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A Low, Cost Portable Ground Station to Track and Communicate with Satellites in VHF Band

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Abstract

In this thesis, we present the architecture and implementation of a low-cost, small, mobile and easily deployable ground station to track and receive signals from satellites that operate on the VHF-band (144 MHz to 147 MHz). The ground station uses a handheld 5-dB gain Yagi-Uda antenna, a low noise amplifier with 23 dB gain and a software defined radio (FUNcube Dongle) to receive the signals. The analog front end's software-defined nature gives it the flexibility to target satellites with diverse power, modulation and error-correcting schemes. Software for satellite tracking, signal decoding and processing is freely-available.

The low cost of the ground station makes its affordable for classroom and laboratory activities in a research or educational institution that involve satellite signal processing in wireless communication courses. The small size and portability of the proposed ground station means it can be adopted in locations with limited access to fixed outdoor antennas, whether because of financial, regulatory or other restrictions. Examples of ground station-tracked and received signals include satellites such as FUNcube (AO-73), International Space Station (ISS) and NOAA satellites. Specifically, the National Oceanographic and Atmospheric Administration (NOAA) series of satellites (NOAA 15, 18, 19) were tracked. The signals received were processed to recover images of the earth using various software. This thesis also presents the details of decoding the image using MATLAB.

Acknowledgements

This thesis signifies innovative research conducted for a year at Department of Telecommunication Engineering Technology, RIT. The department has given me unique opportunities including – working as Research Assistant for implementation of Low Cost Ground Station, Analog Mars Mission as Crew Biologist (Crew 174) at Mars Desert Research Station and paper presentations at International Astronautical Congress 2016, Guadalajara, Mexico. The driving force for the above experiences, achievements are number of remarkable individuals who I wish to acknowledge.

I wish to thank my advisor, Prof. Miguel Bazdresch who has been extremely supportive from the beginning of this research. He has supported me not only by providing Research Assistantship for a year but academically and emotionally through the path to complete this research. Without his kind words and patient teaching, it would have been difficult for me to complete this thesis. I thank Prof. William Johnson who supported me whenever I needed assistance. My special thanks to the committee Prof. William P Johnson and Dr. David Orlicki who have spent their valuable time to read, understand and give technical inputs to my work. I would like to thank all my professors and staff for their support, encouragement and care.

Last but not the least my family, the unconditional love and strength from parents and aunt is the basis of the energy in me. They have cherished and enjoyed with me every great moment and supported me when I was down. Special and final thanks to friends and Mr. Saroj Kumar for making my life complete with love and care.

Contents

Definition of Acronyms used

AM – Amplitude Modulation

APT – Automatic Picture Transmission

AOS – Acquisition of Signal

AVHRR – Advanced Very High-Resolution Radiometer

BER – Bit Error Rate

BPSK – Binary Phase Shift Keying

BPF – Band Pass Filter

CSA- Chinese Space Agency

COTS – Commercially Off -The- Shelf

DSP – Digital Signal Processing

DSBLC – Double Side Band Large Carrier

ESA- European Space Agency

EIRP – Effective Isotropic Radiated Power

FCD – FUNcube Dongle

FSK – Frequency Shift Keying

FCC- Federal Communication Commission

GEO – Geostationary Earth Orbit

GS – Ground Station

HPA – High Power Amplifier

IARU – International Amateur Radio Union

IR – Infrared

ISS – International Space Station

ISRO – Indian Space Research Organization

ITU – International Telecommunication Union

JAXA- Japan Aerospace Exploration Agency

LEO – Low Earth Orbit

LNA – Low Noise Amplifier

LOS – Loss of Signal

MEO – Medium Earth Orbit

ms – miliseconds

NASA – National Aeronautics and Space Administration

OSS – Open Source Software

PA – Power Amplifier

RF – Radio Frequency

SDR- Software Defined Radio

STK – Satellite Tool Kit

TLE – Two Line Elements

UHF – Ultra High Frequency

VHF – Very High Frequency

km – Kilometer

K – Degree Kelvin

Hz – Frequency Measure in hertz

kHz – Kilohertz

MHz - Megahertz

Definition of Symbols Used

Λ – Lambda

P_t – Power Transmitted

G_t – Gain of the Antenna

L_{fs} – Free Space Loss

T_e – Equivalent Temp

G_r – Receiver Gain

C/N – Carrier to Noise Ratio

R_b – Data Rate

E_b/N_0 – Signal to Noise Ratio

L_{bo} – Back-off Loss

E_b – Bit Energy

Tb- time of single bit in seconds (s)

T – Environmental temperature

T_e – Equivalent temperature

N – Total noise

k – Boltzmann's constant (Joules/Kelvin)

B- Bandwidth (Hz)

N_0 – Noise Density

C – Carrier power

G_r – Receiver Antenna Gain

T_s – Operating temperature of Antenna in K

T_a – Antenna temperature in K

T_r – Receiver Noise Temperature in K

γ_R – Rain attenuation in dB/km

CHAPTER 1: Introduction

1.1 Research Motivation

In recent years there has been an increase in hands-on laboratory activities based on digital signal processing, software defined radio, transmission and reception of signals in the engineering communication courses. On the other hand, there has been increasing trend and interest in space technology right from elementary schools to many engineering and technology colleges. Space technology is very diverse and multidisciplinary and involves different streams of engineering and a college provides an apt platform for students to play lead role executing space exploration projects.

A space exploration project is no doubt an experience of considerable value both academic and non-academic. As a result, there can be several challenges in sustaining new courses. The motivation for this research is to use satellite communication to improve the existing wireless communication courses in telecommunication engineering technology program.

1.2 Aim and Objectives

The research aims to:

1. Develop a low cost and portable ground station to track and communicate with small satellites in amateur band.
2. Enhance the Wireless Communication Course by introducing Satellite Communication as experiments in Telecommunication Engineering Technology.
3. Develop a framework for SDR applications in hardware and software.

The objectives of this research are

1. Explore the SDR technologies that can be used for space missions.
2. The signals received from satellites like FUNcube, International Space Station and NOAA satellites and process the signals using MATLAB to determine the power spectral density of the received signals.
3. Post processing of the signals, decode the images from NOAA series of satellites using MATLAB. The APT signals are processed to obtain the baseband signal, achieve frame synchronization, and quantize the pixel information.

1.3 Scope and outline of this thesis

The research started with an aim to implement a low-cost and portable ground station to communicate with small satellite in amateur band. Chapter 2 describes the literature study on satellites, its classification based on weight, satellite subsystems, orbits and small satellites and space exploration projects in universities. Chapter 3 highlights on the satellite communication, architecture, the radio frequency regulations, advantages of satellite communications, as well as the evolution of Software Defined Radio (SDR) and its advantages over conventional radio. In chapter 4, major aspects of ground station, its limitations, challenges, cost, trade off study on the hardware of ground station was conducted. Chapter 5 explains the architecture of ground station was finalized. The ground station is implemented using suitable antenna, SDR and peripheral software. Satellites operating in amateur band were tracked and signals were received. Chapter 6 consists of the satellites tracked, signals received, and processing experiments. In the following chapter, the Automatic Picture Transmission (APT) images from NOAA series of satellites were studied and signals from NOAA was processed using various image processing software. The data was decoded using MATLAB. The final chapter presents some conclusions, the conference papers issued from this work, and plans for future work.

1.4 Publications

- M. Bazdresch, S.Velayudhan, W.Johnson, "A satellite Ground Station for Teaching Digital and Wireless Communications", Proceedings of Frontiers In Education, 2016, Erie, Pennsylvania, USA. DOI: 10.1109/FIE.2016.7757672
- S.Velayudhan, M. Bazdresch, "Satellite-based Experiments for a Graduate Program in Telecommunications Engineering Technology", Proceedings of International Astronautical Congress 2016, Guadalajara, Mexico. IAC-16-E1.4.8*33595
- S.Velayudhan, M.Bazdresch, "A Low Cost Mobile Ground Station for Satellite Communication in VHF Band", Proceedings of International Astronautical Congress 2016, Guadalajara, Mexico. IAC-16-B2.8-GTS3.7*33583

Chapter 2: Satellites and Their Classification

Satellites are heavenly bodies or man-made machines that revolve around a planet or a celestial body. Satellites are two types (i) natural and (ii) artificial. Natural satellites are the celestial bodies that revolve around a planet or a star. Example moon is the natural satellite of the Earth, similarly Titan is one of the satellites of Saturn. Artificial satellites are the man-made machines that are launched into orbits of earth or any other celestial object to study its atmosphere, land surface, chemical composition, or for communication. Satellites launched into the Earth orbits have various applications such as communication, remote sensing, astronomy, oceanography, military applications, surveillance and many more. The attitude at which satellites revolve the Earth allows them to see wide areas on ground and helps collect more data at one time.

2.1 Satellite classification

The satellites are also classified based on (i) weight (ii) orbit height.

(i) Weight: based on weight and size, satellites are classified as large and small. They vary from few milligrams to few tons. The large satellites are expensive and take long time to design, manufacture and launch. National agencies like NASA, ESA, JAXA, CSA and ISRO are some of the leading space agencies that plan and execute space missions for various applications such as communication, broadcast, remote sensing and deep space missions. In recent years, small satellites have developed as a platform for experimental payloads as it can be planned and executed in shorter span of time and at much lesser cost. Universities across the globe have shown keen interest in designing and developing small satellites that are launched into LEO. Large satellites can have life span of more than 15 years where as small satellites have much less life span (few years to few seconds). Satellite classification, weight, life span and cost are shown in Table 1.

Table 1: Classification of satellites

Classification	Weight (Kg)	Life Span (years)	Cost ($)
Large	≥1000	≥15	≥500M
Small	500-1000	5-7	≥100M
Mini	100-500	2-3	≥20M
Micro	10-100	≤1	≤10M
Nano	1-10	≤1	≤1M
Pico	1	1	≤100K
Femto	≤0.1	Few weeks	Few hundred

Pico and femto satellites are also known as cube satellites (CubeSats for short). The informal definition of a CubeSat is a satellite with volume smaller than 1000 cm^3 and weighing less than 1.33kg (Mehrparvar, 2014)

Orbits: the satellite can be launched into (i) Circular (ii) Elliptical orbits.

(i) Circular Orbits: based on the attitude of the satellite from Earth. Orbits are widely classified as:

(a) Geostationary Orbit (GEO): At approximately 35,786 Kms from the mean sea level of the Earth, satellites in these orbits are synchronous to the Earth and looks like they are at a constant position from Earth as their rotation period is same as Earth. Life Expectancy of these satellites are 15-20 years. Large satellites are placed in these orbits usually communication and earth observation satellites. Making and launching a GEO satellite is very expensive to.

(b) Medium Earth Orbit (MEO): Approximately at 10,000Km from Earth, MEO satellites have shorter revolution period (approx. 6 hours). They have long life span and are used for navigation, communication and science experiments. They are expensive to make and launch.

(c) Low Earth Orbit (LEO): Satellites launched between 600 Km – 800Km are known to be in Low Earth Orbit. They have an orbital period of 90 min – 120min, LEO satellites provide platform for remote sensing and mobile communication satellites. Most of the University satellites/small satellites are placed into LEO satellites. Less expensive when compared to GEO and MEO satellites (Boain, 2004).

(ii) Molniya Orbits: Sometimes referred as the Highly Elliptical Orbits (HEO), these have an orbital period of 12 hours at an inclination of 63.4° (David Wright, 2005).

(iii) Sun Synchronous Orbits (SSO): The orbits in which the satellite pass over a given location on Earth at roughly the same time of the day is known as Sun Synchronous Orbits. It means the position of the sun at the time of satellite pass is fixed. This orbit is particularly used for satellites carrying imaging payload (David Wright, 2005).

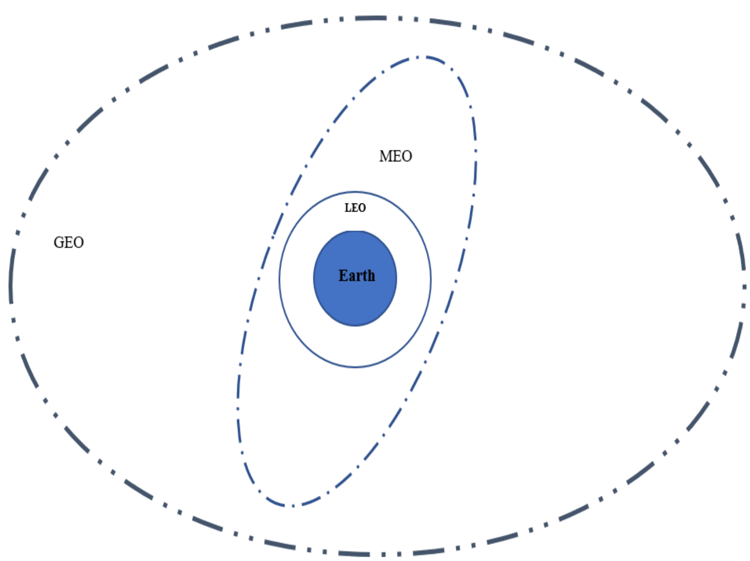

Figure 1: Satellite Orbits based on altitude

2.2 Orbital Parameters

Kepler's laws state (1) the planets move in ellipses with the sun at one focus, (2) the line joining the sun and a planet sweeps out equal areas in equal intervals of time, and (3) the square of the time of revolution of a planet divided by the cube of its mean distance from the sun gives a time that is the same for all planets. The centrifugal force created by the Earth's rotation and the gravity holds the satellite in orbit. The orbital parameters are decided based on the satellite application, the power requirements, the communication window needed and many more. Some terms to know before understanding orbital parameters

i. Angle of Inclination: The angle formed by the satellite and Earth's (equatorial) plane. Angle of inclination can vary from 0°-180°.
ii. Ascending Node: the point where the orbit crosses the equatorial plane from South to North (counterclockwise).
iii. Eccentricity: the ellipse shape that shows us how elongate is the orbit when compared to a circle.
iv. Longitude of ascending node: the horizontal orientation of the ascending node
v. True anomaly: is an angle that varies with time (linearly) but is not any real geometric angle.
vi. Argument of periapsis: the orientation of the ellipse in the orbital plane (Boain, 2004)

The orbital patterns are as described below

(i) Equatorial Orbit: the orbit right above the Equator with 0° inclination. There are no ascending or descending nodes in this orbit and are circular. Satellites placed in GEO are all in this orbit (Tomasi, 2014).

(ii) Inclined Orbit: the orbits that do not travel above the equator and poles and with an angle of inclination. To get more earth coverage at high latitudes, inclined orbits are used (Tomasi, 2014).

(iii) Polar Orbit: The orbits where the satellite orbits through the poles that are perpendicular to the Earth's plane is known as Polar Orbits. The angle of inclination is about 90° and with such orbits, it's possible to cover 90% of the Earth with one satellite. Figure 2 depicts the orbital patterns and the table illustrates the orbital height, radius, orbital time and the velocity of the satellite (Tomasi, 2014).

