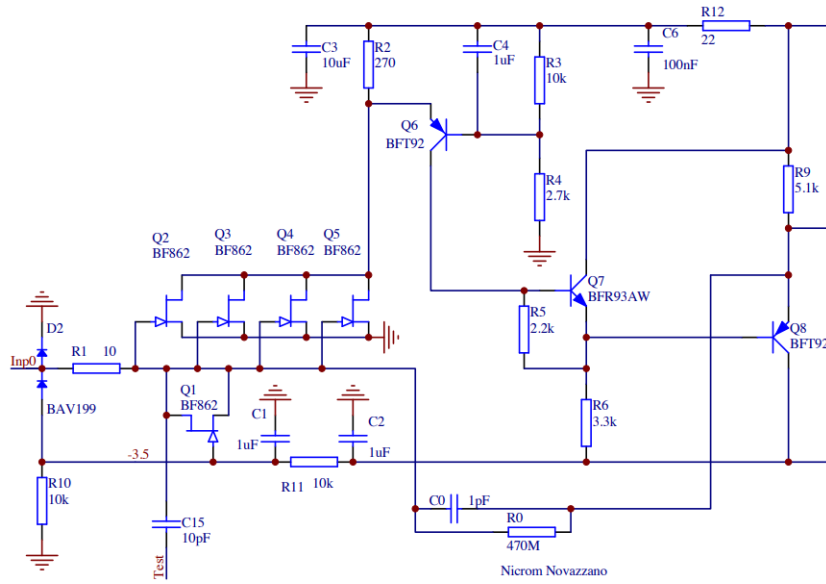


Figure 1.5 : A circuit Used in The Work [4].

biases the gate channel junction. For the use of feedback capacitor, a tiny wire placed approximately 1 mm away from the Photodiode. Next, in Figure 1.7 another circuit

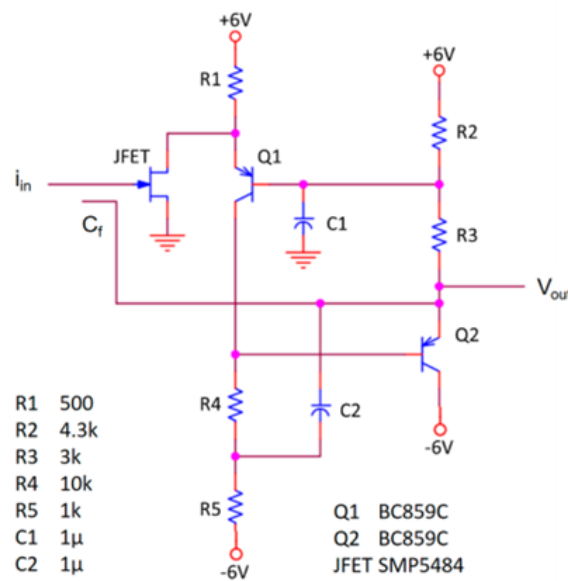


Figure 1.6 : The Charge Sensitive Preamplifier Used as a Fundamental Circuit in Our Work [5].

with similar structure is shown. The purpose of that research is to examine various types of circuit board substrates. There are two CSA designs seen in the figure. PA2 design is different from PA1 in the analog amplifier and the buffer sections in an attempt to increase the sensitivity while preserving the low noise characteristics [6].

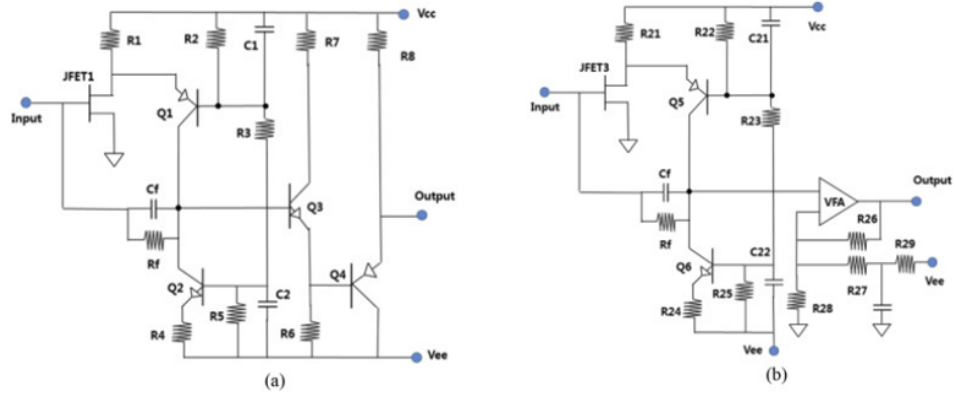


Figure 1.7 : Development of CSA Based on Various Circuit Board Substrates and Evaluation of Radiation Hardness Characteristics [6].

Noise is any electrical signal present in a circuit other than the desired signal. Filter circuits are used to distinguish the desired signal from the other signal sources. For this reason, filters have always been one of the important parts of the circuits. Today, it is used in most of the electronics. There are many types of filters designed for different purposes. Only a detailed description of the circuit in the subject of this project will be given. Filters can be broadly categorized into two main types: passive filters and active filters. Passive filters consist of passive circuit elements such as R (Resistor), L (Coil) and C (Capacitor). If a circuit also contains active elements such as transistors or OPAMPs, it is called an active filter. There are typically four types of filters, either passive or active; low-pass filter, high-pass filter, band-pass filter, band-stop filter. The low-pass filter transmits the low frequencies and stops high frequencies above a cutoff frequency. The high-pass filter transmits the high frequencies and stops the low frequencies. A band-pass circuit passes frequencies in a certain range while stopping the rest. The band-stopping filter passes frequencies outside a certain range, blocking the region that is in range.

In the Figure 1.8 an example active high pass filter is given. These filters allow the frequencies to pass above the cutoff frequency determined by the resistor and the capacitor. The cutoff frequency can be calculated using the Equation 1.20.

$$f_{cutoff} = \frac{1}{2\pi RC} \quad (1.20)$$

The capacitor is $0.003 \mu\text{F}$ and the resistor is $18 \text{ k}\Omega$ from that the cutoff frequency is calculated as 2.95 kHz .

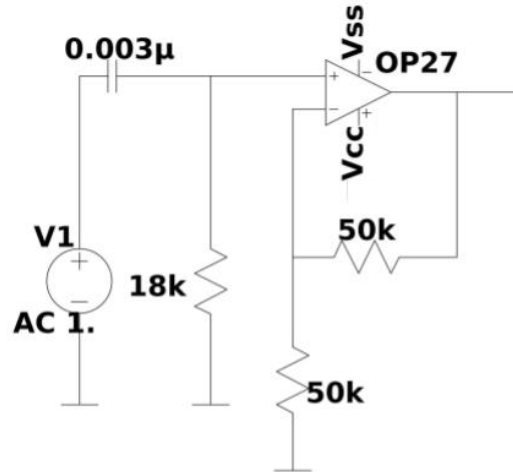


Figure 1.8 : High Pass Filter Circuit

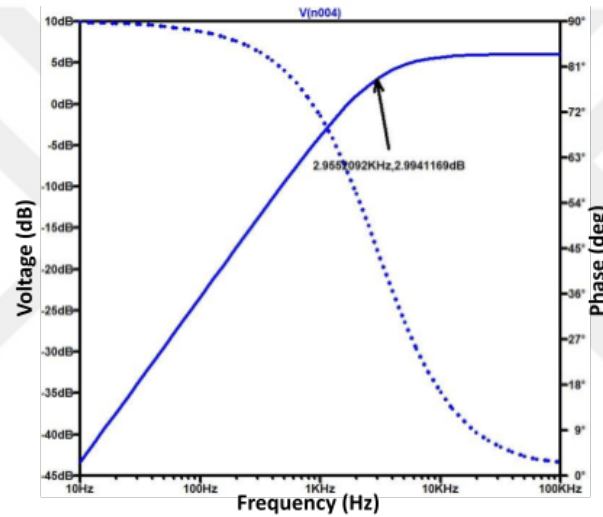


Figure 1.9 : High Pass Filter Circuit Graph

The Figure 1.9 shows the result obtained from the spice simulation. AC sweep setup is 10 points per decade and frequency sweep is from 10 Hz to 100 kHz. It can be seen from the graph that the cutoff frequency is 2.9 kHz which is coherent with the result obtained from the calculation.

Figure 1.10 shows the circuit schematic of the low pass active circuit. In this filter, only frequencies up to the cutoff frequency determined by the resistor and the capacitor are allowed to pass. Cutoff frequency can be calculated using the Equation 1.20, $f_{cutoff} = (1/2\pi 10k\Omega 0.1\mu F) = 159$ Hz.

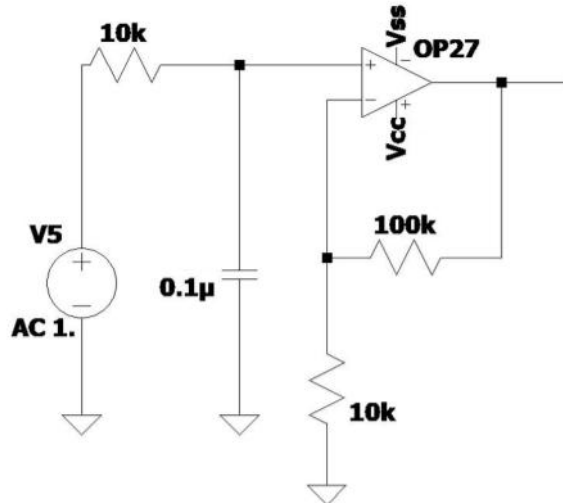


Figure 1.10 : Low Pass Filter Circuit

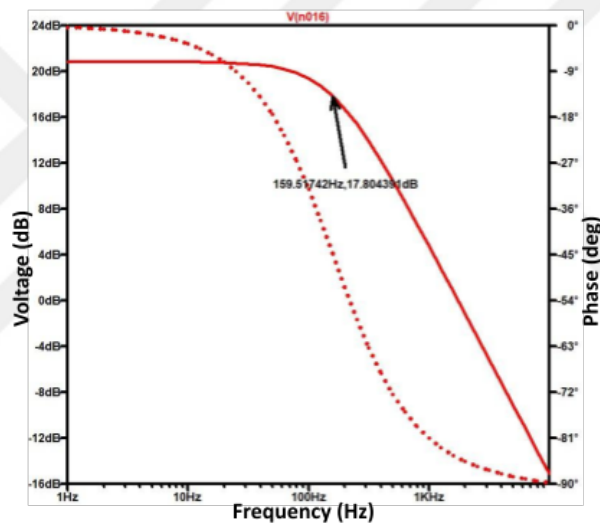


Figure 1.11 : Low Pass Filter Circuit Graph

The Figure shows the analysis result of the low pass filter using spice. AC sweep setup is 10 points per decade and changed from 1 Hz to 10 kHz. From the graph, it can be seen that the cutoff frequency is 159.5 Hz, same as the calculation.