(iv) Apogee: A point in the orbit that lies at maximum distance from Earth

(v) Perigee: A point in the orbit that lies the minimum distance from Earth

(vi) Major axis: A line through the center of the Earth joining the apogee and perigee

(vii) Minor axis: The vertical line that is perpendicular to the Major axis that is at exactly midway between apogee and perigee

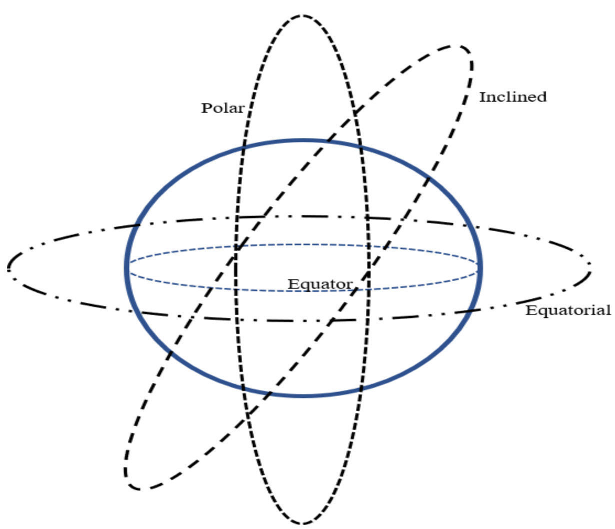

Figure 2: Orbital patterns

2.3 Satellite Subsystems

Satellites are complex machines that work by itself in space. The satellite is divided into subsystems such that the work on it can be done independently and all the systems can be interfaced to make it work as one single unit. Six subsystems together comprise a satellite (Wiley J. Larson, 2005), (Saroj Kumar, 2014), (Gerard Maral, 2009). The launch vehicle, the trajectory of the launch, satellite and its subsystems can be simulated by using STK.

1. Payload
2. Command and Data Handling (C&DH)
3. Attitude determination and Control System (ADCS)
4. Electronic Power System (EPS)
5. On Board Communication System (OBC)
6. Structure

1. **Payload:** the main objective of the satellite will be called the payload example imaging sensors for remote sensing satellites, telescope can be the payload for the astronomy satellites, transponders for communication satellites.
2. **Command and Data Handling (C&DH):** This subsystem can be called the brain of the satellite. It runs a set of complicated codes that are used to keep the satellite functional. It interfaces all the subsystems; C&DH communicates by sending commands and receiving data from other systems within the satellite. It continuously checks the working of every sensor, collects data, address issues if any. The data obtained from different subsystems are then processed and packetized. The data is then sent to the communication system for

dumping data to the ground station. The C&DH system address the health issues of the parameters.

3. **Attitude Determination and Control System (ADCS):** proper orientation of the satellite is needed for achieving the mission goals. The ADCS subsystem uses sensor such as magnetometer, sun sensors, inertial sensor to determine the orientation and corrects it with using actuators like torquer coils and/or reaction wheels. It orients the satellite for imaging payloads to point towards the Earth for better imaging and other satellite functions such as communication, solar panel charging etc.

4. **Electronic Power System (EPS):** Most satellites depend on Solar to meets its power demand. Power margin is calculated for the total power generation depending upon the sun lit period, satellite orientation, number of solar cells on the satellite and the power demand from the satellite such as the power needed for the other subsystems. There are solar panels that generate electricity and supply to the various subsystems of the satellite while batteries play the secondary source of power. The batteries are charged during the solar lit period of the orbit. During the eclipse period (when there is no sun to provide solar energy) the batteries support the working of the satellite.

5. **On board Communication System:** The satellite data must be sent to Earth for further analysis. The only way to communicate with the satellite is a wireless communication system. The International Telecommunication Union (ITU) allots the frequencies depending upon the communication system requirements to facilitate interruption free communication. The OBC consists of controller, transceiver and antenna system. There are two types of data that are transmitted (downlink) to the Earth and commands and other

satellite operations that are received (uplink) to the satellite. The OBC system has three types of data to transmit and receive are

(i) Beacon: the basic health parameters of the satellite.

(ii) Telemetry and payload: The in-detail data about the working and health of each component of the satellite and the payload data such as image, astronomy data, communication data etc.

(iii) Tracking and Commands: commands required for the normal functioning or certain control needs are uplinked to the satellite. These commands are received by the satellite and then sent to the C&DH for processing.

6. **Structure:** the primary objective of the structure is to provide mechanical support to all the other subsystems of the satellite. It encloses and protects the subsystems from the harsh space environment. Stress, strain and load conditions are carefully analyzed before manufacturing the structure to sustain the space environment and the launch. After satellite integration various tests such as vibration, environmental tests are conducted periodically to prove that the satellite will be stable during and after launch.

2.4 Small satellites and universities developing them

In the recent years there is an increase in engineering courses that aim to provide hands-on experience to student community at affordable cost. The low development time, variety of missions, launch opportunities, contribution from small industries and the use of COTS components resulting in reduced cost of building satellite make the small satellites attractive to student community. Small satellites like nano, pico and femto satellites are common in university research as it provides platform to experimental payloads. The universities have designed and developed small satellites that have been successfully launched into orbit. The satellite technology involves a multidisciplinary research that needs expertise in the areas such as mechanical, electrical, electronics, physics, communication, etc. to work on concept, design and develop a complete satellite mission. A few examples of university-led satellite projects are given in Table 2.

Table 2: List of University satellites

Satellite Project	University	Payload
QB 50	Von Karman Institute	Research
AAU Cubesat	Aalborg University	Research
Firefly	NASA & Siena College	Remote Sensing
KSAT 2	Kagoshima University	Remote Sensing
STUDSAT	Consortium of College, India	Remote Sensing
Quakesat	Stanford University	Disaster Warning

2.5 Satellite Applications

Advances in space technology in recent years have an impact on day to day life. Some of the most influential satellite applications are as listed below.

1. Military communication
2. Remote sensing
3. Communication
4. Navigation
5. Astronomy
6. Weather monitoring and disaster management

Chapter 3: Satellite Communication

Satellites can be used to communicate through dispersed locations across the globe with many benefits: an employee to access company's resources and email; citizens can have access to satellite televisions and wireless phone connections.

3.1 Overview of satellite communications

The large number of CubeSats limits the availability of VHF, UHF and S-band frequencies. Since the launch of OSCAR-1 from Discoverer-1 into LEO its signals were received by many amateur radio operators worldwide. Over 50 years now, universities, commercial organizations and governments develop CubeSat to perform space research and rely on the amateur band for communication. The increase in small satellite development and launch has increased the need for licensing and an efficient way of using the limited bandwidth that is available. The possible solutions to solve this issue is to equip the satellites with Software Defined Radio (SDR). The advantage of SDR's are re-configurability, autonomy and adaptability. These advantages increase the efficiency of the communication subsystem. (Mamatha Maheshwarappa, 2014).

3.2 Architecture of Satellite Communication

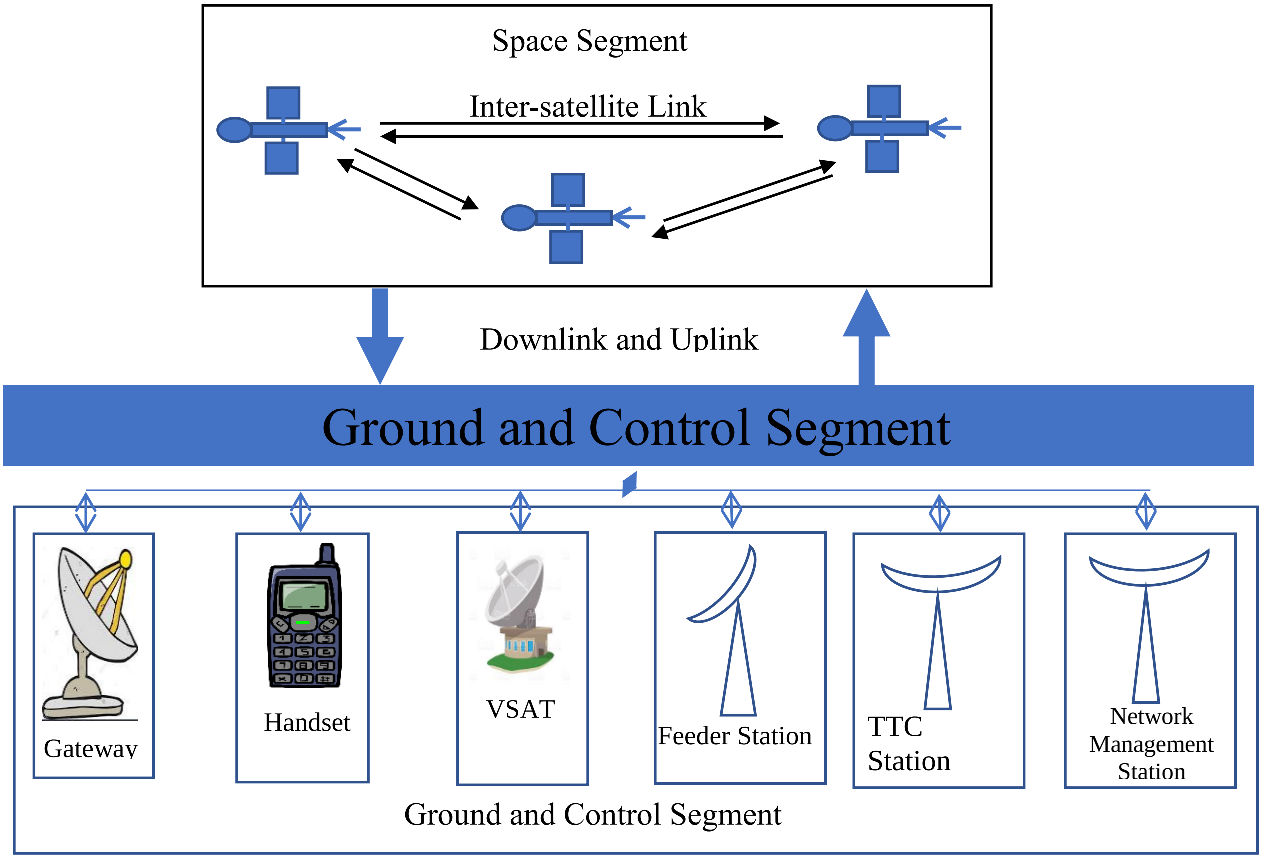

Figure 3: Satellite Communication Architecture

The figure above illustrates a satellite communication architecture and its interface with entities on Earth. The satellite communication can be divided into (i) Space segment (ii) Control segment and (iii) Ground segment.

(i) Space Segment: it consists of one or more satellites in a constellation flight that communicate with each other using inter-satellite link and communicate with the Earth using Ground stations.

(ii) Control Segments: in charge of receiving and monitoring the satellites through telemetry data. Sending control commands to the satellite for the normal functioning of it.

(iii) Ground station segment: connecting the satellites to the user directly or indirectly the ground station manages all the traffic. Ground stations can be huge structures consisting of large antenna systems or even small handsets with small antenna and other equipment.

3.3 Radio Regulation

The advance in wireless communications led to the need for economical and efficient use of radio frequency. Both satellite and land communication make use of the electromagnetic radio spectrum to transfer data from point to point. There is a constant increase in need to coordinate the frequencies among all nations (Elbert, 2008). This led to the formation of International Telecommunication Union, that aims to promote the peaceful use of radio frequencies among the member countries to achieve communication objectives (Gerard Maral, 2009).

3.3.1 International Telecommunication Union (ITU)

The International Telecommunication Union is an organization under the United Nations that administers the use of radio frequency among its member countries. Radio Regulations (RR) is published by the ITU, reviewed by the committee that is formed by the member countries. Between the years 1947 – 1993 there were two committees, (i) CCIR (Comitè Consulatif International des Radiocommunications), and (ii) CCITT (Comitè Consulatif International Tèlègraphique and Tèlèphonique), that administered and regulated the frequencies. The documents submitted by the countries regarding the use of radio frequency is reviewed by International Frequency Registration Board (IFRB) (Elbert, 2008).

Though the radio signals know no international boundaries, ITU has divided the world is divided into three regions:

(i) Region 1: Europe, Africa

(ii) Region 2: North and South America

(iii) Region 3: Asia and the Pacific

3.3.2 Communication Services and Frequency Allocation

The frequency spectrum lies between 0.1 MHz to 1000GHz. The frequency range that is useful for satellite communication is that above 100MHz. The frequency bands are named as VHF, UHF, L, S, C, X, Ku, Ka. The frequency allotted for radio communication services are as in the Table 3 below (Elbert, 2008).

Table 3: Satellite Services with operating frequencies

Communication Service	Frequency band	Uplink/Downlink frequency
Broadcasting Satellite	Ku	12 GHz
	S	2.6/2.5GHz
	S	2/2.2 GHz
Fixed Satellite	Ka	30/20GHz
	X	8/7GHz
	Ku	14/12-11GHz
	V	50/40GHz
	C	6/4 GHz
Mobile	Ka	30/20GHz
	L	1.6/1.5GHz

3.3.3 Frequency Reuse

One of the advantages of using radio frequency is that is can be reused. When the allotted frequency band is full to its capacity, the capacity of the spectrum can be increased by increasing the gain (size) of the antenna. Reducing the beam width is another method where different beams of same frequency in directed to different geographic locations on the earth, the capacity can be increased. Polarization also can be used as a method, by transmitting different information to different earth stations by orienting the polarization 90°out of phase using the same frequency will lead to frequency reuse (Tomasi, 2014).

3.4 Advantages of Satellite Communication

Due to the benefits of satellites, they are extensively used for communication applications. They play a vital role in communication, because a satellite can cover a large area on Earth at a given point of time. Another benefit is that satellites communicate using wireless systems, which allows mobility. The advantages of satellite communications are summarized below (Elbert, 2008).

1. **Wide area of coverage:** the orbit into which the satellites are launched provide wide area coverage that does not comply with the boundaries of countries or continents. One satellite placed in GEO can cover one third of the Earth surface, this means three satellites when placed in GEO can cover most of Earth except the poles. Satellites in GEO orbits are used for communication purposes due to the wide area coverage.
2. **Wide bandwidth available:** the communication capacity in hertz is known as the bandwidth. The satellites users enjoy abundant bandwidth. The GEO satellites the C band (3.5 – 6.5 GHz) and Ku band (10.5 – 14.5 GHz).
3. **Wireless communication:** Within the footprint of the satellite, a user can access the communication. The effective radio link is established between the satellite and the user as long as the received signal power is larger than the receiver's sensitivity; this condition is known as "closed". If the user is mobile, then the system's design needs to consider performance degradation introduced by the Doppler effect.

4. **Easy and quick installation of ground networks:** After the launch of a satellite, setting up an operational ground station takes less time. The only constraint in installing a ground station will be the geography of the site. Installing a ground station is much simpler than installing terrestrial infrastructure that involves gaining the rights for way long cable routes and tower installation and many more.
5. **Terrestrial Infrastructure independent:** Communication satellites are basically transponders in space, having a repeater in space provides microwave relay station on Earth. It is particularly useful where installing a radio base station is expensive or the geography is not favorable.
6. **Uniform service:** the satellites coverage area defines the service area for uniform service. The fragmentation of service that is caused while connecting from one network to the other using terrestrial infrastructure is overcome while using communication satellites.
7. **Total service from provider:** The communication service provided by satellite can be operated by a government agency or a single company. This way the user depends on just one entity to provide service nationwide network. Using this method, full service can be provided by the organization without fragmentation of the network.
8. **Low cost:** the setup of DTH service to home is very simple that the home owners can install easily. The hand held/portable radio stations can be installed using simple components with a total cost not more than $1000 (Gerard Maral, 2009).

Chapter 4: The Ground Station

The primary objective of a ground station (GS) is to provide communication point for satellites. The satellites transmit data to the ground station when it passes over it at regular intervals of time. The orbit of satellite defines the times the satellite is visible to the GS. The telemetry and payload data are transmitted to the Earth and the telecommands for the in-orbit operations are received by the satellite; in this way, the ground station provides a platform for satellite control and communication.

4.1 Satellite when viewed from Earth

A satellite's orbit has effect on the visibility of satellite on Earth. The orbital parameters and patterns are discussed in Section 2.3.

4.1.1 Understanding certain definitions

1. Track of the Satellite

The path that satellite traces on Earth is the locus point of intersection of the satellite vector and earth center.

2. Angle of Elevation

The vertical angle formed between the horizontal plane and the direction of the signals transmitted from the satellite is known as the angle of elevation (elevation angle). Greater the angle of elevation, shorter the distance the signal should propagate. The elevation angle will vary from 0°-180°. When the elevation angle is small, the distance is longer, the signals suffer atmospheric loss and noise is added into the signal waves. To receive signals from a passing satellite, the minimum angle of elevation must be 5°.

3. Azimuth

The horizontal angle in the direction of Earth station antenna points is known as the azimuth angle. Azimuth is measured from 0°-360° from the North in the clockwise direction in the Northern Hemisphere and the South in the Southern Hemisphere.

4. Visibility

The visibility of satellite for communication depends upon the orbit in which the satellite is launched. The proposed ground station was used to track satellites that were launched in the Sun Synchronous LEO. The location of the GS on the Earth surface (the latitude and longitude) limits the visibility of satellite due to Earth's curvature. A satellite placed in a polar Sun synchronous Low Earth Orbit, the satellite rotates from north pole to south pole (approximately depending upon the inclination angle of the orbit), with reference to a location on Earth a satellite will be visible to the GS four times in a day.

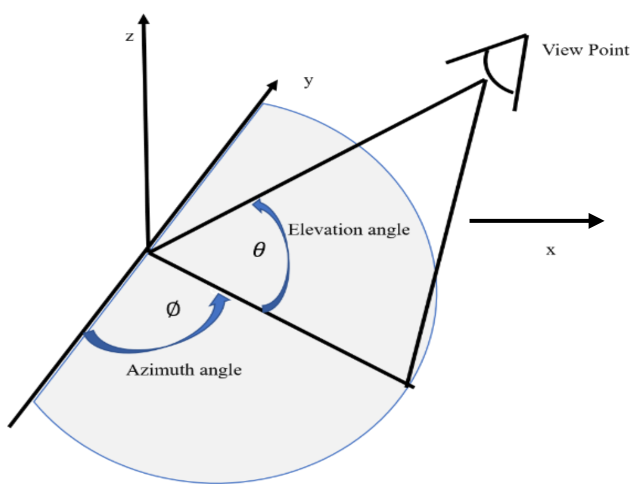

Figure 4: Illustration of Azimuth and Elevation angles

5. Doppler Shift

The Doppler effect/shift is one of the most important issues among many others like distance from Earth, atmospheric losses, radiation effects. The value and drift rates are large in non-GEO when compared to the satellites in GEO. The features of the Doppler shift are that its proportional to the carrier frequency, the satellites in LEO suffer positive Doppler shift and can be corrected by offsetting the carrier frequency.

4.3 Functionality of Ground Station

After the launch of a satellite, ground station plays an important role in communicating with it. The GS has many functions to perform such as preparing the ground station for tracking, receive data during the pass, understand the telemetry data during the pass to know the health parameters of the satellite and the payload data received is processed in the GS after the pass. The GS transmits commands for operations of the satellite (Divya Shankar, 2013).

4.3.1 Pre-pass phase

During the pre-pass phase, the GS is prepared for tracking satellites (Du, 2005). The steps involved in pre-pass phase are

1. Path prediction: The satellite track, time duration of the pass and the direction of the satellite movement is all predicted using the orbital calculation. Orbital calculation is an intricate set of calculations performed to know the satellite details such as altitude, velocity, satellite time etc. Path prediction can be done using tracking software and Two-Line Elements.

Two-Line Elements (TLE): North American Aerospace Defense Command (NORAD) keeps track of all the elements in space and provides data about them. Two-line elements are a set of encoded of Orbital elements such as satellite number, inclination, eccentricity, argument of perigee, mean anomaly, mean motion, revolution of epoch, check sum etc. Using the TLE the azimuth and elevation (position of the satellite) is determined using which the antenna is steered to that position to establish the communication link. The example of TLE of AO-73 is as shown in Figure 5

```
FUNCUBE-1 (AO-73)
1 39444U 13066AE   17337.73354852  .00000307  00000-0  44279-4 0  9998
2 39444  97.6116  12.8515 0059751  71.9297 288.8414 14.81590610216717
```

Figure 5: An example TLE for AO-73
Source: celestrak.com

2. Hardware: The hardware such as antenna, transceiver, control mechanisms are checked for its working before the pass. In sophisticated GS, the antenna is big and cannot be moved using hands. The antenna is placed on a rotor that rotates 0°- 360° (azimuth) and 0°-180° (elevation). The rotors are checked for its rotation. Transceivers are tuned to the reception frequency.
3. Command list: The set of commands to be transmitted to the satellite are planned and scheduled.
4. Simulation: The commands are simulated to check for any errors.

4.3.2 Pass phase

As the satellite comes into the visibility of ground station, the antenna is pointed towards the satellite. Based on the path prediction, the point at which the communication link is established with the GS and satellite is known as Acquisition of Signal (AOS) and the point at which the communication lost is known as Loss of Signal (LOS). In sophisticated ground stations, the antenna is mounted on rotors that have the capability to rotate through the azimuth and elevation. The receiver is tuned to the downlink frequency to receive the beacon and telemetry parameters. The received signals are decoded to know the health of the satellites. The payload data is also received. The set of commands are transmitted to the satellite and the acknowledgements are received from the satellite (Divya Shankar, 2013) (Du, 2005).

4.3.3 Post pass phase

After the pass of satellite, the telemetry and payload data are analyzed in the post pass phase. The received telemetry is decoded to know the details of the health of the satellite. The payload data are decoded. The software used for post processing can be an open source, and it can be developed in standard programming languages such as C, C++, Visual Basic, etc. (Divya Shankar, 2013) (Du, 2005)

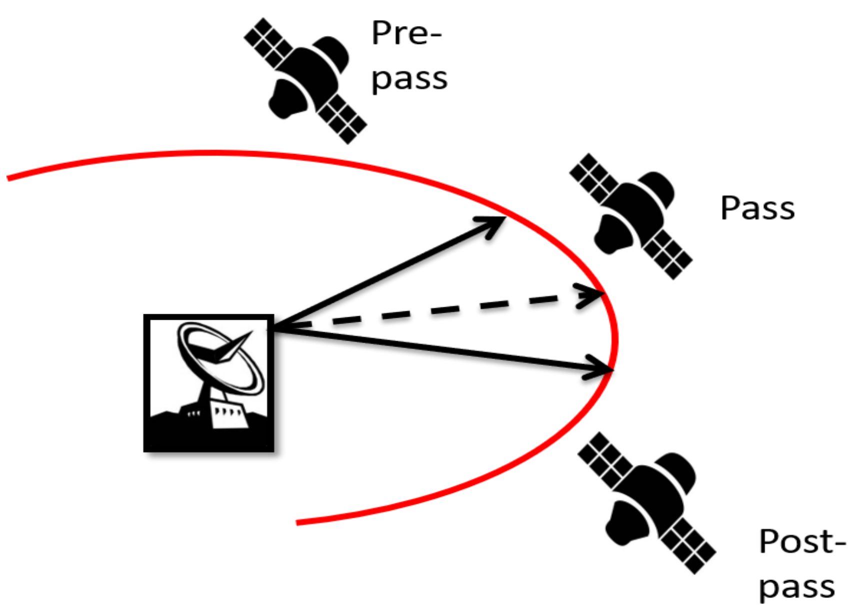

Figure 6: Illustration of phases of Ground Station

4.4 Ground Station Architecture

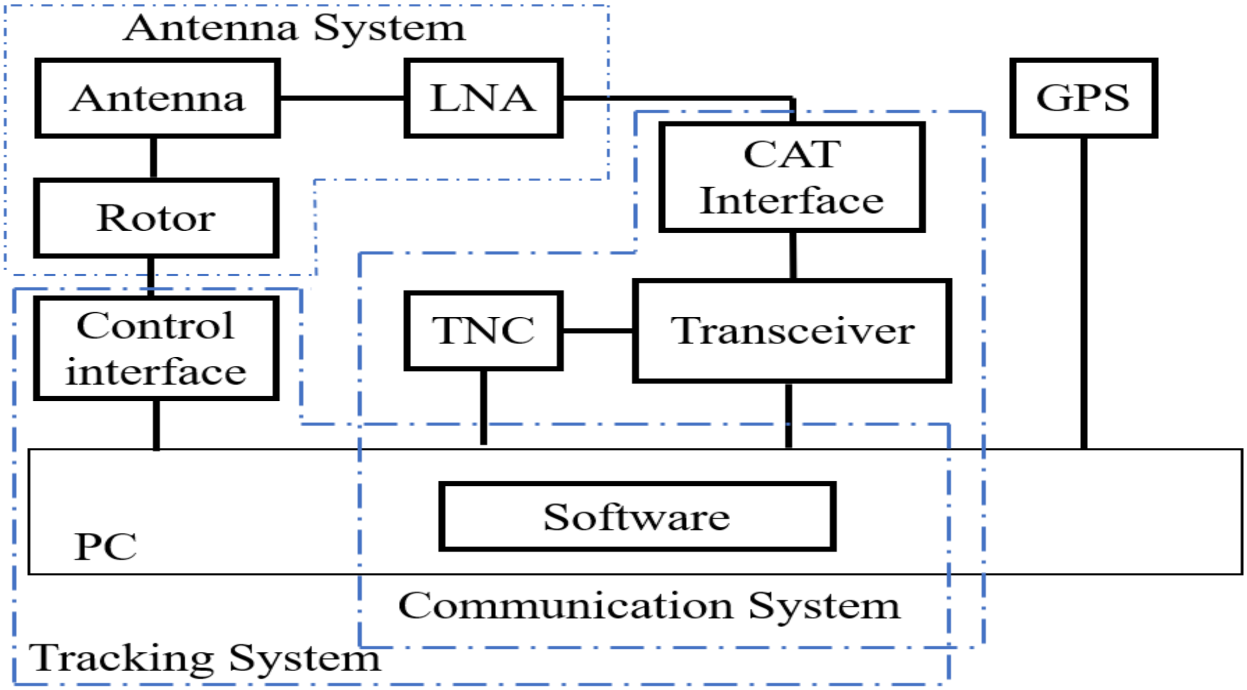

Figure 7: Ground Station Architecture

4.4.1 Antenna System

The antenna is the first and most important element of the communication chain. The key features that define the antenna are:

(i) Gain: the increase in the level of signal to a point, decibels is the unit of gain and is based on the logarithmic scale. A gain of 3 dB doubles the signal level. The gain and beamwidth re inversely proportional. Therefore, increase in gain is decrease in bandwidth.

(ii) Polarization: The orientation of the signals that are transmitted from satellite to that of the receiving antenna and vice versa. Polarization are two types (i) Linear (vertical and horizontal) and (ii) Circular (Right Hand Circular Polarized and Left Hand Circular

Polarized). The circular polarized antennas are preferred both on spacecraft and ground station to have more stable communication link.

(iii) Beamwidth: the width of the antenna pattern. The wider the beam, the more sources the antenna can receive concurrently (which also increases the probability of picking up interfering signals). The antenna with high gain usually have narrow beamwidth and needs to be pointed accurately at the satellite to establish the link. The omni directional antennas usually transmit or receive in many directions and are preferred when the antenna system does not have an accurate method to point and track the satellite.

4.4.2 Tracking System

The antenna is to be pointed in the direction of the entry of the satellite into the GS cone or window. To know the predicted path of the satellite, a tracking system is used. In a sophisticated ground station, the antenna is mounted on a rotor that rotates in 0°-360° (azimuth) and 0°-180° (elevation). The rotor is interfaced with a lab jack that corrects the pointing direction using the predicted path of the satellite and current position of antenna. In the proposed ground station, the antenna is handheld and the person operating the system needs to know the position of the satellite to establish the communication. The satellite path prediction can be done using software such as

(i) Nova for Windows

(ii) Orbitron

(iii) Website: N2YO.com, satflare.com, satview.org

4.4.3 Communication System

The communication system consists of the uplink and the downlink module. The communication system can be divided into two:

(i) Half-duplex communication system: At one point of time, only transmission or reception is possible.

(ii) Full-duplex communication system: The system can transmit and receive signals from source at the same time.

The uplink and downlink modules are explained in detail as below

Uplink Model

The chain of communication from the Earth to the satellite is known as the uplink model. The data that needs to be transmitted such as the control commands, messages modulated using Amplitude Modulation (AM), Frequency Modulation (FM), Phase Shifting Keying (PSK), Quadrature Amplitude Modulation (QAM). The modulated signal is filtered using a bandpass filter (BPF). After filtering, the signal is then mixed with the carrier frequency. The carrier signal with the data is then filtered using BPF. The filtered signal is then amplified using a Power Amplifier. The signal is then transmitted using an efficient antenna system to the satellite.

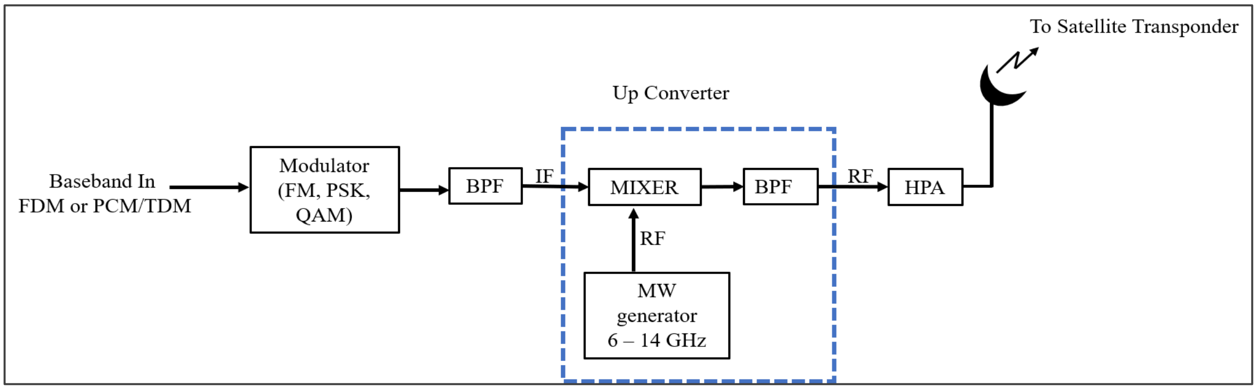

Figure 8: Uplink model of Communication System

Downlink Model

The data from satellite that is sent to the ground for processing is known as the downlink. The signals received from satellite is filtered using a BPF to avoid the unwanted signals. To reduce the noise, the signal is passed through a Low Noise Amplifier (LNA). The signal is then passed through a mixer that removes the carrier frequency. The signal is then passed through a bandpass filter. The signal is then demodulated to retrieve the data.