2. INSTRUMENTATION OF GAMMA DETECTOR

When developing a radiation detector, it is crucial to make a design with low noise and high efficiency. The circuit diagram in Figure 2.1 shows the block diagram of the detector designed for this work. The first element of the detector is the sensor, the photodiode. It is in charge of converting the energy of the particles passing through to a tiny current. The next section is known as the charge sensitive preamplifier, where it is essential to convert the current from the photodiode into a corresponding voltage signal. After acquiring the voltage output, a shaping amplifier is required for filtering, integrating and simply amplifying the signal. Another circuit was included to convert analog signals into digital signals above a certain threshold level for counting purposes. An integrated digital sensor group was also included into the data stream for atmospheric parameters. A microprocessor is used for collecting, displaying and storing the data.

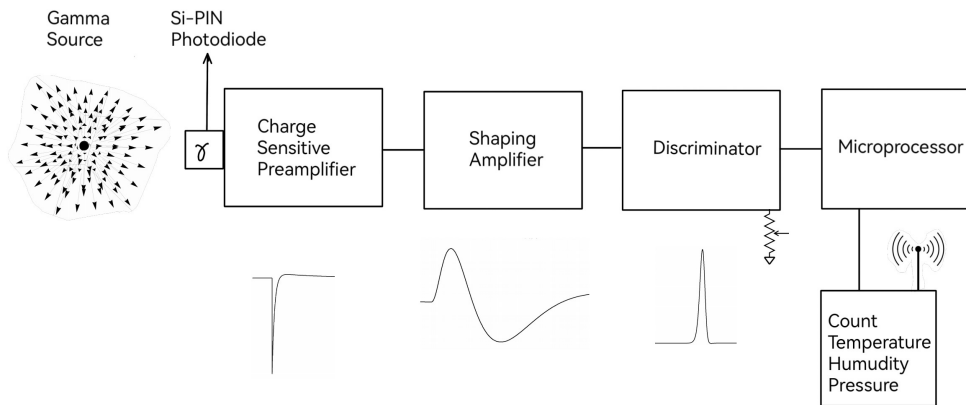


Figure 2.1 : Detector Circuit Steps Diagram

The aims were to build this structure with the simplest way using on-shelf components and keeping the cost as low as possible. An extremely low cost, relatively large area BPW34 [7] Silicon PIN Photodiode is used in our detector. It has 5.4 mm length, 4.3 mm width and 3.2 mm height providing 7.5 mm² radiant sensitive area. The initial design, which operated with a single photodiode, demonstrated commendable

efficiency. The signals from gamma sources were successfully detected for multiple photodiodes connected in series to enhance the detection area. Subsequently, a decision was made to explore the utilization of multiple photodiodes for future examination. Silicon photodiodes are converting the light energy to electrical current, therefore output current is directly proportional to the energy of light (radiation in our case) falling on their surface. They can be connected to each other in parallel or series. Using multiple photodiodes have numerous advantages and few disadvantageous. In case of back to back connection, one increases the effective thickness of the silicon, which leads to have increasing probability to stop the photons resulting in the full energy deposition. This will be useful for the spectroscopic measurements. However, connecting the photodiodes in parallel increases the total capacitance, which is not a desired situation for the noise. In series connection, the capacitance decreases. However, if the photon interacts only with one of the photodiodes in the array, the current generated in should pass through all the photodiodes connected in series.

By connecting photodiodes in series, a higher current output can be achieved. However, this setup may also lead to an increase in dark current. In the series connection case, the opposite is true. The flow of electric current occurs from one photodiode to another, resulting in an increased voltage output. However, if even a single photodiode is damaged, the entire system becomes inoperable. On the other hand, the noise will be sum of the individual photodiode noise, resulting more noise in the output. The best can be done is to connect the photodiodes in groups of parallel and series to increase both the thickness and the area. However, the trade-off issues between the efficiency and signal quality should be deeply investigated to find the optimum. Consequently, the single photodiode setup is chosen for our detector development.

2.1 Charge Sensitive Preamplifier

After a detailed research and examination, the circuit in Figure 1.6 was chosen as the base of our preamplifier circuit. Multiple experiments have been conducted to choose the best components in the circuit. We started with the JFET, the most crucial part of the CSA. The original work uses SMP5484 as JFET. Two different JFETs, the BF245

and the BF862, were considered as potential replacements for the SMP5484 and these were tested during the evaluations. Some measurements took place from the bulk BF245 to determine the one with the lowest noise. Before physically building the circuit, the simulations using Lt spice software took place. These simulations helped us to understand the operation of the circuit. In order to replicate the output of the Si-PIN photodiode, the circuit is fed with a pulse of 1 mV amplitude and 10 ns duration as shown in Figure 2.2. The response of the charge sensitive preamplifier circuit is

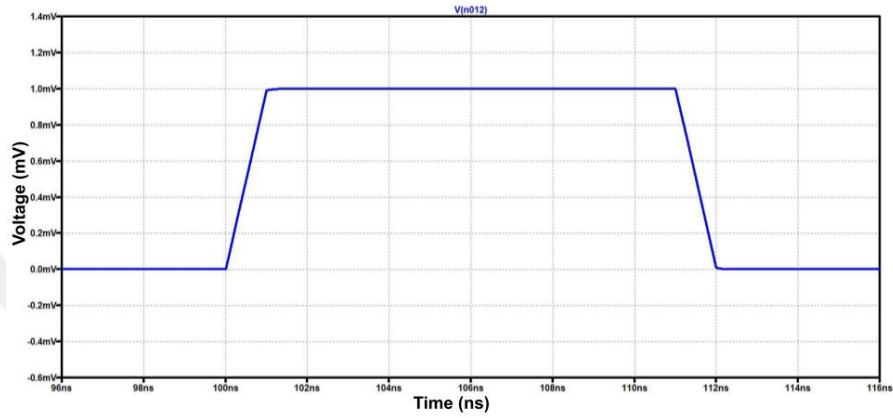


Figure 2.2 : Si-PIN Photodiode Output Signal Used in the Simulation

given in the Figure 2.3. The x-axis is time duration of the simulation and the y-axis shows voltage output. The peak to peak voltage is 3 mV and the width of the signal is almost $1.7\mu s$. The BF862 JFET was also tested in the same experiment, being

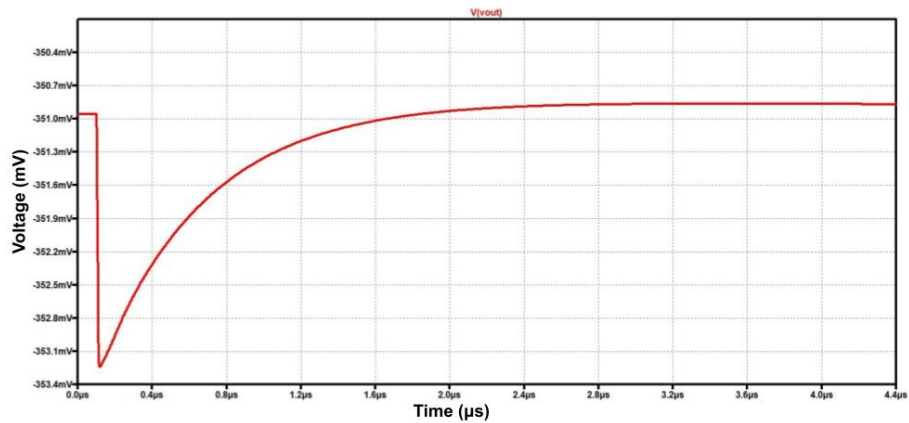


Figure 2.3 : CSA Simulation with BF245

in surface-mount device (SMD) form with an equivalent noise input voltage of $0.8 \text{ nV}/\sqrt{\text{Hz}}$. The Figure 2.4 shows the simulation result. The peak to peak voltage of

the signal is approximately 35 mV and the width of the signal is about $2.9\mu\text{s}$. The results suggest that the BF862 was a better option for the use in the CSA circuit. The experimental measurements also proved the same.

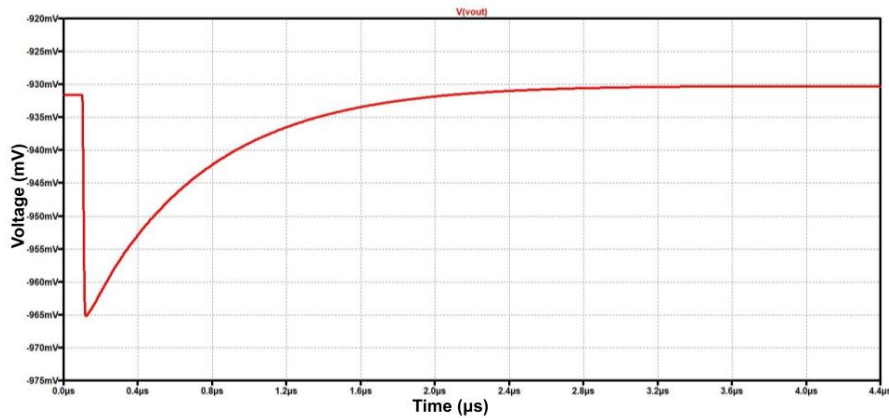


Figure 2.4 : CSA Simulation with BF862

After the simulations, the CSA circuit is constructed and the Figure 2.5 shows the real signal output of the CSA obtained from the oscilloscope. The vertical scale is 50 mV and the horizontal scale is 0.5 ms of the oscilloscope. ^{137}Cs is used as gamma source while testing the circuit.

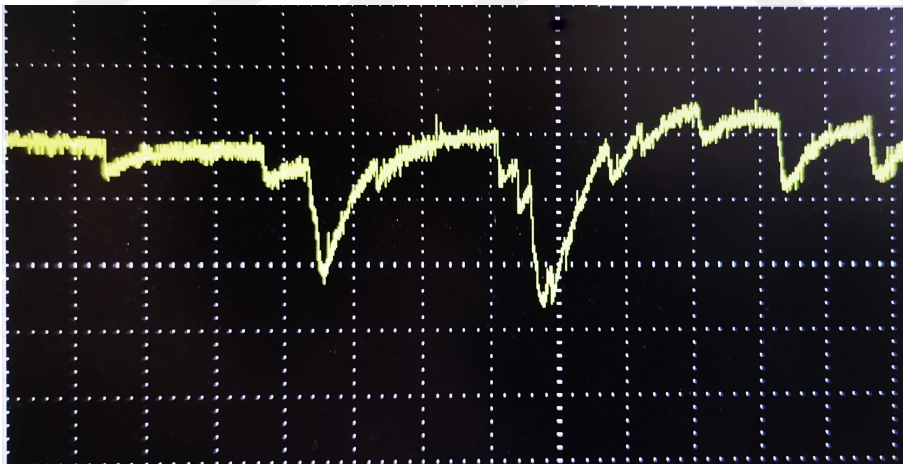


Figure 2.5 : CSA Output from ^{137}Cs Gamma Source

2.2 Signal Processing

The signal acquired by successfully converting the current from the photodiode into voltage need to be modified. The shaping amplifier circuit is designed to amplify the

MCA measurements. Two resistors are connected to the positive input of the buffer stage. This significantly improves the DC stability. Similar technique is applied for the other OPAMP used as a comparator with hysteresis in the following stage. If the signal is above a certain threshold, set by the 22 kohm potentiometer, the OPAMP generates a negative pulse and the pulse stretcher changes the sign of the pulse and extends the time duration of it to 30 μ s. The threshold was set above the noise level where 59 keV gamma line of ^{241}Am can be still observable.

2.3 Power Circuit

The detectors are planned to be operated in the open field in the vicinity of power outlet. Solar panels provide clean energy and they can easily charge the batteries with the proper power circuitry. The Figure 2.8 shows the battery charging circuit diagram. Two separate solar panels were used to charge the batteries and two independent charging circuits were made. The voltage from the solar panels are first dropped to 4V for charging the Lion batteries. During the operation, 3.7 V from the batteries are stepped up to 5V for powering the electronics.

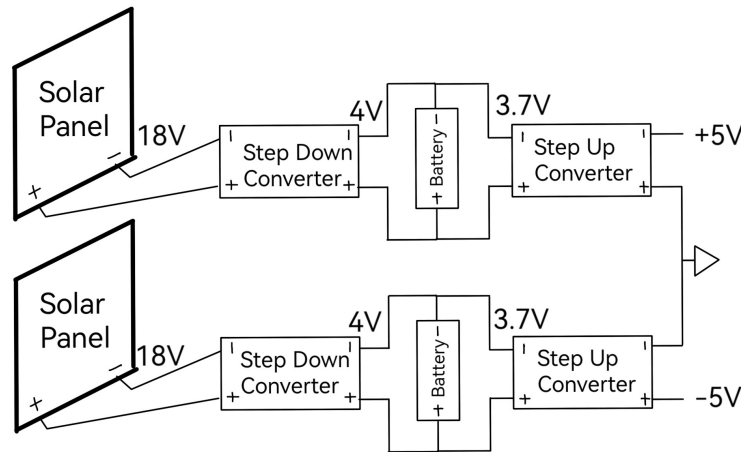


Figure 2.8 : Battery Charging Circuit Diagram

At this stage, in order to keep the design as low noise as possible, a conservative power filter circuit has been added after the step-up converter which runs in switching mode and noisy. The diagram of the filter circuit is given in Figure 2.9.

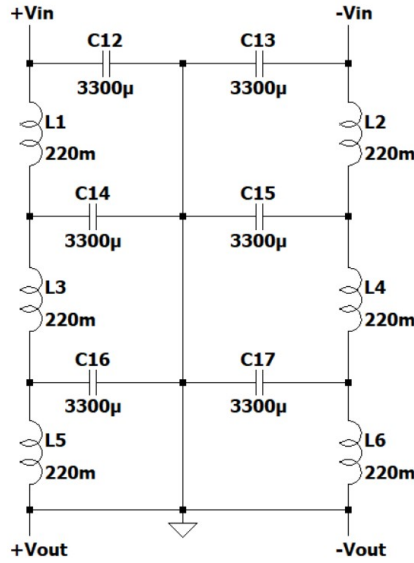


Figure 2.9 : Schematics of Power Supply Filter

2.4 Remote Communication

Measured activity of the environmental radiation in the field should be sending properly to the base station. In this case, there are many methods that can provide wireless communication. Bluetooth, Wi-Fi, LoRa, satellite communication can be given as examples. Each technology has its own advantages and disadvantages. The requirements and the scope of the project lead the choice of LoRa. LoRa stands for long range. It is a low power device and provides wireless communication over long ranges. Due to the fact that the distance between the stations is not more than few km, the LoRa communication method has been a convenient choice. The LoRa module uses Semtech chips and enables IoT devices to communicate with the Lora WAN network. The data transmission is suitable for the data packets that are resistant to corruption over long distances and have low bit rates. Its frequency can be changed between 433 MHz and 915 MHz. In this work, the frequency was set to 500 MHz. LoRa module also uses the SPI (Serial Peripheral Interface) interface. In the SPI protocol, communication is fast and bidirectional.

2.4.1 Receiver station

The main purpose of the receiving circuit is to receive the data from the transmitter circuit accurately and complete. In the Figure 2.10 schematic of the receiver is given. Control processes are made with the ATmega2560 chip. The incoming data is taken

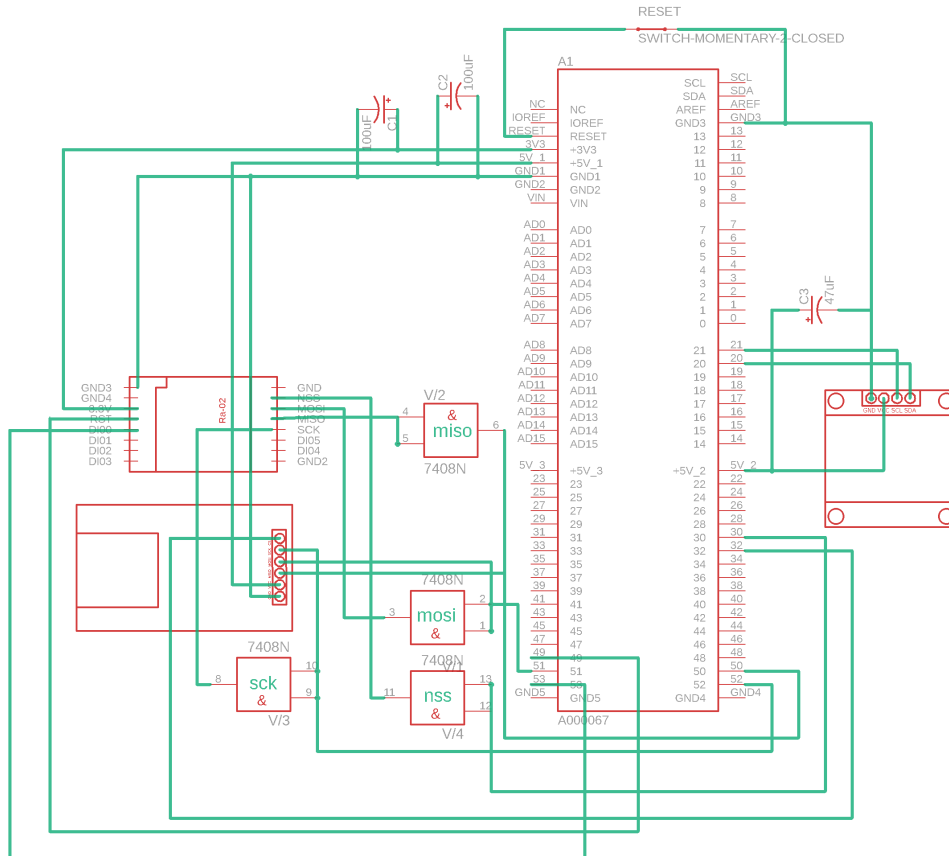


Figure 2.10 : The Schematic of the Receiver Circuit

in by the receiver circuit along with the LoRa module. This data is displayed on the OLED screen as soon as it arrives. The display uses the I²c protocol. There are no other elements using the I²c in the circuit. An SD card module is used for saving the data. The SD card module provides communication using the SPI protocol. The LoRa module uses the SPI interface and the communication between the master and slave SPI devices is shown in Figure 2.11. SCK is the clock signal, and it helps all modules work in synchronized. MOSI (Master Out Slave In) signal let the master send the data to the slave device. The master receives the data from the slave with MISO (Master in Slave Out). The CS (Chip Select) enables slave device communicating with the master. If the