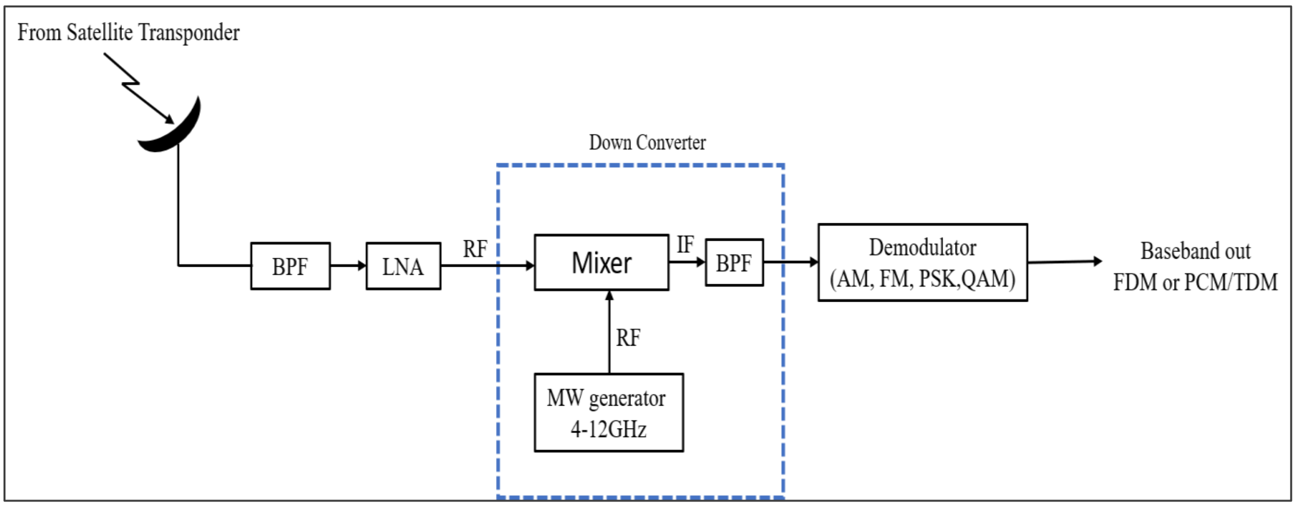

Figure 9: Uplink model of Communication System

4.4.4 Post processing

The signals received will be encoded and packetized. The received signal needs to be processed to make it readable. The signals can be processed live (during the pass) or the signals can be stored as audio files and processed after the pass. Using front end software such as High Definition Software Defined Radio (HDSDR), Ham Radio Deluxe (HRD), SDR Sharp (SDR#) can be used to store the signals in audio format. The signal processing includes filtering, demodulation, synchronization, pattern detection, image decoding etc. The tools used for post processing of the signals like MATLAB, GNU Radio, C programming, Python, Visual Basic. Programs can be developed to perform the signal processing.

4.5 Link Budget

4.5.1 Satellite Parameters for Link Analysis

Link analysis is a set of intricate calculations of the gains and losses within the link. The gains and losses are estimated, some are calculated, and the result is system performance (Divya Shankar, 2013). The link margin should be more than 0 dB for establishment of Link and more than 10 dB for a low-cost system. Some satellite parameters used in link analysis are shown below (Tomasi, 2014).

1. Back-off Loss: Earth station transmission system uses High Power Amplifiers (HPA) to transmit signals to the satellite. The gain is dependent on the input signal for the non-linear devices used in satellite communication systems. There is a compression of Power using a HPA. The equivalent loss that is caused by the output level back off is known as the Back-off loss and is expressed as L_{bo}.
2. Transmit Power and Bit energy: is the product of the power transmitted and the time of single bit transmission. Represented by E_b, bit energy is given by

   $$E_b = P_t \text{ x } T_b$$

   Where, P_t – transmitted power (W) and T_b – time of a single bit (s)
3. Effective Isotropic Power: the equivalent power that is transmitted from the antenna. It is represented by EIRP and is given by the equation

   $$EIRP = P_t \text{ x } G_t$$

   Where P_t = power transmitted, G_t – gain of the transmission antenna

4. Equivalent Noise Temperature: there is noise added to the receiver is known as the Noise Figure. It is often introduced by the terrestrial microwave systems and such noises need to be differentiated during the calculations for satellite links. The environmental temperature (T) and the equivalent noise temperature (T_e) are used when evaluating satellite systems. Therefore, the total noise power is expressed as

$$N = K * T * B$$

$$T = N/(K * B)$$

Where, N – total noise power (W), K – Boltzmann's constant (J/K), b – bandwidth (Hz), T – environmental temperature

5. Noise Density: the normalized noise power is known as Noise Density. Denoted by N_0 Noise density is mathematically calculated as

$$N_0 = \frac{N}{B}$$

$$N_0 = \frac{K\text{x}\, T_e * B}{B} = K * T_e$$

Where, N_0 – noise density (W), K – Boltzmann's constant (J/K), T_e - equivalent temperature (K), B – bandwidth (Hz)

6. Carrier to Noise Density Ratio: represented by C/N_0 is the wideband carrier power to the Noise density. The carrier to noise density ratio is given by the equation

$$\frac{C}{N_0} = C/(K * T_e)$$

$$\frac{C}{N_0}(\text{dB}) = C(\text{dBW}) - N_0\ (\text{dBW})$$

Where, C – carrier power, N_0 – noise density, K – Boltzmann's constant, T_e – equivalent temperature

7. Energy of Bit-to-Noise Density Ratio: is way to compare systems with different transmission rates, encoding techniques etc. It is a product of carrier to noise ratio and the noise bandwidth to bit rate ratio. It is denoted by Eb/No symbol and is an important and often used parameter to evaluate a digital communication system. It is given by the equation

$$\frac{E_b}{N_0} = \frac{\frac{C}{f_b}}{\frac{N}{B}} = (C * B)/(N * fb)$$

Where, E_b – energy per bit, C – carrier power, N_0 – noise density, N – system noise, B – noise bandwidth and f_b- bit rate

8. Gain to Equivalent Noise Temperature Ratio: is the ratio of the gain of the receiver antenna(G_r) to the equivalent system noise temperature (T_e). Denoted by G_r/T_e, Gain to Equivalent Noise Temperature is given by the equation

$$\frac{G_r}{T_e} = G_r - 10\log(T_s)$$

$$T_s = T_a + T_r$$

Where, G_r – gain of the receiver antenna, T_s – operating temperature in degree Kelvin (K), T_e – Equivalent temperature in degree K, T_a – Antenna Temperature in degree K and T_r – Receiver effective noise temperature in degree K

4.5.2 Factors affecting Link Analysis

1. Rain, Ice, Fog: is the product of the specific attenuation (γ_R dB/km) and path length of the wave (L_e km) is known as attenuation due to rain. The attenuation due to ice, fog can be estimated. (Gerard Maral, 2009)

2. The Faraday Rotation: the plane of polarization is rotated when signal passes through the ionosphere. The rotation angle is inversely proportional to the square of the frequency.
3. Atmospheric gases: the angle of elevation, latitude, water vapor and frequency causes attenuation in the signal.
4. Sandstorms: attenuation inversely proportional to the visibility and greatly depending on the humidity. It can be between 1-2 dB for path of 3 km.
5. Multi Path Contribution: the signals are received through reflections from ground, obstacles are known as multipath attenuation. This effect is reduced if the GS is equipped with the directional antenna.
6. Depolarization: the differential attenuation and phase shift between two orthogonal characteristic polarizations caused by rain results in depolarization.
7. Scintillation: the variation in the amplitude caused by the refractive index of the ionosphere and troposphere is known as Scintillation.

Chapter 5: The Proposed Ground Station

Understanding the concept of Ground Station and its working, a portable ground station was proposed as an academic project. Its architecture, hardware used, features and the outcome of the GS set up is explained in the Sections that follow.

5.1 The proposed ground station

The proposed ground station is a low cost and portable GS that can be used to track satellites in UHF and VHF amateur frequencies. Literature study was performed to understand the requirements and to select the equipment of the proposed ground station. The link margin was calculated to mathematically verify the communication link establishment using the selected antenna and receiver. The ground station is developed using a high gain Yagi Uda antenna, Low Noise Amplifier, a software defined radio and software that tracks, receives and processes the signals from satellites.

The highlight of the proposed GS is its low cost and portability. The project aimed at introducing satellite communication in the wireless laboratory courses. The GS was set up and satellites such as FUNcube (AO-73), International Space Station (ISS), National Oceanographic and Atmospheric Administration (NOAA) series satellites were tracked and signals received were post processed. The beacon signals received were processed for power density of carrier frequency, intermediate frequency. The images from the NOAA satellite series were decoded using WXtoImg, APTDecode and our own Matlab implementation, described later in this thesis.

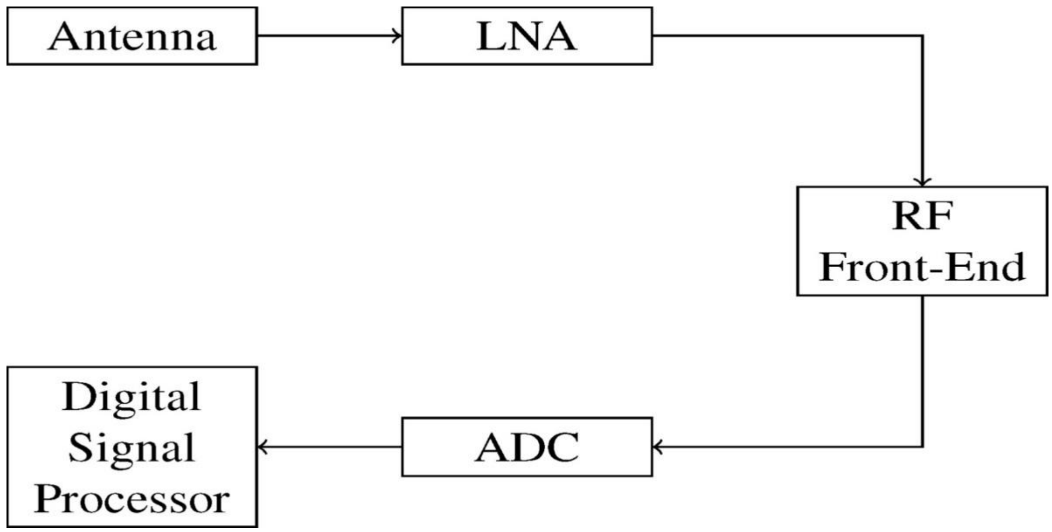

Figure 10: Proposed Ground Station Architecture

5.2 Features of the proposed ground station

The highlight of the GS set up is its cost and portability. The proposed ground station is very affordable. The cost is as listed in the table below, the cost of the laptop is omitted as its price varies greatly and most of us already own a laptop.

5.2.1 Cost

The cost of setting up a ground station is around $8000, the advancements in communication technology has reduced the cost of the ground station set up. University projects are limited on the expense, the highlight of this project is the cost. The components selected to set up the ground station are affordable. The cost of laptop is omitted since the price vary greatly and a laptop is generally available for use.

Table 4: Cost of the components in USD (including shipping and handling)

Item	Cost (USD)
Antenna	90
LNA	80
Receiver	200
Connectors	10
Cables	10
Total	390

5.2.2 Portability

Light weight equipment is easy to carry and handle. It can be taken to places where there is no infrastructure to support satellite tracking and set up quickly. The approximate weight of each equipment is weighed and tabulated as in Table 8. The use of COT components reduces the purchase of large and sophisticated equipment, its maintenance and use of large space to set up the GS.

Table 5: Approximate weight and size of each component

Item	Length(in)	Width(in)	Height(in)	Weight(g)
Antenna	37.5	20.25	-	250
FUNcube Dongle	3.3	0.7	0.4	50
LNA	2	1.6	0.6	75
Battery	2.6	2.6	3.7	680
			Total	1055

5.3 Final Architecture and Hardware of Ground station

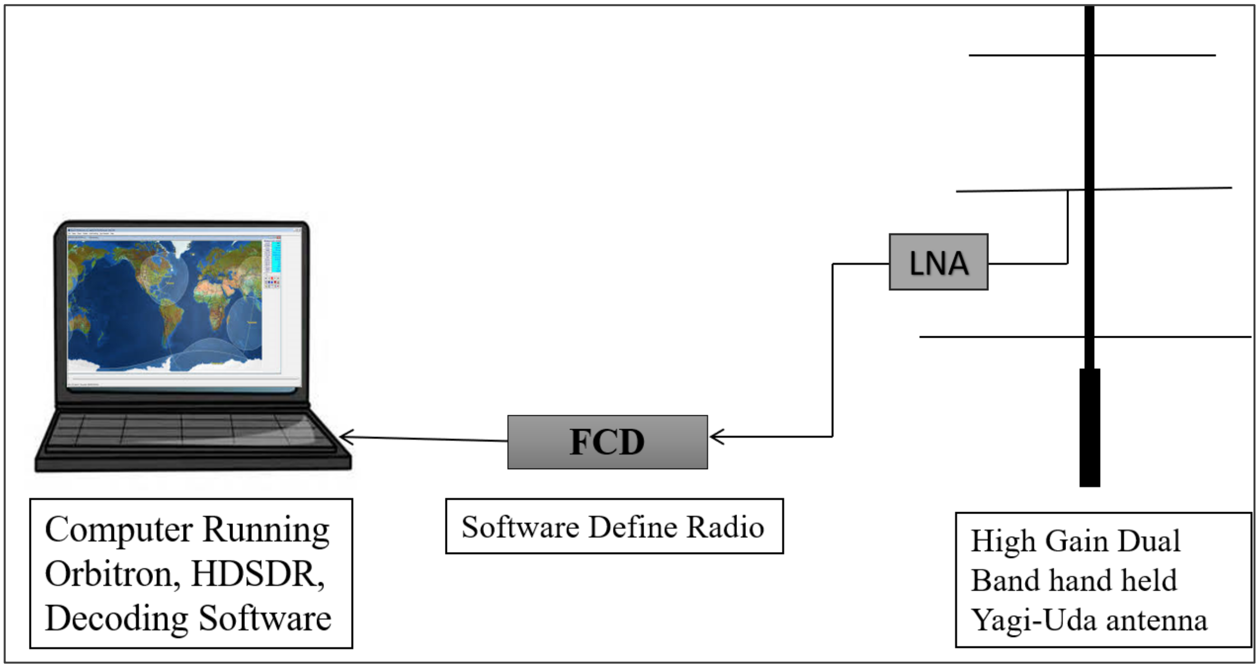

Figure 11: Final Architecture of Ground Station

Hardware of Ground Station

5.3.1 Antenna

Considering the factors such as gain, beamwidth, polarization, antennas used for ground station are omnidirectional antenna. Omnidirectional antennas have the advantage that it can receive and transmit signals in many directions. There are different types of antennas such as Yagi Uda, Turnstile can be used. In the proposed GS, a high gain Yagi Uda antenna is chosen.