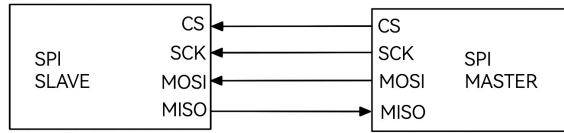


Figure 2.11 : Serial Peripheral Interface Data Communication Between Master and Slave SPI Devices

slave pin is LOW, the master and the slave device can communicate with each other. If they are HIGH, they do not communicate. In the receiver station there are two SPI modules which are LoRa and SD card. In this circuit, ATmega2560 microcontroller is the master. LoRa and SD card module are two independent slaves. The connection diagram of the multiple slave device to the master is given in the Figure 2.12 In the

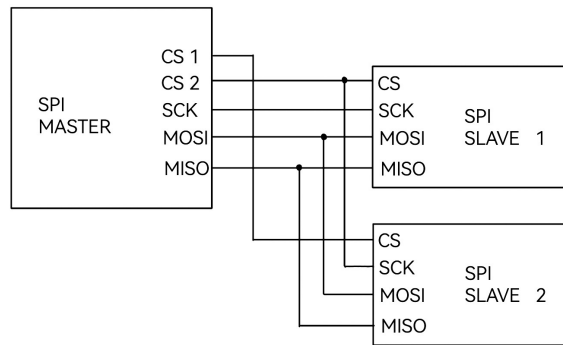


Figure 2.12 : The Connection Diagram of Multiple Slave Device to Master

connection of multiple SPI devices, three of the SPI lines are connected together. The clock of each slave must connect together to the master clock. Therefore, two slaves and masters can work in sync. MOSI and MISO must be connected together with the master. Lastly, the CS slave select pin also called chip select pin must be connected separately. In principle, two slaves can not communicate at the same time, and they should communicate one by one. Consequently, if there are two or more slave devices, only the slave device communication with master is kept LOW, and all others are HIGH to terminate the communication. This basic system did not work with the SD card module and LoRa module together in the first trials. Only one of them worked at a time. Later on, some modifications took place in the SD card module. The problem here is the chip does not turn off the MISO line when SD not in use. Because of this, the other SPI device can't work at that moment. The chip's link to the MISO must

be cut in order to resolve this issue. After that modification two modules work at the same time but lots of corrupt data occurred. The modified SD card is shown in the Figure2.13.

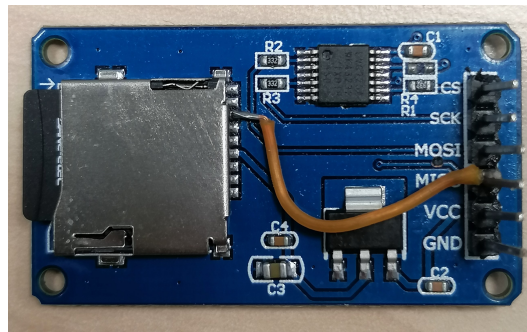


Figure 2.13 : The Modified SD Card Module

SD card module operates with 3.3V, but it has a voltage regulator inside. Therefore, it can accept the 5V as well. However, the data line also must be converted to 3.3V, the chip inside the SD card invert 5V to 3.3V and 3.3V to 5V. As it is known, MISO is the master in slave out. The signal comes out from the slave is 3.3V and Arduino chip can still take it as logic HIGH. LoRa also works with 3.3V, but doesn't have a voltage converter inside. An AND gate is utilized to solve this issue and balance the signal voltages of both modules. The schematic of the circuit can be seen in the Figure 2.10. Three signals; CS, SCK and MOSI are the input for the slaves and output for the master, respectively. They are connected to the input of the AND gate, which is powered by 3.3V. Therefore, AND gate behaves like 5V to 3.3V and this level is safe for the LoRa. With this method, both LoRa and SD card modules worked fine together with no corrupt data. The Figure 2.14 shows the PCB of the completed Arduino mega shield of receiver circuit.

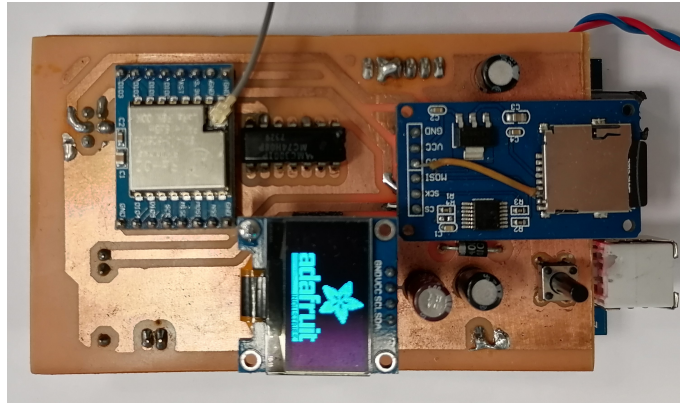


Figure 2.14 : The PCB of Arduino Mega Shield of the Receiver Circuit

2.4.2 Transmitting station

The main purpose of the transmitting station is to collect the data and send it to the receiving station. The schematic of the transmitting circuit is given in the Figure 2.15. Control of the elements in the circuit is achieved by the ATmega328p chip. The LoRa module is used for the communication in the circuit. Temperature, pressure and humidity data are obtained from the digital sensor (BOSCH BME280). Real time clock (RTC) was used for determining the time accurately. Once it is set, it has an internal EPROM to back up the current time even if the power is lost. BME280 sensor and RTC communicate using I²c protocol. The addresses of both modules were checked to be different to prevent the conflict. By defining different chip select pins for both modules, it was ensured a problem free operation. The Lora module is the module that uses the SPI interface in the circuit, ATmega328p is master, LoRa is slave. As shown in the figure 2.11, only MISO can be defined as the output for the slave and the others as input. However, a pull-down resistor has been added to all but MISO so that the LoRa module cannot get stuck during the listening stage and transmit inaccurate data. The detector's digital signal is connected to the digital 3 (D3) pin of the Arduino Nano in the transmitting station. Arduino Nano has two interrupt pins, 2 and 3. Interrupt pins allow the microcontroller to temporarily pause its main program and handle specific events. This mechanics is advantageous that it can respond to external event quickly and prevent from missed events. The counting of radiation pulses is done by the hardware, not the software. After the function is defined in the code, the interrupt

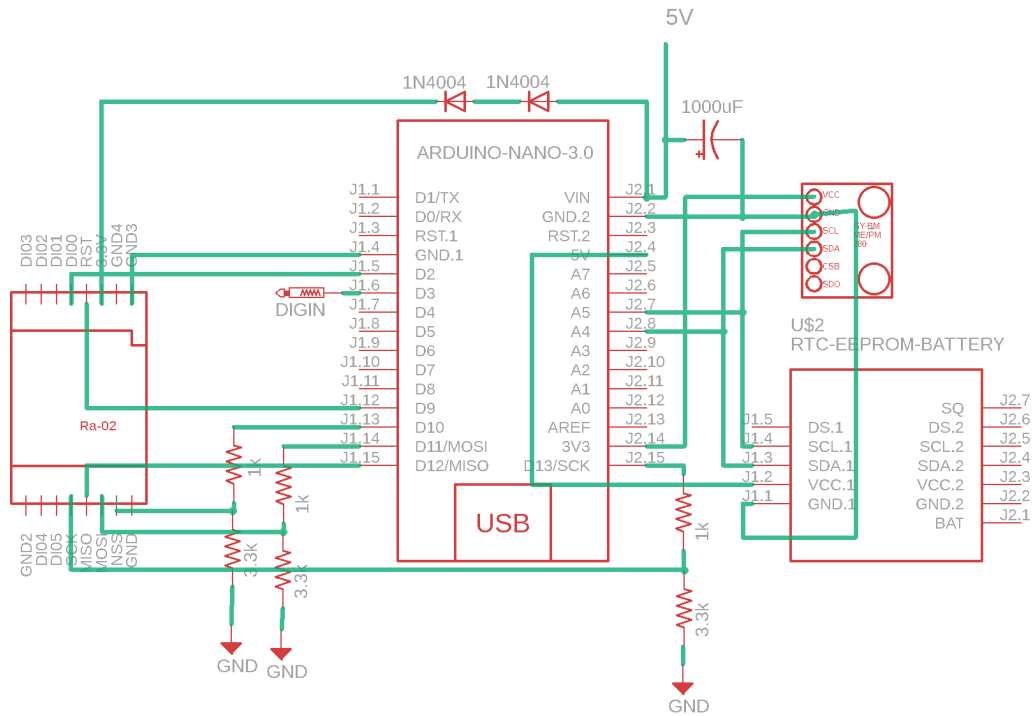


Figure 2.15 : Circuit Schematic of Transmitting Station

pin performs its assignment. It is effective to use interrupt pins not to lose any data from the detector. One example data is shown in the Table 2.1 The data structure in

Table 2.1 : Example Data

Station	Count	Day	Month	Year	Hour	Min	Sec	Temp.	Hum.	Pres.	Voltage	Pulse
1	0	29	3	2024	11	55	0	23.69	38.15	1003.98	4.10	123
1	1	29	3	2024	11	55	10	23.69	38.15	1004.01	4.10	148
1	2	29	3	2024	11	55	20	23.68	38.18	1004.03	4.10	129
1	3	29	3	2024	11	55	30	23.68	38.17	1004.03	4.10	126
1	4	29	3	2024	11	55	41	23.68	38.16	1003.06	4.10	126
1	5	29	3	2024	11	51	0	23.67	38.19	1004.05	4.10	124
1	6	29	3	2024	11	56	1	23.66	38.21	1004.04	4.10	134

Table 2.1 is as following. Station number is the first data. If there is more than one station, it is to find out which station sends the data. The data number is followed by the date and time. The next columns are the time and the digital sensor parameters: temperature, humidity and pressure. The next ones are the system voltage, which indicates the instantaneous voltage reading of the rechargeable battery. The voltage could not be monitored directly using the battery's plus and minus terminals because the Arduino circuit was powered with a step-up voltage converter circuit. A confusion

would arise because of the ground connections were different. An optocoupler was used to prevent this conflict. Optocouplers provide electrical isolation between the input and the output. An optocoupler has an LED and a semiconductor photo-sensitive device such as photo-transistor in it. The LED emits light, this light is detected by a photo-transistor. The Figure 2.16 shows the diagram circuit of the photocoupler. Input is connected to the battery and output is connected to the analog pin of Arduino to obtain the voltage of the battery. After the proper conversion from the 10 bit binary, the voltage value of the battery is obtained and displayed in Volts. Last data is the counted number of pulses for a predefined time. It is the digital signal comes from the detector in response to the detected gamma radiation. The counting of the pulses is done inside the code. All the data is sent with a comma separated. This helps to read it as CSV file. Figure 2.17 shows the PCB printed circuit of the transmitter station. The

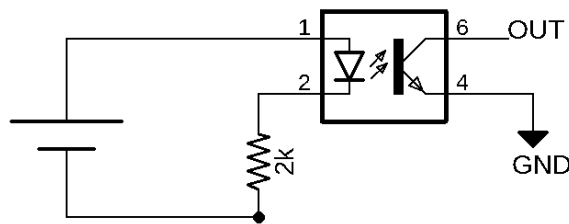


Figure 2.16 : A Photo FET Optocouplers Circuit

whole circuit is designed in the Eagle software then printed to the PCB.

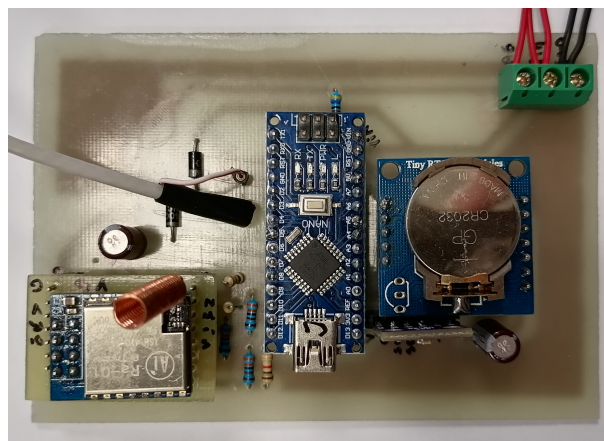


Figure 2.17 : Transmitting Station PCB



3. MEASUREMENTS

3.1 Test Measurement with Standard Sources

Once all stages of the detector were completed, the system underwent testing using gamma test sources that were specifically designed for the laboratory purposes. The examination was carried out using two sources: ^{137}Cs and ^{241}Am , activity of the both ^{137}Cs and ^{241}Am is $10\ \mu\text{Ci}$ (micro curie). They were produced on 1st June 1977. The Figure 3.1 shows the test setup. When testing the system, sources were placed right next to the photodiode. The black dot shows the position of the photodiode. The

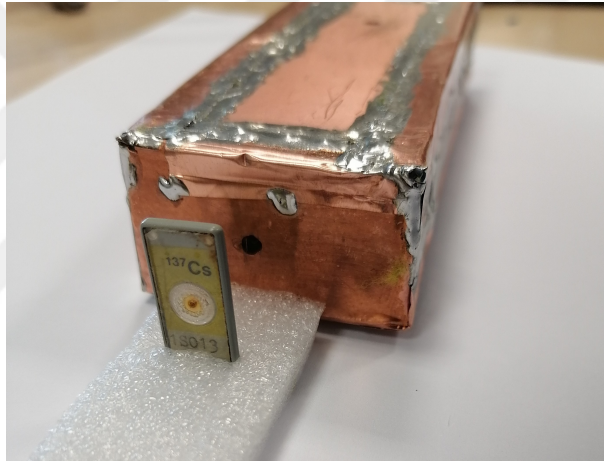


Figure 3.1 : Measurement Setup

detector counted ^{137}Cs source every 10 seconds from 11:17 AM to 16:38 PM. Then the collected data was analyzed. Temperature, humidity and pressure measurements are taken with the digital sensor. In all related graphs, the x-axis shows the time in minutes, where full timescale is about 5 hours. The Figure 3.2 shows the temperature vs time. The temperature has been steadily increasing until a certain period of time around noon and has begun decreasing after reaching a peak value at 24°C . In the Figure 3.3 it has been observed that humidity fluctuates and decreases over time. The

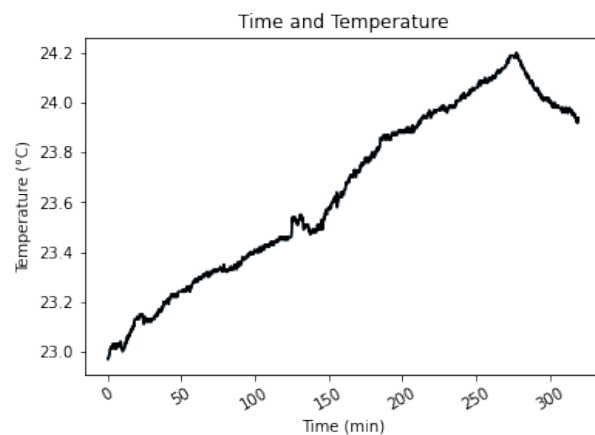


Figure 3.2 : Temperature During ^{137}Cs Data Taking

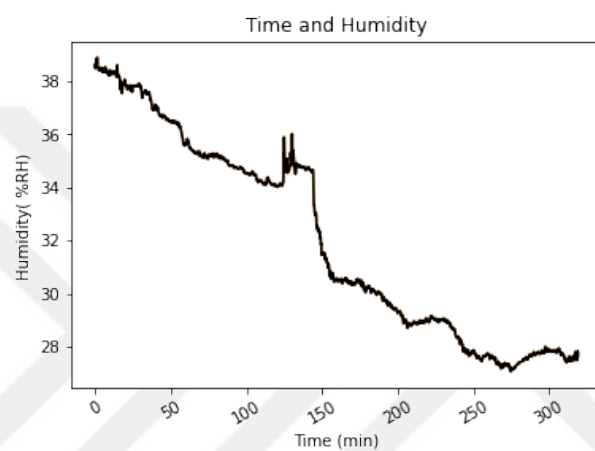


Figure 3.3 : Humidity During ^{137}Cs Data Taking

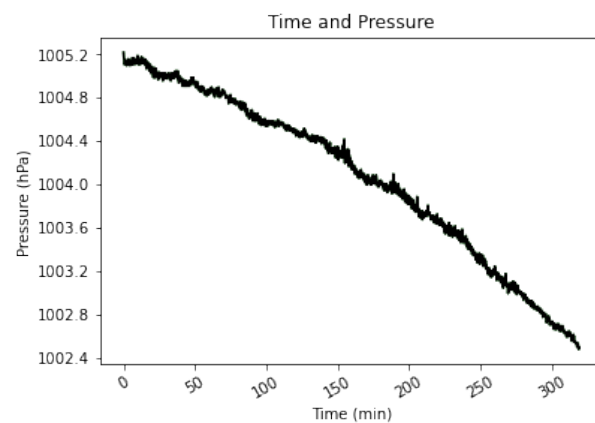


Figure 3.4 : Pressure During ^{137}Cs Data Taking

Figure 3.4 shows the change of pressure over time. It is clear from the graph that the pressure has decreased over time.

3.1.1 Signal shapes

After the detector is finalized, the signal shapes are analyzed using an oscilloscope.



Figure 3.5 : An Analog and the Digital Signals from ^{137}Cs 662 keV gamma



Figure 3.6 : An Analog and the Digital Signals from ^{241}Am 59 keV gamma

The Figure 3.5 shows the signal obtained from the ^{137}Cs gamma source experiment. The signal displayed above (yellow line) represents the output of the shaping amplifier, while the signal displayed below (green line) represents the output of the digitized one. The Figure 3.6 shows the signal results obtained from the ^{241}Am gamma source.

3.1.2 Stability of pulse heights

The Figure 3.1.3 shows the stability of the counts taken from the detector over a time interval. The data collected in this case clearly show a level of similarity and fluctuations are within the expected statistical range.

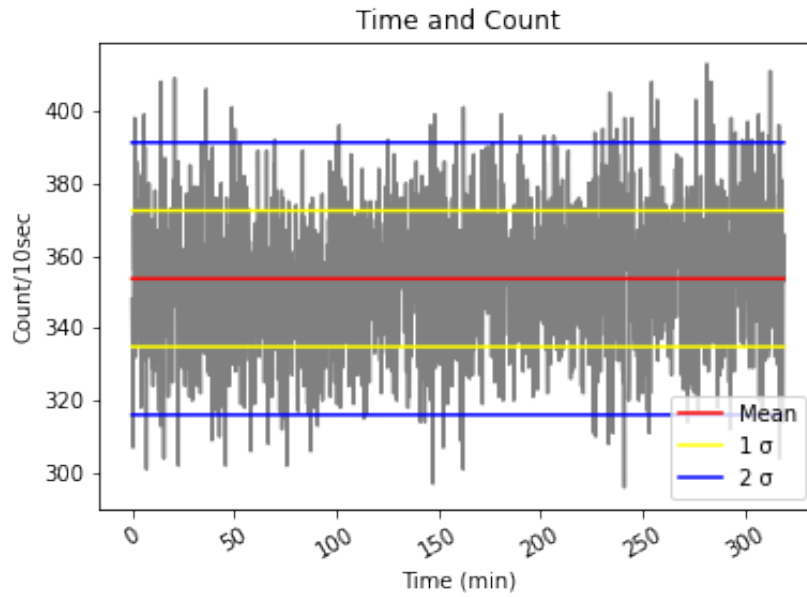


Figure 3.7 : Time Evaluation of ^{137}Cs counts. Each Point is Taken for 10 Seconds