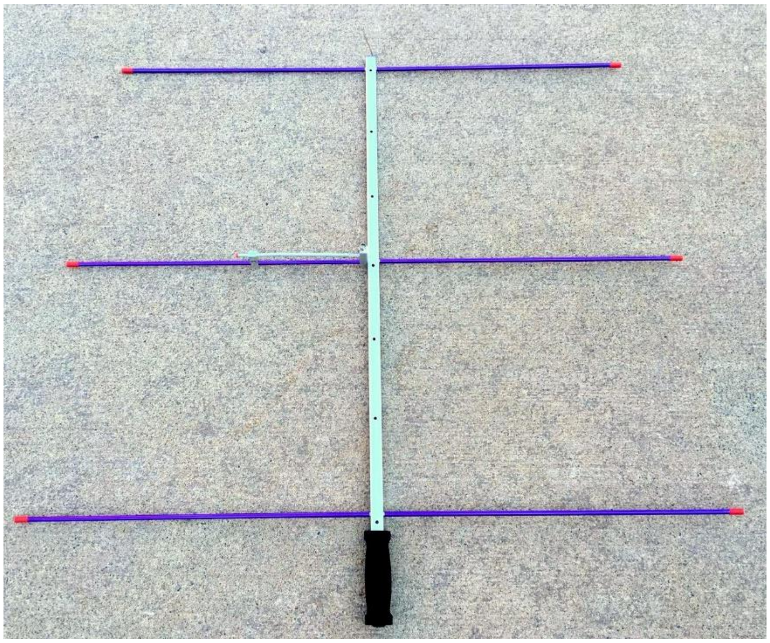

Figure 12: Hand-held Yagi-Uda antenna with 5dB gain

5.3.2 Low Noise Amplifier (LNA)

A Low Noise Amplifier (LNA) is added close to the antenna to decrease the noise in the signal received. A preamplifier can also be used to increase the signal strength. The chosen LNA features are as follows

Table 6: Features of LNA

Frequency range	28MHz – 2500MHz
High Gain	23.5d B @ UHF 23.5d B @VHF
Size	25mm*25mm built on Printed Circuit Board
Current Rating	55m A – 65 m A
Voltage	6-9V
Cost	Low

Figure 13: Low Noise Amplifier with gain of 23.5dB @VHF frequencies

5.3.3 Transceiver

The transceivers range from the conventional radios to the software defined radios. Transceivers detect radio signals in the operating range of frequencies and decode the signal. When connected to a computer with appropriate interface, the signals received can be recorded. Similarly, the data to be transmitted can be digitalized and transmitted through the transceiver to the antenna and to satellite. The conventional radios are replaced by Software Defined Radio. The focus of this thesis Software Defined Radio (SDR) (Maheshwarappa, 2016). The architecture of SDR is as below

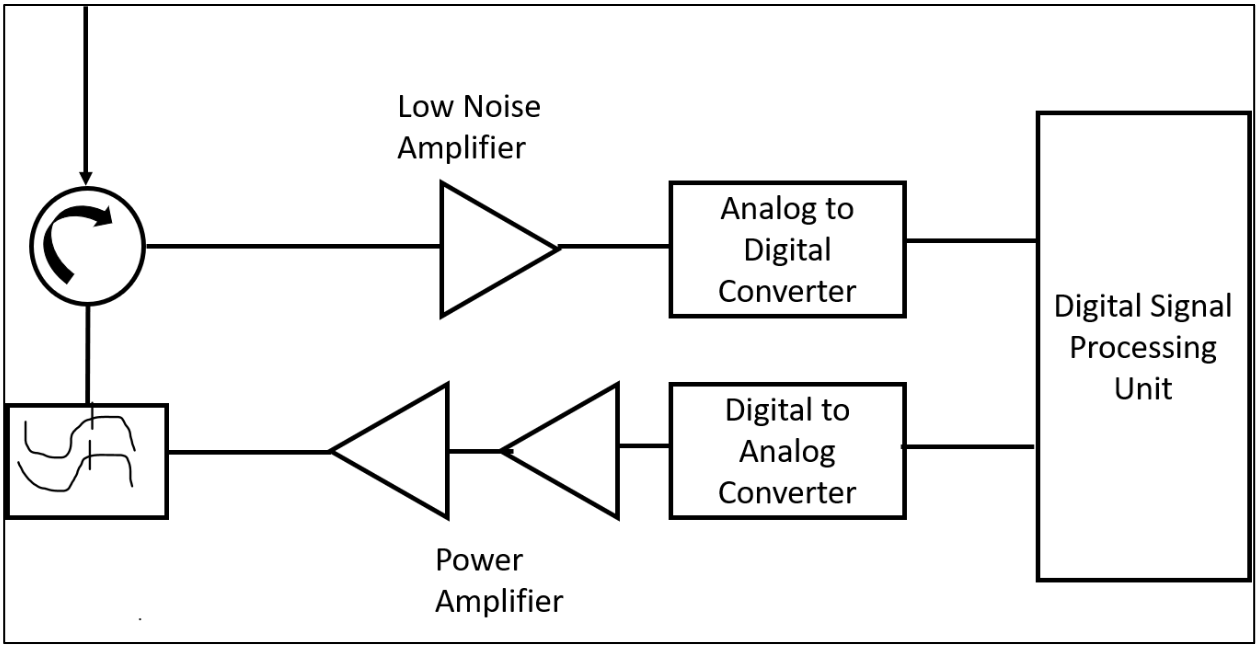

Figure 14: General Architecture of SDR

Difference between a conventional radio and a software defined radio (SDR)

Table 7: Difference between conventional radio and SDR

Conventional Radio	Software Defined Radio
Design is fixed	Design is flexible
The complexity is in the hardware	The complexity of design is in the software and it's a reconfigurable platform
Cannot be upgraded during the mission	Software can be upgraded during the mission
The design complexity present in hardware	The complexity present in software
Single band/mode of operation	Multi band/mode of operation
Limited processing	More processing, needs faster processor and ADC's

The SDR used for GS is FUNcube Dongle (FCD). SDR the FUNcube Dongle is a simple design that connects the antenna and a USB connection on the other end. Designed to work on amateur bands from 150kHz to 1.9GHz, SDR performs demodulation, decoding and frequency conversions. Based on its popularity and demands, FUNcube Dongle was updated to FUNcube Dongle Pro+. FCD has many applications and was designed to be a receiver or FUNcube satellite (Long)

Figure 15: Software Defined Radio

The specifications of FCD are as follow

Table 8: Features of FCD

Frequency range	150kHz to 240MHz 420MHz to 1.9GHz
Noise Figure	VHF – 3.5d B UHF – 3.5d B
Sampling Frequency	192kHz
Connection	Standard SMA female antenna port USB 1.x
Operating System	OSX, Windows, Linux
Filter	3-5 order bandpass

5.3.4 Power Amplifier

A power amplifier can be used in the communication chain during the uplink. A power amplifier increases the signal strength that is transmitted to the satellite. The power amplifier can be selected based on the needs to uplink communication chain (Divya Shankar, 2013).

5.3.5 Terminal Node Controller

A terminal node controller is used to packetize the data that must be transmitted to the satellite. The list of commands generated are given to the TNC that packetizes the data inserting the headers, and frames the data and then sends it to the transceiver. From the transceiver the data is sent to the antenna for transmission. The TNC can use different protocols and the commonly used protocol is AX.25 for small satellite.

5.4 Link analysis

Most CubeSats transmit approximately 20 dBm of power. Our front-end, the FunCube Dongle, has a sensitivity specified as -100 dBm (Culross, 2011), (Howard Long, 2011). For digital signals, we need to ensure that the signal to ratio is larger than 10 dB. Using these figures, we can do a link budget calculation that will tell us whether the ground station will operate successfully and will allow us to estimate its expected performance.

Link analysis was done to make sure the proposed set up will be able to establish the communication with the satellite.

The carrier to noise ratio for the downlink is given by

$$\frac{C}{No} = EIRP * \frac{1}{L} * Gr/(K * Te)$$

where EIRP is the effective isotropic radiated power, L is the total loss in the link including free-space and equipment losses, G_r is the receiver gain, T_e is the equivalent system noise temperature, and K is Boltzmann's constant.

We assume the following system parameters:

- Power transmitted from satellite antenna P_t = 300 mW
- Transmitted carrier frequency f_c = 145.935MHz
- Transmitter antenna gain G_t = 0dB
- Receiver antenna gain G_r = 5dB
- Receiver noise figure N_f = 3dB

We assume that [.] represents the logarithmic value in decibels.

The EIRP is given by

$$EIRP = P_t * G_t$$

$$[EIRP] = [P_t] + [G_t]$$

$$[EIRP] = 10\,log(0.3) + 10log(1)$$

$$[EIRP] = -5.3\text{dB}$$

The wavelength λ is calculated as

$$\lambda = c/f_c$$

$$\lambda = 2.07\text{m}$$

The free space loss is

$$L_{fs} = (4\pi h)^2/\lambda$$

Where h is the height of satellite from Earth. This results in

$$L_{fs} = 20\log(4\pi * 600 * 10^3) - 20\log(2.07) = 131.3\text{dB}$$

The antenna is not circularly polarized; thus, we assume that the polarization loss is L_p 3dB and the atmospheric losses to be L_{atm} 0.8 dB. The total propagation loss is calculated as

$$[L] = [L_{fs}] + [L_p] + [L_{atm}] = 131.3 + 3.0 + 0.8$$

$$[L] = 135 \text{ dB}$$

The manufacturers of arrow antenna do not publish specifications about the antenna gain. We assume antenna gain is G_r= 5dB, Noise figure N_f= 3dB and environment temperature is 300K. Therefore, Equivalent Temperature $Te = (2 - 1) * (300K) = 300K$

The receiver's figure of merit is $\frac{G_r}{T_e} = -19.8$ dB.

The carrier to noise ratio in decibels

$$\frac{C}{N} = EIRP * \left(\frac{1}{L}\right) * \left(\frac{Gr}{Te}\right) * \left(\frac{1}{kBif}\right)$$

$$[C/N] = [EIRP] - [L] - [G_r/T_e] - [k] - [B_{if}]$$

$$\left[\frac{C}{N}\right] = -5.2 - 135 - 19.8 + 228.6$$

$$[C/N] = 68.6 \text{ dB}$$

We know that FUNcube data transmission rate R_b = 1200 bps using BPSK modulation. The bit energy is given by

$$[E_b] = C/R_b$$

Thus, signal to noise ratio is given by E_b/N_0 = 37dB

The bit error rate (BER) is set to 10^{-5}, the signal to noise ratio = 10 dB. The GS link margin is then

$$M = E_b/N_0 - \text{(desired BER)}$$

$$M = 37 - 10 = 27\text{dB}.$$

Given this result, we can be confident that the proposed GS will be able to record useful signals from most satellites and the ISS. However, this link budget is somewhat optimistic. We have not accounted for many sources of interference and other losses that occur in practice. For example, recent experiments show that the FM broadcast band introduces significant power into the receiver, resulting in degraded LNA performance.

5.5 Software

Software are used to predict the path of the satellite, signal decoding, image display mostly these software's are freeware that can be downloaded from internet directly. The software's used in the GS are as below.

Tracking software: Two software's commonly used in GS are (i) Nova for Windows (NfW) and (ii) Orbitron. Satellites can be tracked online on websites such as N2YO. Nova for Windows (NfW): is a satellite tracking software by Northern Lights Software Associates (Owen, 2000). Some popular features of NfW are stunning maps, unlimited observers and views, tracks satellites, Moon, planets, Sun, accurate and fast, built in auto-tracking, online support, Alarms for AOS and LOS, direct download and update of TLE. The set-up and instructions are clearly documented in

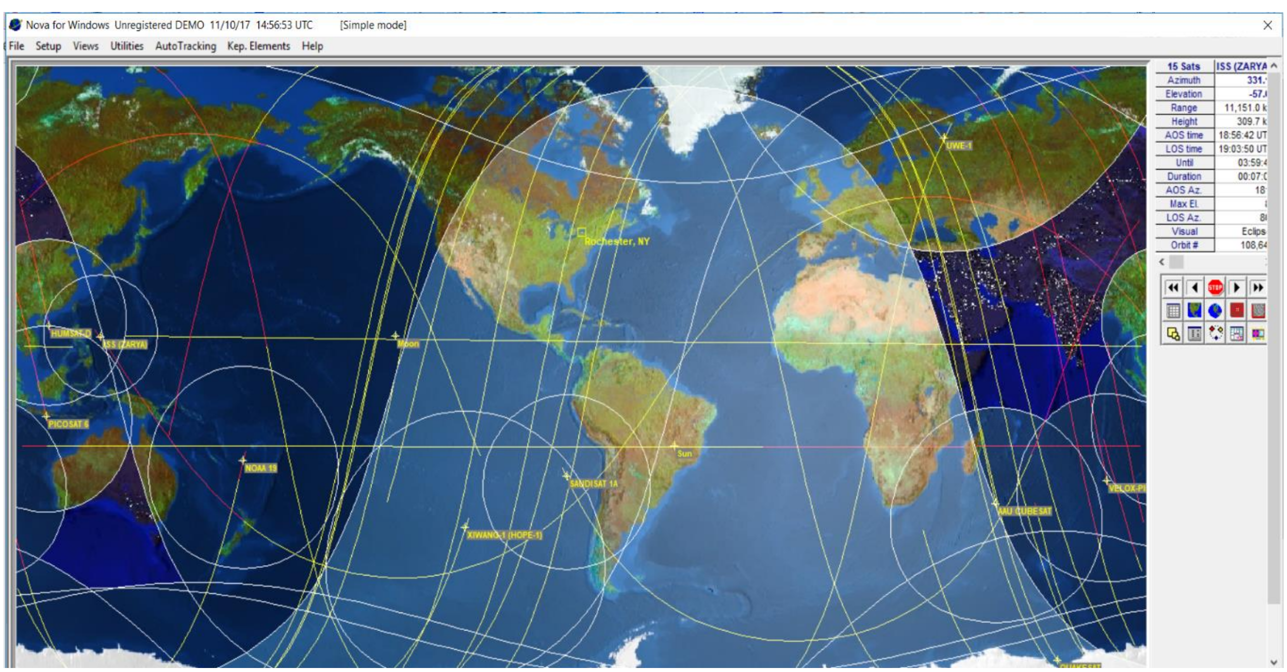

Figure 16: Rectangular World Map view using NfW

the User's manual for NfW (Owen, 2000). There is a demo version of NfW after the trial, the software license can be purchased online.

(i) Orbitron: is a card ware, it means Orbitron can be used for free. The software features are direct update of TLE, simulation of the pass, rotor interface, world map and the view of the ground station cone of window for communication on the same display window. Figure 17 shows the view of Orbitron window with satellites and its path. Orbitron can update TLE online or manually. The satellite pass can be simulated before the actual pass to know the track of the satellite.

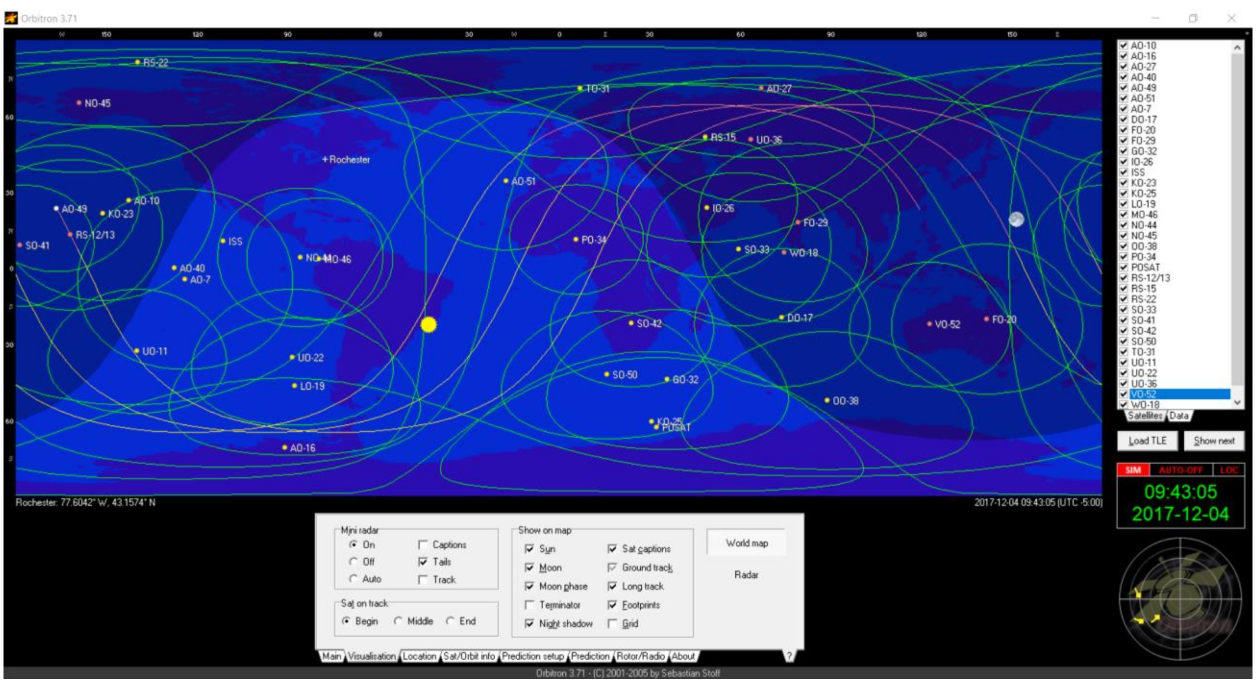

Figure 17: View of the world map using Orbitron

Communication Software: To interface the radio to the computer to display the signals, software is used. There are many software's that can be used such as Ham Radio Deluxe (HRD), High

Definition Software Defined Radio (HDSDR), SDR Sharp (SDR#). HDSDR and SDR# are freeware that can be easily downloaded from websites.

HDSDR: can be easily downloaded from website, it is a program for Microsoft Windows. Its features are large spectrum and waterfall display, I/Q modulated signal pair for transmitted input signal, record and play back of the signals, save the signals as .wav file, communication modes such as SSB, AM, FM, CW, noise reduction, inbuilt adjustable band pass filters, noise blankets. Clear documentation and user manual to learn the tool.

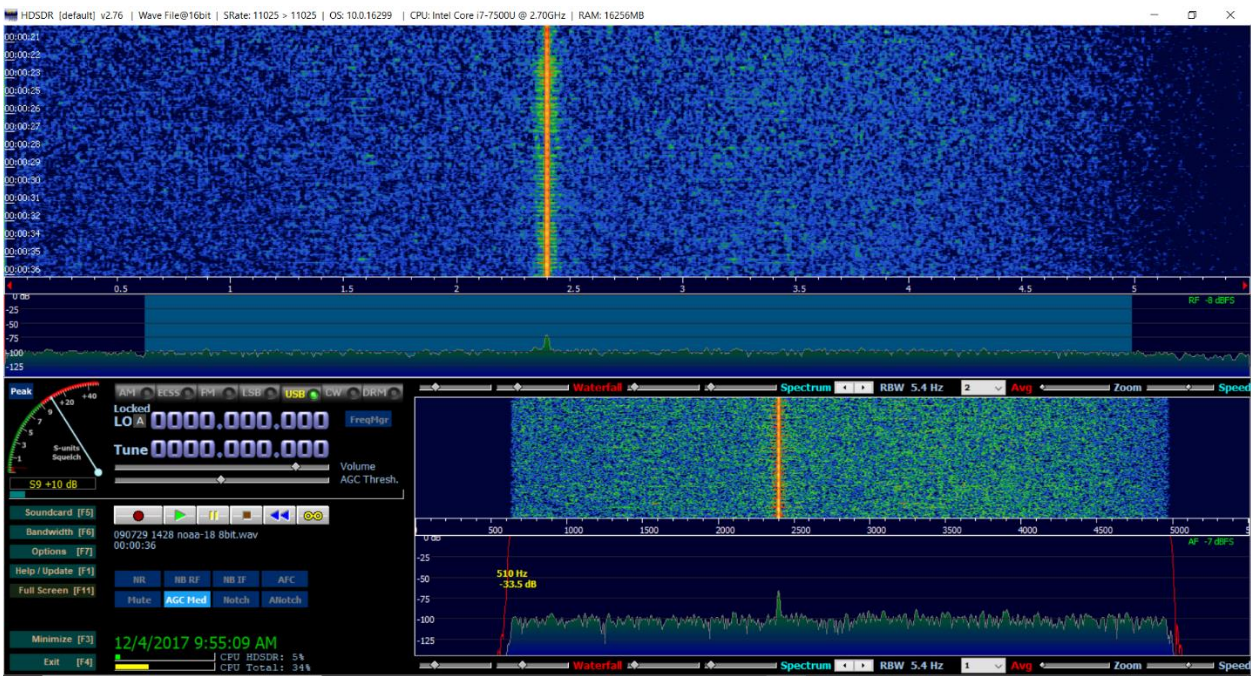

Figure 18: Front panel of HDSDR

SDR Sharp: denoted as SDR#, it features the following advantages (i) scan button for simple scan through the group, (ii) DMR support, (iii) frequency remains to be constant by holding the shift key while moving the spectrum left or right, (iv) recording the signal. Figure 19 shows signal reception using SDR sharp.

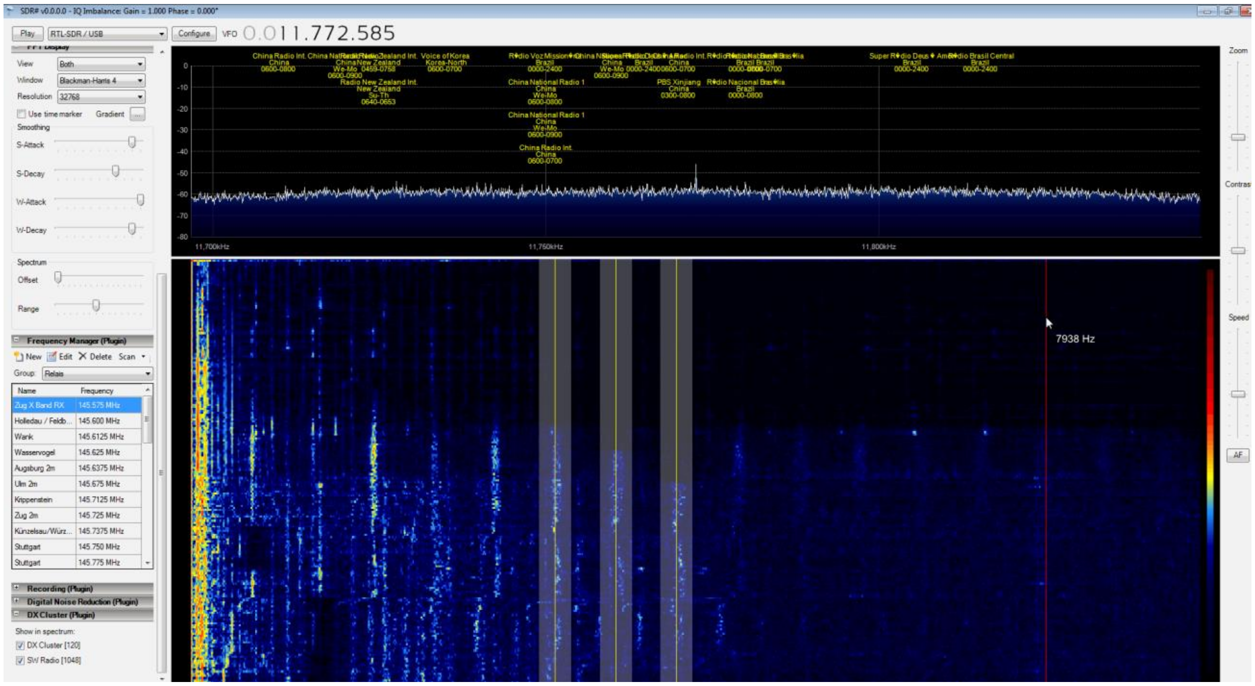

Figure 19: View of the SDR# window
Source: rtl-sdr.com

Chapter 6: Using the proposed GS

Satellites operating in VHF frequency band were tracked using the proposed GS. The technical details of satellites tracked, signals received, and the processing performed on these signals are explained in this chapter.

6.1 Satellite FUNCUBE

The project FUNcube was started by the AMSAT-UK and was developed by a team from AMSAT-UK and AMSAT-NL. It is a pic-satellite that has a transponder payload that aims to involve school students to track and receive telemetry data from the satellite. It operates on UHF and VHF frequencies that can be used by radio operators worldwide (Johnson, 2013).

Technical details of FUNcube -1

The technical details and an image of FUNcube-1 is as in Table 4 and Figure 12.

Table 9: Technical Details of AO-73

Name	FUNCUBE-1
Satellite Id	AO73
Orbit	Polar Sun Synchronous
Altitude	678 km
Inclination	97.7°
Category	Pico
Payload	Transponder
Orbital Time	97.3mins
Downlink Frequency	145.950 – 145.970MHz
Uplink Frequency	435.150-435.130MHZ
Beacon Frequency	145.395MHz
Bandwidth	2kHz
Modulation	BPSK
Data rate	1200 bps

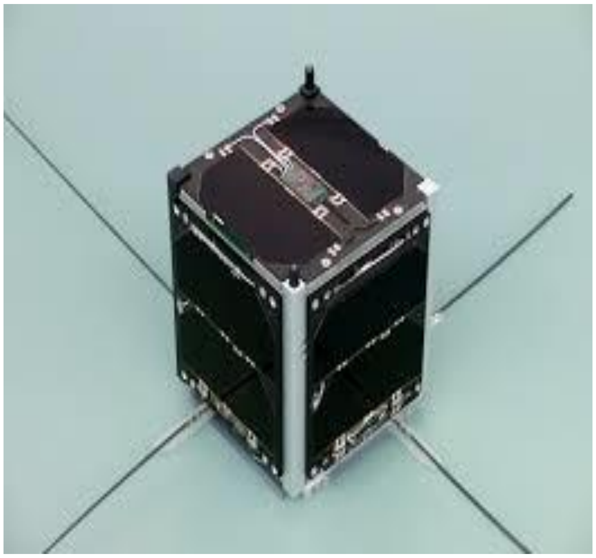

Figure 20: Flight model of FUNcube
Source (Johnson, 2013)

FUNcube was tracked outdoor using Orbitron for satellite path prediction, HDSDR as the front-end software to receive signals from the satellite. The signals received was further analyzed for its power density, unmodulated intermediate frequency. Figures below show the process of tracking, signal reception and analysis.

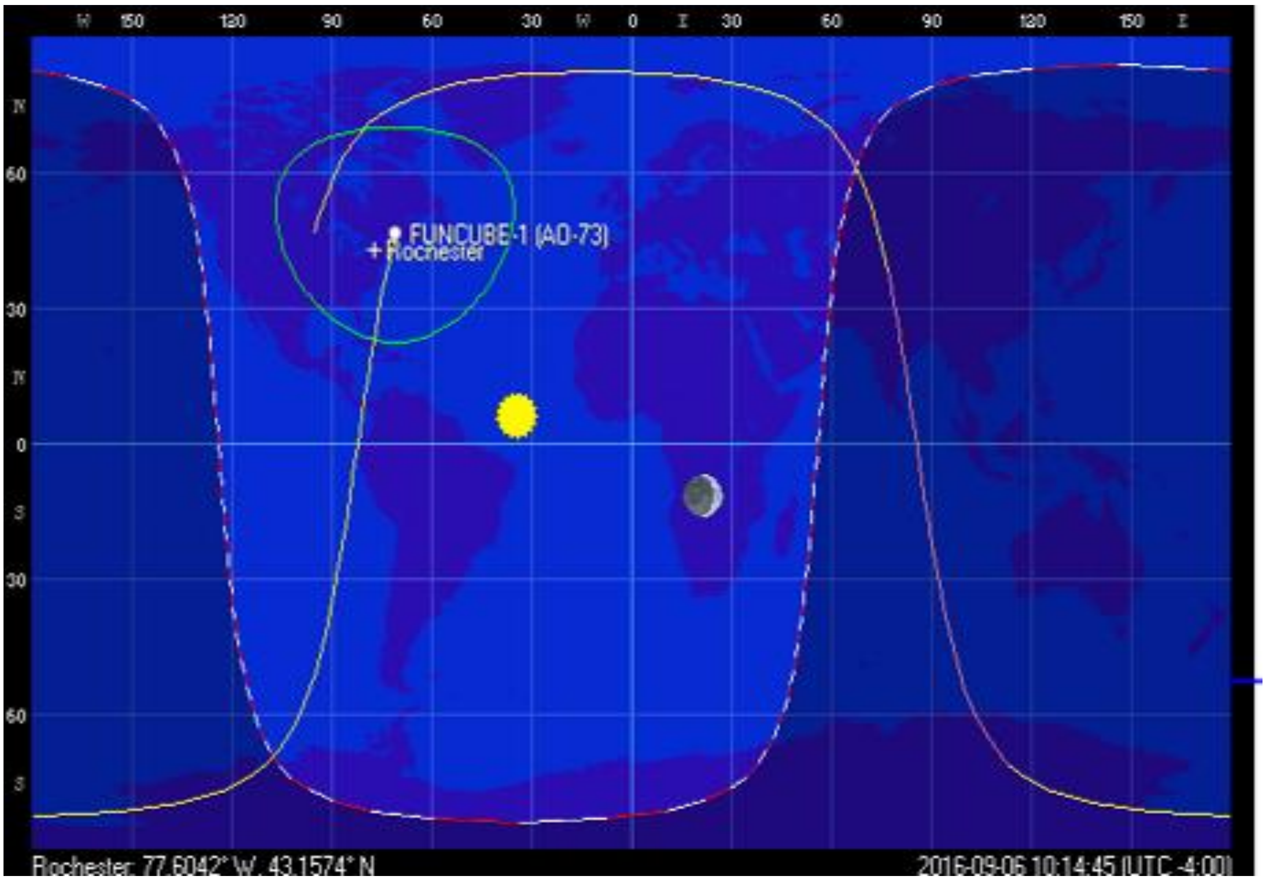

Figure 21: On-going pass of AO-73 over Rochester,NY

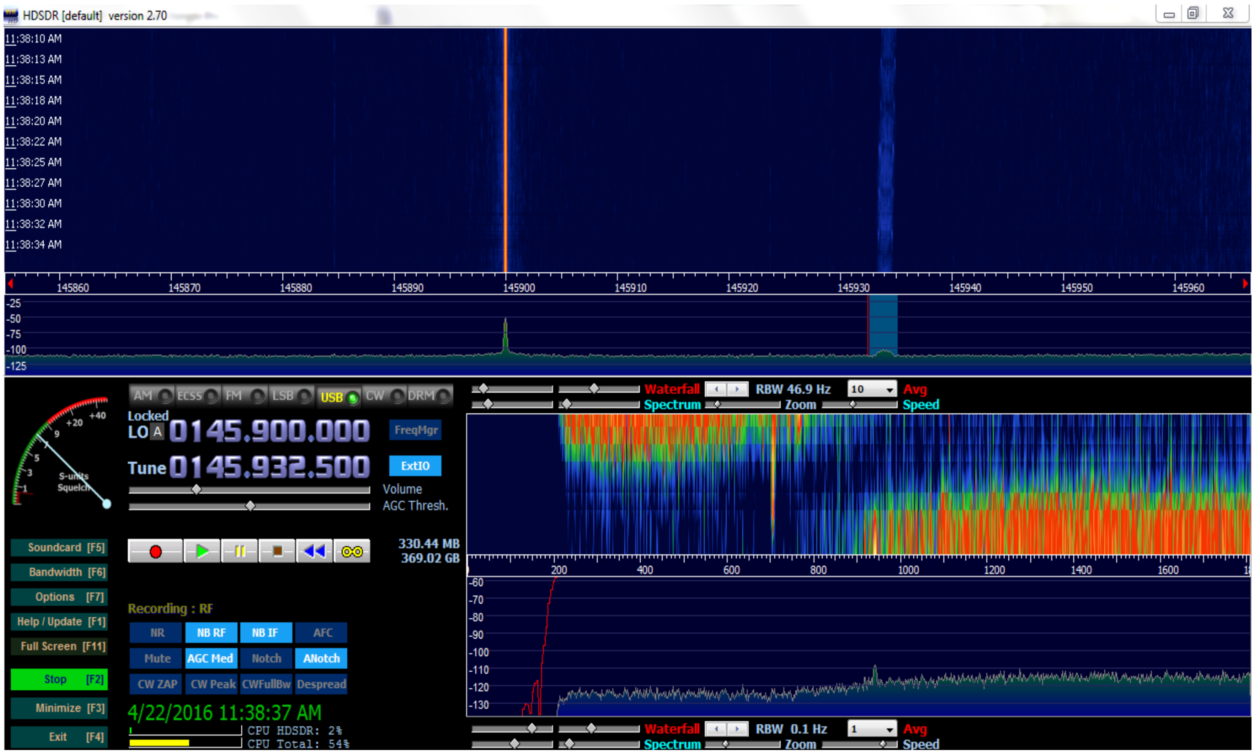

Figure 23: Beacon reception from AO-73

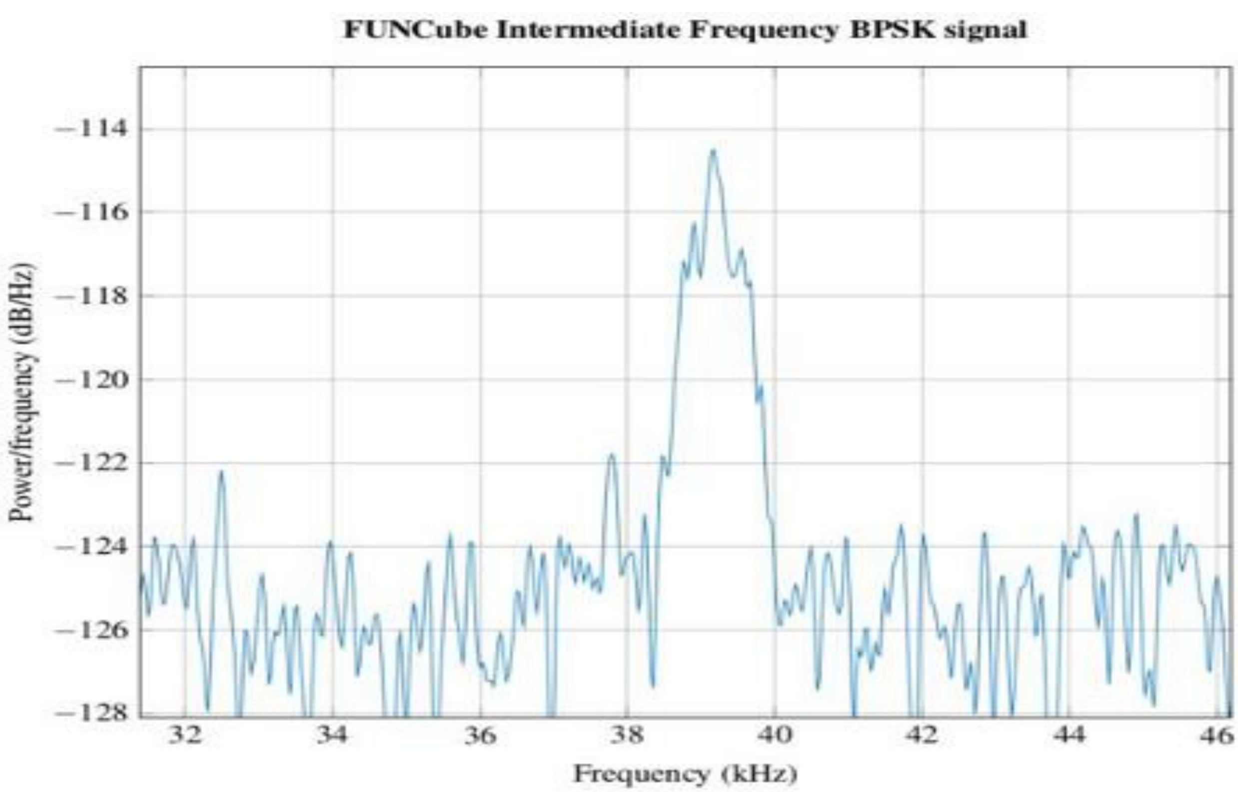

Figure 22: Power spectral density of intermediate frequency of BPSK signal from AO-73

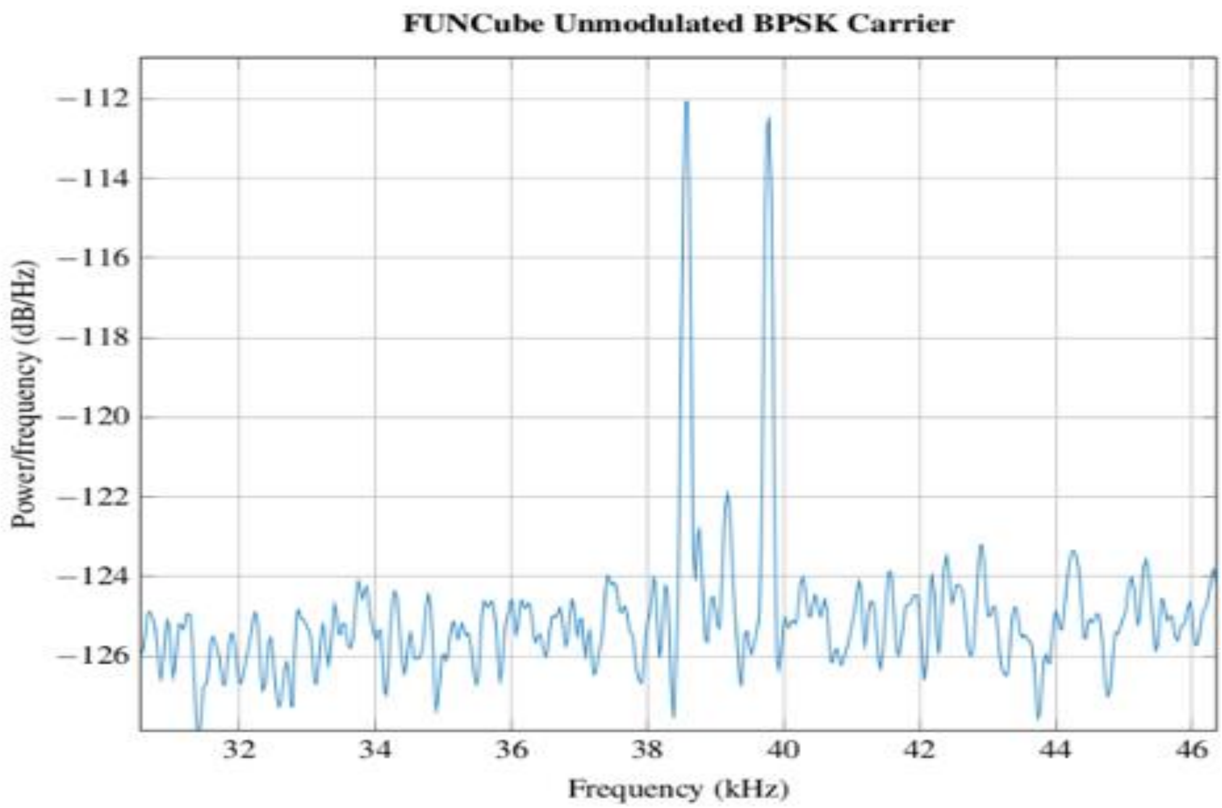

Figure 24: Power spectral density of the unmodulated BPSK carrier of AO-73

6.2 International Space Station

The International Space Station (ISS) is a large habitable space craft that orbits the Earth in the LEO. It is the result of a constant effort of 16 countries led by the NASA, USA. The ISS was assembled module wise, the first one began in 1998. The first module was called Zarya. The ISS is even now recognized as ISS-ZARYA named after its first module. The purpose of ISS was scientific research, micro gravity, space exploration, education and culture outreach and many more. ISS is 16 years old now and is continuously occupied by astronauts (Catchpole, 2008). The technical details and the image of ISS is as in Table 10 and Figure 25.

Table 10: Technical details of ISS

Name	International Space Station
Satellite Id	ISS-Zarya
Orbit	LEO
Altitude	405.16km
Inclination	51.6°
Orbital Period	93 mins
Beacon	145.825MHz
Uplink	145.825MHz
Downlink	145.825MHz
Data rate	1200 bps
Modulation	AFSK

Figure 25: International Space Station(ISS)
Source: NASA

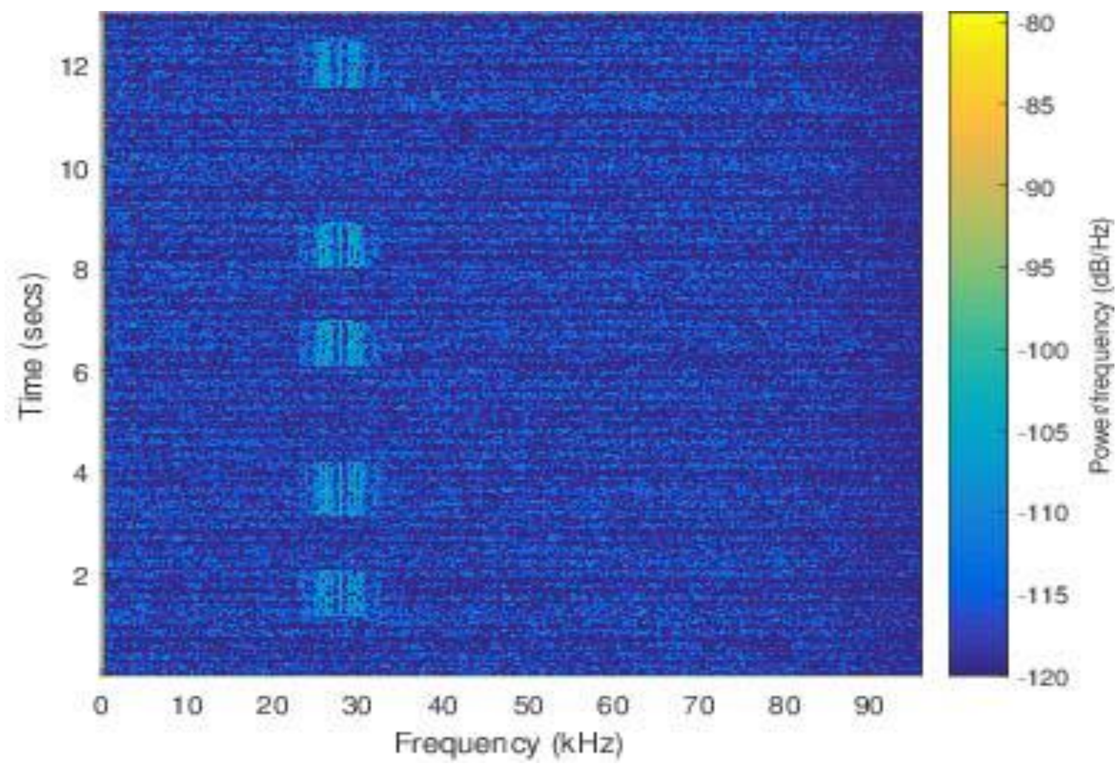

Figure 26: Beacon reception from ISS

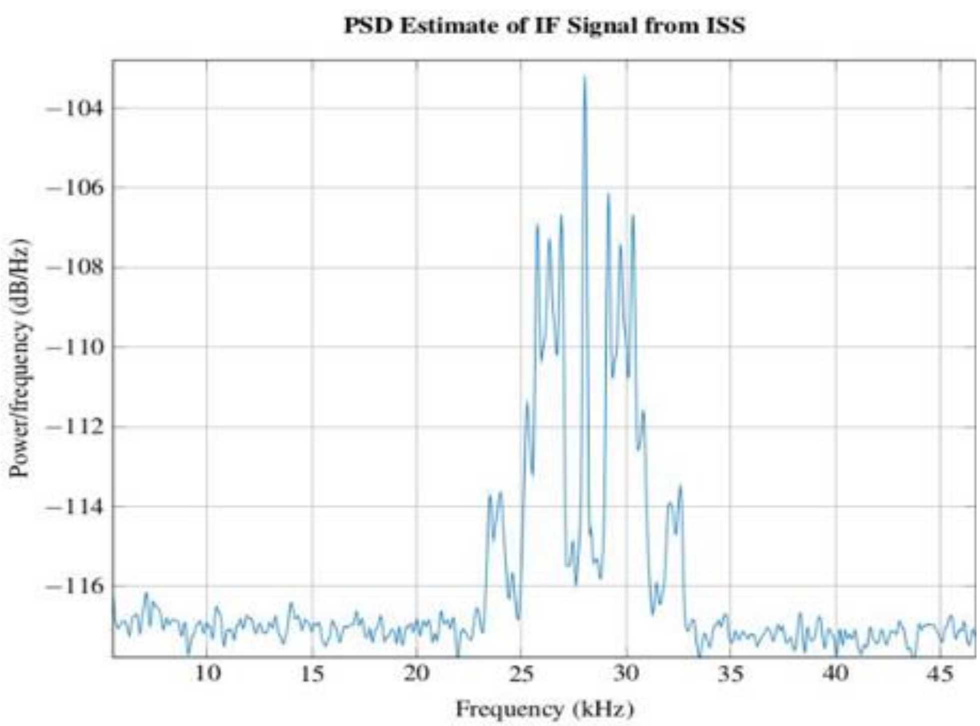

Figure 27: Power spectral density of signals from ISS

6.3 NOAA Satellites

National Oceanographic and Atmospheric Administration is an American agency formed in the year 1970 to understand the environment and to provide better forecast of weather, natural hazards, study of the oceans and atmosphere. A series of satellite names POES, NOAA-N were launched by NOAA to serve the purpose. NOAA satellites transmit APT images at VHF frequencies. The GS was able to track and capture signals from NOAA -18 and 19.