3.1.3 Gaussian distributions

The Figure 3.8 shows the histogram created from the projection of the data given in the Figure 3.1.3. The projection of the time evaluated data obtained from is shown

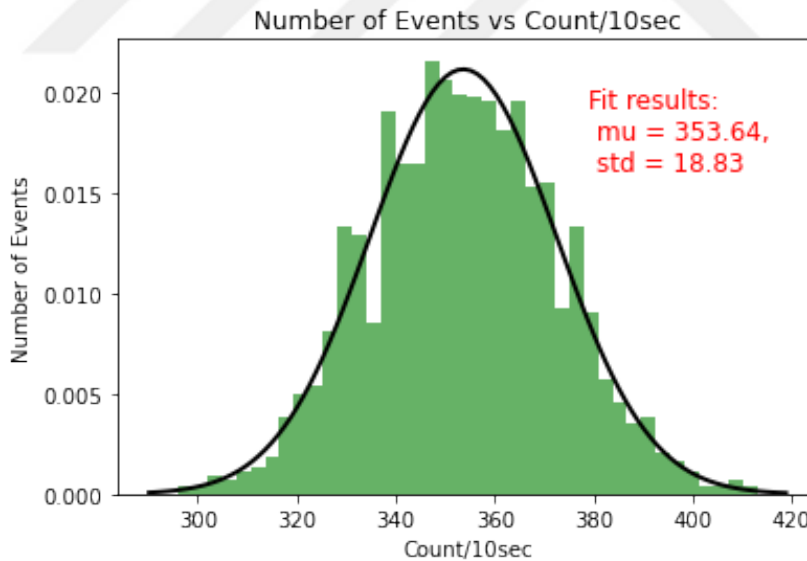


Figure 3.8 : Histogram Distribution of the ^{137}Cs Counts Obtained from Figure 3.1.3

on the 3.8, along with the addition of a Gaussian fit. The x-axis is the counts taken per ten seconds, and the y-axis represents the number of events. The smooth line is Gaussian and fit parameters are written on the graph. The structure and the sigma of the

distribution show the data obeys the nuclear statistics, pointing no systematic problem in it. The data on the graph shows a clear adherence to the Gaussian distribution also the mean of the data is 353.64 and standard deviation is 18.83. A distribution is considered to fit the Gaussian distribution sufficiently if the square of the mean is similar to the standard deviation obtained from the fit of the Gaussian distribution. In this case, the square root of 353.64 is 18.81, and it is almost the same.

3.1.4 Fast fourier analysis

A Fast Fourier Transform (FFT) is an algorithm that computes the Discrete Fourier Transform (DFT) of a sequence, or its inverse (IDFT). Fourier analysis converts a signal from its original domain (often time or space) to a representation in the frequency domain and vice versa. The DFT is obtained by decomposing a sequence of values into components of different frequencies [8]. The use of FFT in this project is to investigate noise characteristics of the detector, since FFT separates a signal into discrete frequency components. It is possible to convert the given information from the time domain to the frequency domain. Using the information given, thoroughly investigate the noise is possible. In the project, the signals in the vicinity of any radioactive source are taken from the oscilloscope as CSV file, and then they are analyzed to understand the noise. The Figure 3.9 shows one of the example of the noise data in time domain which is studied. The Figure 3.10 shows the fast fourier transform analysis of the noise data shown in the Figure 3.9

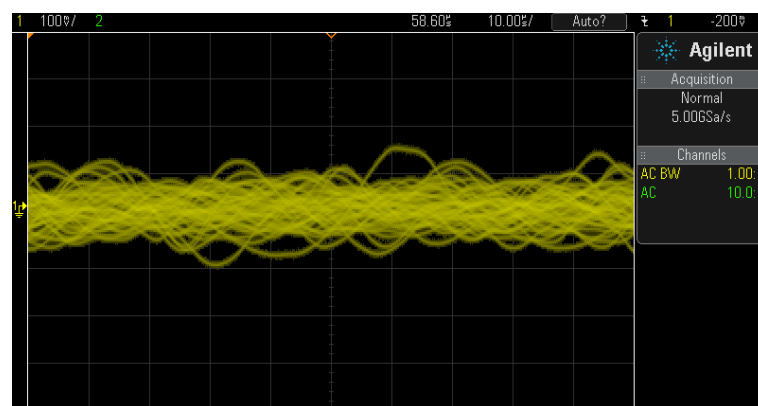


Figure 3.9 : Noise in Time domain. 100 ms Full Scale.

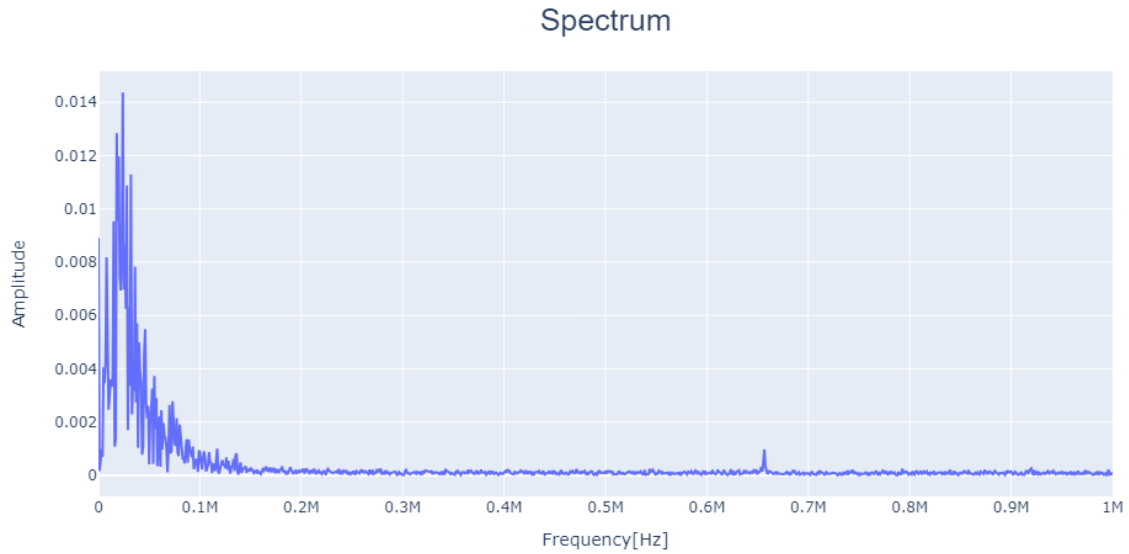


Figure 3.10 : Fast Fourier Spectrum of Noise

3.1.5 Test of linearity of the counting rate

The radiation intensity changes with the distance, as distance increase, intensity decrease. The relation between intensity and distance is proportional with the square of the distance. We are not interested here with the correctness of the inverse square law. However, to test the linearity of the counting under different activities, this test was conducted. The detector is kept stationary, and the gamma source is moved correspondingly. The measurement taken is given in the Table 3.1. The measurements were done from 1 cm to 6 cm for the steps of 1 cm. Five data is taken in each distance and the average of the counts are noted.

Table 3.1 : Inverse Square Law Test Results

Distance(cm)	Count/10sec
1	45.28
2	15.65
3	8.27
4	5.30
5	4.43
6	3.58

The Figure 3.11 shows the inverse square of distance on x-axis and count per 10 second in y-axis. The data points clearly indicate that the change is expected to follow a linear pattern, showing our detector behaves linear in different count rates.

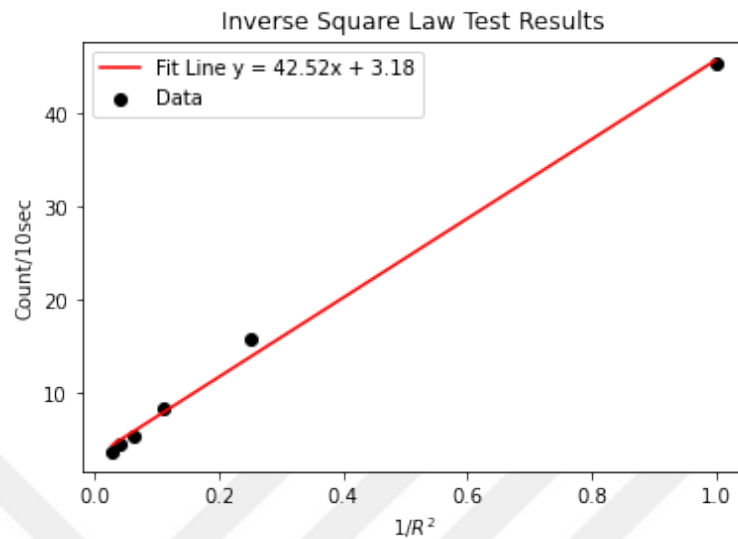


Figure 3.11 : Test of Linearity Due to Different Count Rates

3.1.6 Relative efficiency

Four gamma sources were used for calculating the efficiency of the detector. The energy resolution of our detector is poor. For the counting of the environmental activity, the energy resolution is not an important parameter. However, the efficiency is important. One of the definition of efficiency is the ratio of the number of stopped particles in the detector volume divided by the number of particles enter the detector volume. To find out how many particles are stopped in the detector volume, one has to look at the full energy deposition in the detector volume. Since our silicon detector has only $300\ \mu\text{m}$ thick, only very few number of low energy X and gamma rays would stop and provide full energy deposition. For that reason, one expect to have very small efficiency for our detector. Because of the difficulties to disentangle the event with full energy in the detector volume, we define the efficiency as the number of particles produce signal (at any detectable energy) divided to the ones generated from a radioactive source with the known activity. For the efficiency calibration, average gamma energies were calculated by weighting the peak energies of the individual gamma lines using absolute intensities of the transitions for every source if it has more

than one strong gamma line. The gamma energies used are shown in Table 3.2 and Table 3.3 are the ones calculated with this method. Activities are determined from the exponential decay law based on the initial activities of the sources and the time duration between the production date and the measurement date. The efficiency were determined for two different detector source distances, 2 mm (Figure 3.12) and 12 mm (Figure 3.13). In these figures, the x-axis shows the average energy and y-axis shows the corresponding efficiency. Upon examining the behavior of the two graphs, it becomes evident that they exhibit similar patterns.

Table 3.2 : Detector Efficiency at 2 mm Detector Source Distance

	Am-241	Ba-133	Cs-137	Co-60
Average Energy(keV)	59	269	662	1253
Measured Count Rate(Count/sec)	150.11	23.83	130.75	0.57
Activity(dis/sec)	370224.00	19095.00	13865.00	871.57
Efficiency(%) $\times 1000$	40.55	124.80	94.84	65.40

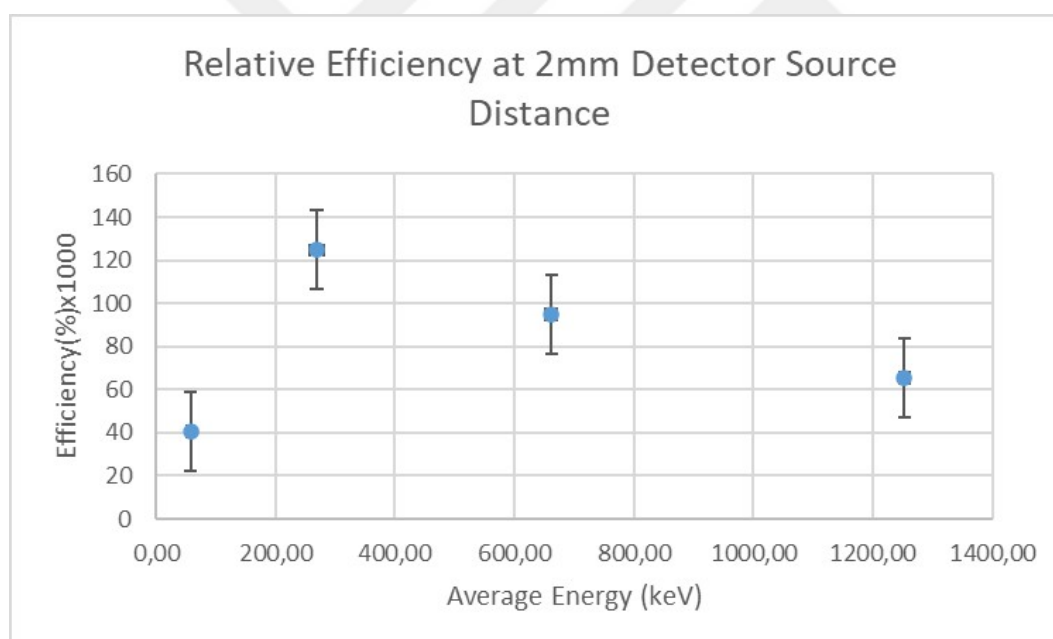
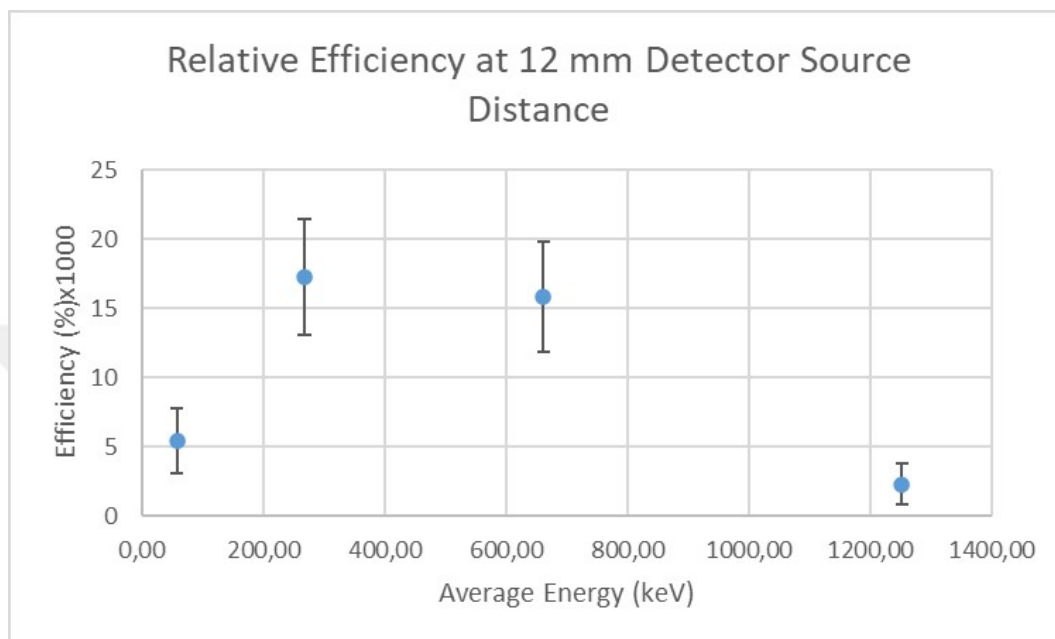


Figure 3.12 : Relative Efficiency at 2mm Detector Source Distance

Table 3.3 : Detector Efficiency at 12 mm Detector Source Distance

	Am-241	Ba-133	Cs-137	Co-60
Average Energy(keV)	59	269	662	1253
Measured Count Rate(Count/sec)	20.00	3.30	21.58	0.02
Today's Activity(dis/sec)	370224.00	19095.00	13865.00	871.57
Efficiency(%) $\times 1000$	5.40	17.28	15.85	2.29

**Figure 3.13 : Relative Efficiency at 12mm Detector Source Distance**

3.1.7 Energy calibration

The energy calibration takes place between the photopeak amplitudes (Volts) and their corresponding energies. For that reason, a MCA is used for determining the photopeak energies. To obtain the relation between the channel numbers of MCA and the peak energies, ^{241}Am , ^{133}Ba , ^{137}Cs and ^{152}Eu sources are used. The Figure 3.14 shows one of the example of MCA output for the ^{133}Ba source. Since the energy resolution of the detector is poor, the photo-peak energies determined from the endpoint calibration. The Figure 3.15 shows the energy calibration graph.

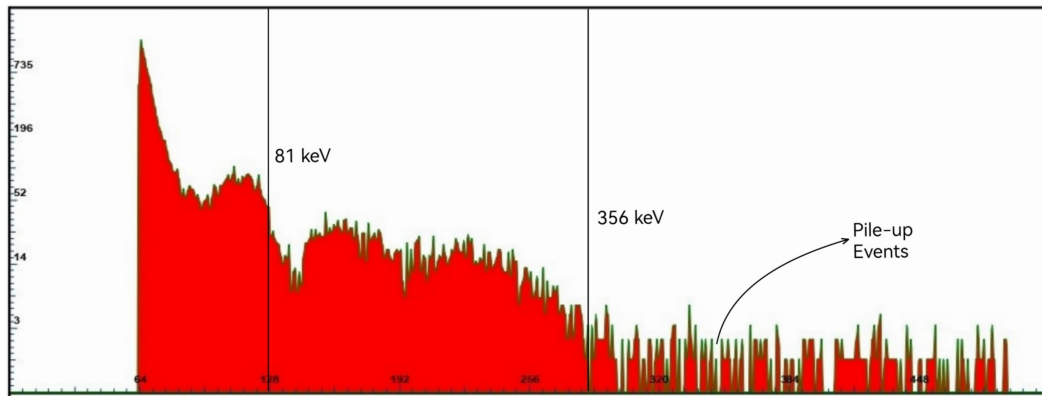


Figure 3.14 : The Output of An MCA to Analyze Ba-133 Source

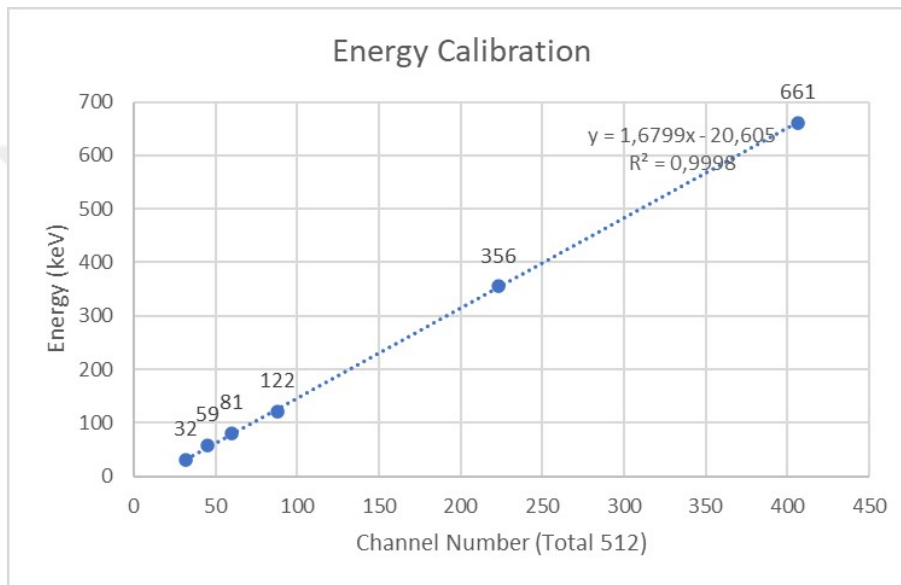


Figure 3.15 : Energy Calibration Graph

3.1.8 Geyikli soil sample test

Detector is tested with the soil sample which is taken from the Geyikli. Two measurements are taken with soil and without soil. The Table 3.4 shows the result taken from the experiments. If we calculate the rate of the measurement with soil, it is 50.9

$$\text{With Soil Rate} = \frac{52.2 + 49.5}{2} = 50.9 \quad (3.1)$$

also the rate of the measurement without soil is 7.1.

$$\text{Without Soil Rate} = \frac{6.9 + 7.2}{2} = 7.1 \quad (3.2)$$

From the calculations, the measurement with soil is 7.2 times of the measurement without the soil.