Table 11: Technical details of NOAA satellites

Satellite Name	National Oceanic Atmospheric Administration
Satellite Id	NOAA 15,18,19
Orbit	Polar Sun Synchronous
Altitude	870Km
Category	Large
Orbital period	102mins
Inclination	99°
Payload	Imaging
Downlink Frequency	137.35MHz

Figure 28: NOAA 19
Source: NASA

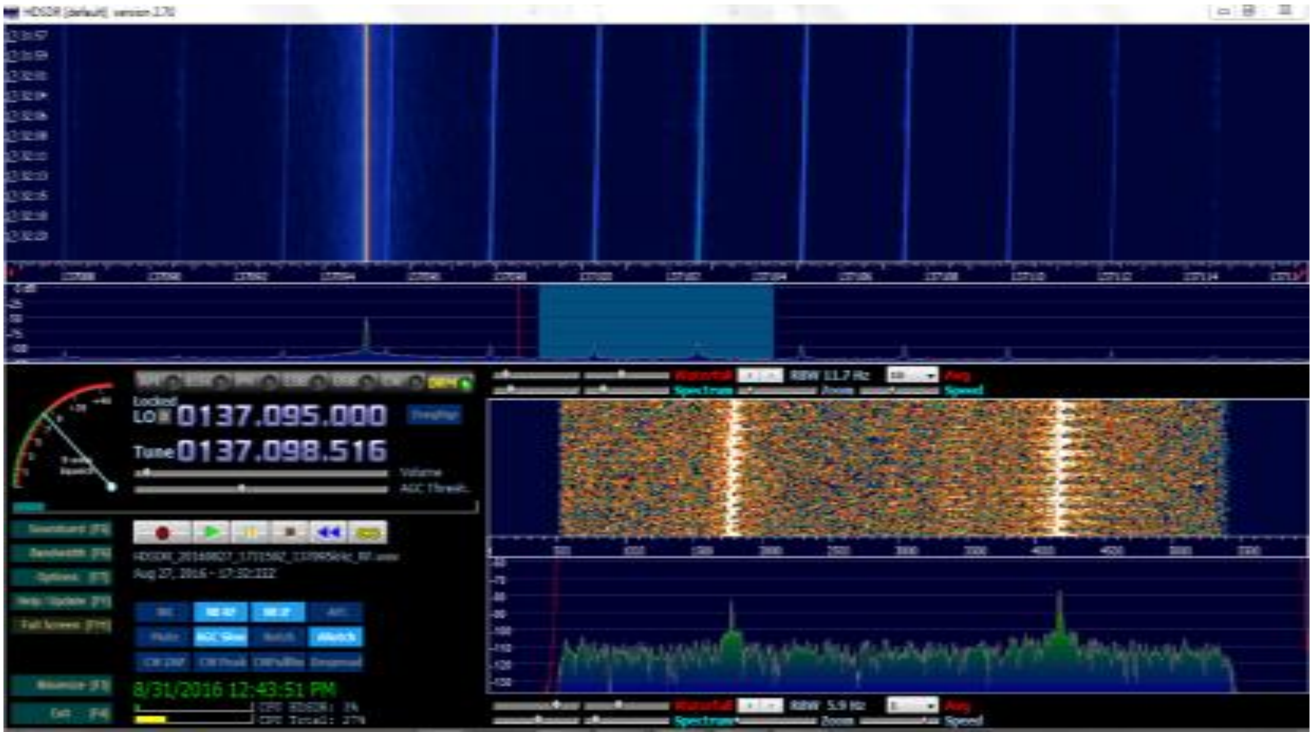

Figure 29: APT signal reception from NOAA satellite

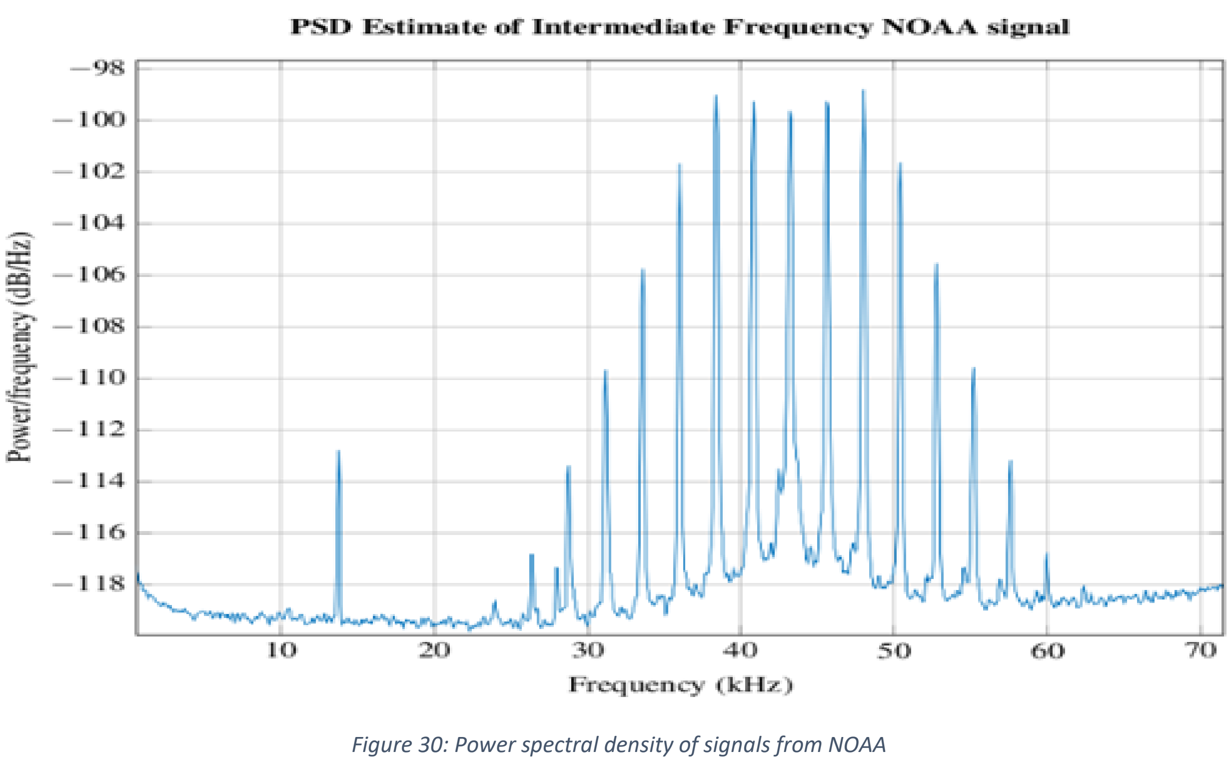

Figure 30: Power spectral density of signals from NOAA

Chapter 7: Satellite Image Recovery

7.1 Automatic Picture Transmission

Real-time video images are produced by the analog APT system that can be received and decoded by a low-cost ground stations. The sub-carrier frequency of 2400 Hz is Amplitude Modulated with the 8 most significant bits of the 10bit digital AVHRR data. The result of this is an analog signal with varying amplitude as a function of AVHRR digital data. Two spectral channels of AVHRR are multiplexed to produce channel A APT data and channel B from another spectral data. The third line is omitted and then the process is repeated. The APT data contains 1/3 of the AVHRR 360 scan lines/min (Commerce, 2009; Kawaya Swana, 2006). Therefore, the signals are received at 120 lines/min of the video. The APT frame format is as shown in figure below.

The 500ms line of image has 250ms of IR data and 250ms of visible light. The 250ms consists of Earth data and the sync pulse and telemetry frames. The data can be described in detail as follows

1. IR Sync Sequence: the IR scan line starts with square wave sync sequence at 832Hz. The receiver detects the 832Hz to detect the IR image. The IR sync and the visible light sync together make up the tick-tock sound while receiving APT signal.
2. IR Pre-Earth Scan: the IR sensor scans empty space before scanning the Earth. This appears as white strip down the IR image as cold is represented as white. There are black horizontal lines in the image that is the minute markers inserted by the spacecraft clock.
3. IR Earth Scan: the warm objects appear black or shades of gray while the cold objects appear white or light gray, the 250ms of the data contains the scan of Earth’s surface.
4. IR Telemetry: the IR data frame ends with the telemetry bits. The telemetry information can be used to obtain the temperature data.

5. Visible Sync Sequence: the IR data is followed by the Visible image. Like the IR sync, visible sync begins with seven pulse sequence at 1040Hz. It appears as narrow vertical stripes on the left side of the image.
6. Visible Pre-Earth Scan: A black strip on the side of the visible image is the scan of deep space. The white lines in the image is the 1min marker inserted by the spacecraft clock.
7. Visible Light Earth Scan: The major portion of the 250ms visible data is Earth scan data. The land, clouds and oceans appear in varying shades of black and white.
8. Visible Light Telemetry: The end of the visible data is the telemetry but it's not similar to the IR wedges.

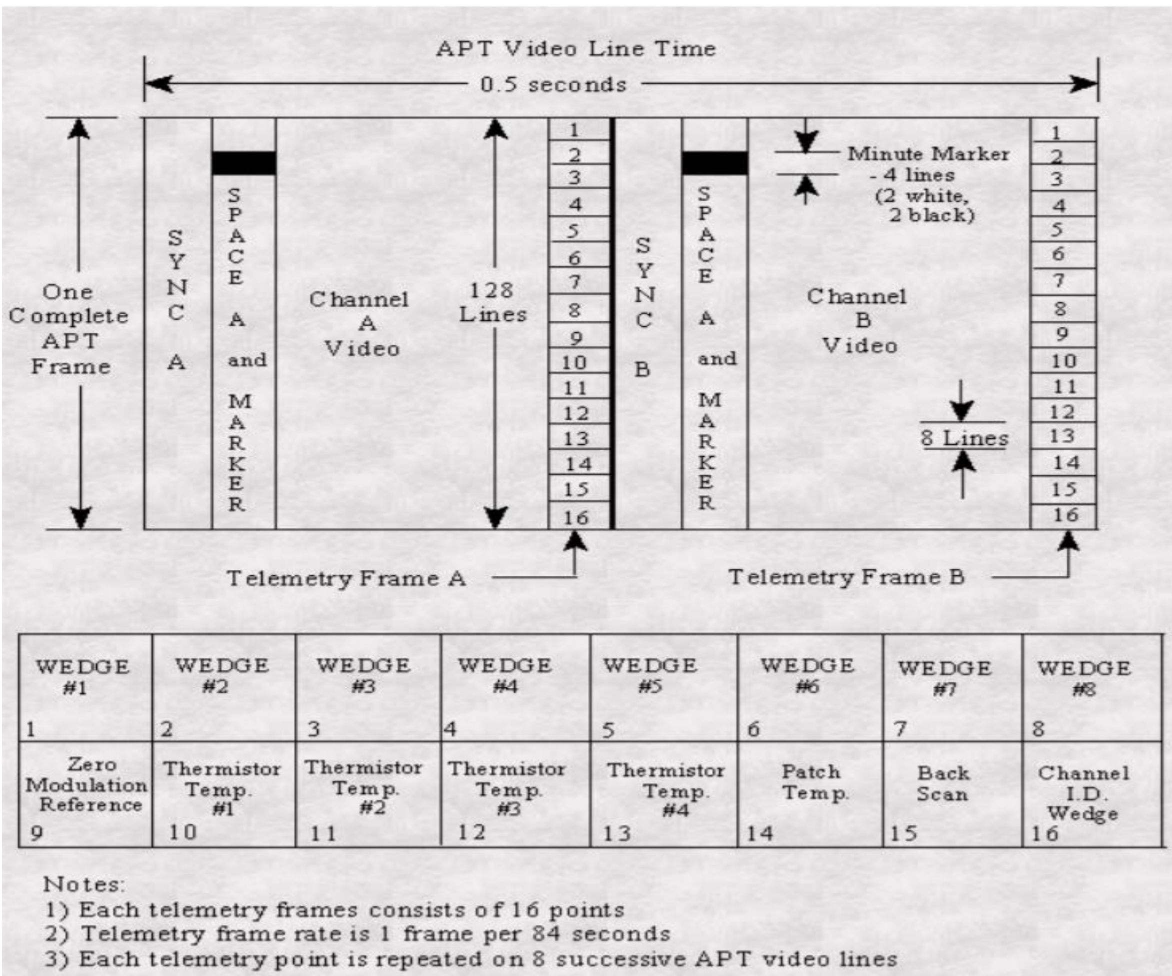

Figure 31: APT signal characteristics
Source (Commerce, 2009)

7.1.1 APT Characteristics

Table 12: Feature of APT in NOAA satellites

Carrier Modulation	Frequency Modulation
Subcarrier Frequency	2.4kHz
Data resolution	4km
Line Rate	120 lines/min
Transmission Frequency	137.5MHz or 137.62 MHz
Transmission Power	5W
Polarization	Right Circular Polarized

7.1.2 APT Parameters

Table 13: Details of APT signals

Frame Parameters	Length	128lines
	Rate	1 frame/64secs
Line Parameters	Number of words	2080
	Number of sensor channels	2
	Number of words/sensor channel	909
	Rate	2lines/sec
Word Parameters	Digital to Analog accuracy	8MSB's of each bit word
	Rate	4160 words/sec

7.1.3 Image Display

The satellite data received can be demodulated and the image can be displayed. Steps followed to display the image are:

(i) Amplitude demodulation of the 2.4kHz, the output is the actual image. Image processing can be done on the demodulated signal and image can be displayed.

(ii) The demodulated signal is converted to digital data. It is converted to numbers between 0-255 in case of 8-bit computer. The sampling frequency will influence the image resolution.

(iii) Specific intensity/brightness must be assigned to each element of digital picture. The black and white image form a linear gray scale. With other image processing techniques color to the range of digital values can be obtained.

(iv) The scan lines aligned accurately to form the final image. The software should recognize the beginning of the scan line and then positioned properly on the screen.

7.2 Synchronization

Synchronization is an important process in the digital receiver. There are different types of synchronization and can occur at several places within the receiver.

(i) Symbol Phase Synchronization: Sampling is chosen at T interval

(ii) Symbol Frequency Synchronization:

(iii) Carrier Phase Synchronization

(iv) Carrier Frame Synchronization

In the APT data from the satellite has 7 pulses introduced both at Visible and IR range each defined as Sync A and Sync B respectively. These sync pulses are correlated with the signal received to know the start of the image data. Correlation is a method of shifting one of the signals in time and calculating how well these signals match at each shift. Correlation can be used in communication systems to find appropriate sampling time, aligning signals in time The details of the synchronization as below.