Table 3.4 : Geyikli Soil Sample Counting Test Results

.	Count for One Day (Count/s)	Count for One Hour (Count/s)
With Soil	52.2×10^{-3}	49.5×10^{-3}
Without Soil	7.2×10^{-3}	6.9×10^{-3}



4. CONCLUSION

The purpose of this study was to build a low-cost gamma ray detector which can be used for the detection of environmental gamma activity. To achieve this goal, a charge sensitive preamplifier based on a low noise JFET is used for amplifying the current generated from a single Si-PIN photodiode used as radiation sensor. Detector electronics and power filters are carefully studied to obtain acceptable signal-to-noise ratio to reduce the detection limit to 40 keV which is more than enough for covering the gamma rays originated from natural radioactivity. A detection limit of approximately 40 keV is achieved without any special effort such as cooling. The detailed studies for the stability of the detector, understanding the noise characteristics, integration with microprocessor and other peripherals took place in this work. This detector is already open to many improvements like using multiple photodiodes for increasing the effective area and its sensitivity. The design allowed to use multiple devices to monitor an outdoor field or an indoor area, and the software embedded into the microprocessor permits to store and analyze the data from multiple devices. The data is collected wireless using LoRa modules. Some of the advantages of this device are; the unit is self solar-powered and it does not require any Wi-Fi or cell connection. This reduces the installation difficulties.



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APPENDICES

APPENDIX A : Transmitting Station Code

APPENDIX B : Receiving Station Code





APPENDIX A : Transmitting Station Code

```
1 #include <SPI.h>
  #include <LoRa.h>
3 #include "RTCLib.h"
  #include <Wire.h>
5 #include <Adafruit_Sensor.h>
  #include <Adafruit_BME280.h>
7 RTC_DS1307 rtc;
  Adafruit_BME280 bme;
9 int counter = 0; //The number of the data being sent.
  int sV = 0; //The battery voltage
11 float Temperature;
  float Pressure;
13 float Humidity;
  volatile int IRQcount; //Count of digital signal
15 int pin = 3; //Input of digital signal (Interrupt pin)
  int pin_irq = 1; //IRQ that matches to pin 3
17 unsigned long startMillis;
  unsigned long currentMillis;
19 const unsigned long period = 10000; //Data taken per period
                                     //( milliseconds)
21 const byte ledPin = 13; //LED built-in
  int icount=0;
23
void setup() {
25   Serial.begin (9600);
    attachInterrupt(pin_irq, IRQcounter, RISING); //Interrupt pin
27   delay(25);
    detachInterrupt(pin);
29   pinMode(ledPin, OUTPUT);
    startMillis = millis(); //initial start time
31
    while (!Serial); //serial monitor wont miss any output from program
33   LoRa.setPins(10, 9, 2);
    LoRa.setSPIFrequency(500E6);
35   Serial.println("LoRa Sender");
    //Test for LoRa
37   if (!LoRa.begin(500E6)) {
        Serial.println("Starting LoRa failed!");
39        delay(2000);
        while (1);
41   }
    //Test for BME sensor
43   unsigned status;
    status = bme.begin(0x76);
45   if (!status) {
        Serial.println("Could not find a valid BME280 sensor,
47         check wiring, address, sensor ID!");
        Serial.print("SensorID was: 0x");
49        Serial.println(bme.sensorID(), 16);
        Serial.print("          ID of 0xFF probably
```

```

51     means a bad address, a BMP 180 or BMP 085\n");
    Serial.print("    ID of 0x56-0x58 represents a BMP 280,\n");
53     Serial.print("    ID of 0x60 represents a BME 280.\n");
    Serial.print("    ID of 0x61 represents a BME 680.\n");
55     while (1) delay(10);
    }
57 //test for RTC
    if (! rtc.begin()) {
59     Serial.println("Couldn't find RTC");
    Serial.flush();
61     while (1) {
        delay(10);
63     }
    }
65
    if (! rtc.isrunning()) {
67     Serial.println("RTC is NOT running, let's set the time!");
    //rtc.adjust(DateTime(F(__DATE__), F(__TIME__)));
69
    }
71     rtc.adjust(DateTime(F(__DATE__), F(__TIME__))); //comment this
                                                    //after set the time
73 } //void setup end

75 void IRQcounter() {
    IRQcount++;
77 } //counter for logic signal

79 void loop() {
    int sV = analogRead(A6);
81     float voltage = 7.389 - (sV * 5.0 / 1023.0);
    voltage = voltage / 1.5469; //Voltage of Li-On Battery
83
    //Bme 1. Measurements
85     Temperature = bme.readTemperature();
    Pressure = (bme.readPressure() / 100.0F);
87     Humidity = (bme.readHumidity());
    delay(1000);
89
    //PULSE
91     DateTime now = rtc.now();
    currentMillis = millis();
93     if (currentMillis - startMillis >= period)
        { //pulse count start
95
        digitalWrite(ledPin, !digitalRead(ledPin));
97         startMillis = currentMillis;

99         //Bme 2. Measurements
        Temperature = 0.5 * (Temperature + (bme.readTemperature()));
101        Pressure = 0.5 * (Pressure + (bme.readPressure() / 100.0F));
        Humidity = 0.5 * (Humidity + (bme.readHumidity())); //Average Values
103
        LoRa.beginPacket();
105        LoRa.print("1"); //Station Number
        LoRa.print(','); //Separate each value with comma

```

```

107     LoRa.print(icontains); //Number of data sending
        LoRa.print(' ');
109 //TIME
    LoRa.print(now.day(), DEC); //Day
111     LoRa.print(' ');
        LoRa.print(now.month(), DEC); //Month
113     LoRa.print(' ');
        LoRa.print(now.year(), DEC); //Year
115     LoRa.print(' ');
        LoRa.print(now.hour(), DEC); //Hour
117     LoRa.print(' ');
        LoRa.print(now.minute(), DEC); //Minute
119     LoRa.print(' ');
        LoRa.print(now.second(), DEC); //Second
121     LoRa.print(' ');

123 //TEMPERATURE

125     LoRa.print(Temperature); //Temperature
        LoRa.print(' ');
127

    //HUMIDITY
129     LoRa.print(Humidity); //Humidity
        LoRa.print(' ');
131

    //PRESSURE
133     LoRa.print(Pressure); //Pressure
        LoRa.print(' ');
135

    //Battery voltage
137     LoRa.print(voltage); //Voltage of Lion Battery
        LoRa.print(' ');
139

    //pulse
141     LoRa.print(IRQcount); //Number of logic signal
        IRQcount=0;
143

    LoRa.endPacket();
145     icount++; //Increase the number of data by one

147 //Sended data look like;
        //Station,Counter,Day,Month,Year,Hour,Minute,Second,Temperature,
149 //Humidity,Pressure,Voltage,Pulse
        } //pulse count end
151 } //void loop end

```

Listing A.1: sender-appendix.ino



APPENDIX B : Receiving Station Code

```
1 #include <SPI.h>
  #include <SD.h>
3 #include <LoRa.h>
  #include <Wire.h> //I2C library for the OLED
5 #include <Adafruit_SSD1306.h> //OLED driver
  #define SCREEN_WIDTH 128 // OLED display width, in pixels
7 #define SCREEN_HEIGHT 64 // OLED display height, in pixels
  #define OLED_RESET -1
9 #define SCREEN_ADDRESS 0x3D ///< Address; 0x3D for 128x64
  Adafruit_SSD1306 display(SCREEN_WIDTH, SCREEN_HEIGHT, &Wire,
11 OLED_RESET);
  char alpha;
13 const int chipSelect = 32; //SD cs
  int ss = 30; //CS of LoRa
15 void setup() {
    Serial.begin(9600);
17    while (!Serial);
    //LoRa
19    pinMode(ss, OUTPUT);
    Serial.println("LoRa Receiver");
21    LoRa.setSPIFrequency(500E6);
    LoRa.setPins(30, 49, 53); //NSS, RESET, IO0
23    if (!LoRa.begin(500E6)) {
      Serial.println("Starting LoRa failed!");
25      while (1);
    }
27
    //SD
29    pinMode(chipSelect, OUTPUT);
    Serial.print("Initializing SD card...");
31    // see if the card is present and can be initialized:
    if (!SD.begin(chipSelect)) {
33      Serial.println("Card failed, or not present");
      // don't do anything more:
35      while (1);
    }
37    Serial.println("card initialized.");

39    //Display
    display.begin(SSD1306_SWITCHCAPVCC, 0x3C);
41    display.display();
    delay(1000);
43    display.clearDisplay();

45 } //void setup end

47
49 void loop() {
  String dataString = "";
  display.clearDisplay();
```

```

51 display.setTextSize(1);
display.setTextColor(WHITE);
53 display.setCursor(0,0);//cursor to upper left

55 // try to parse packet
int packetSize = LoRa.parsePacket();
57 if (packetSize) {
    // read packet
59     while (LoRa.available()) {
        alpha=(char)LoRa.read();
61         display.print(alpha);
        display.display();
63         dataString += String(char(alpha));
    }
65     Serial.println(dataString);
    // open the file. Only one file can be open at a time,
67     // so you have to close this one before opening another.
    File dataFile = SD.open("datalog.txt", FILE_WRITE);
69     // if the file is available, write to it:
    if (dataFile) {
71         dataFile.println(dataString);
        dataFile.close();
73     }
    // if the file isn't open, pop up an error:
75     else {
        Serial.println("error opening datalog.txt");
77         display.setTextSize(2);
        display.print("404");
79         display.display();
    }
81 } //if (packetSize) end
83 } //void loop end

```

Listing B.1: receiver-appendix.ino

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OTHER PUBLICATIONS, PRESENTATIONS AND PATENTS: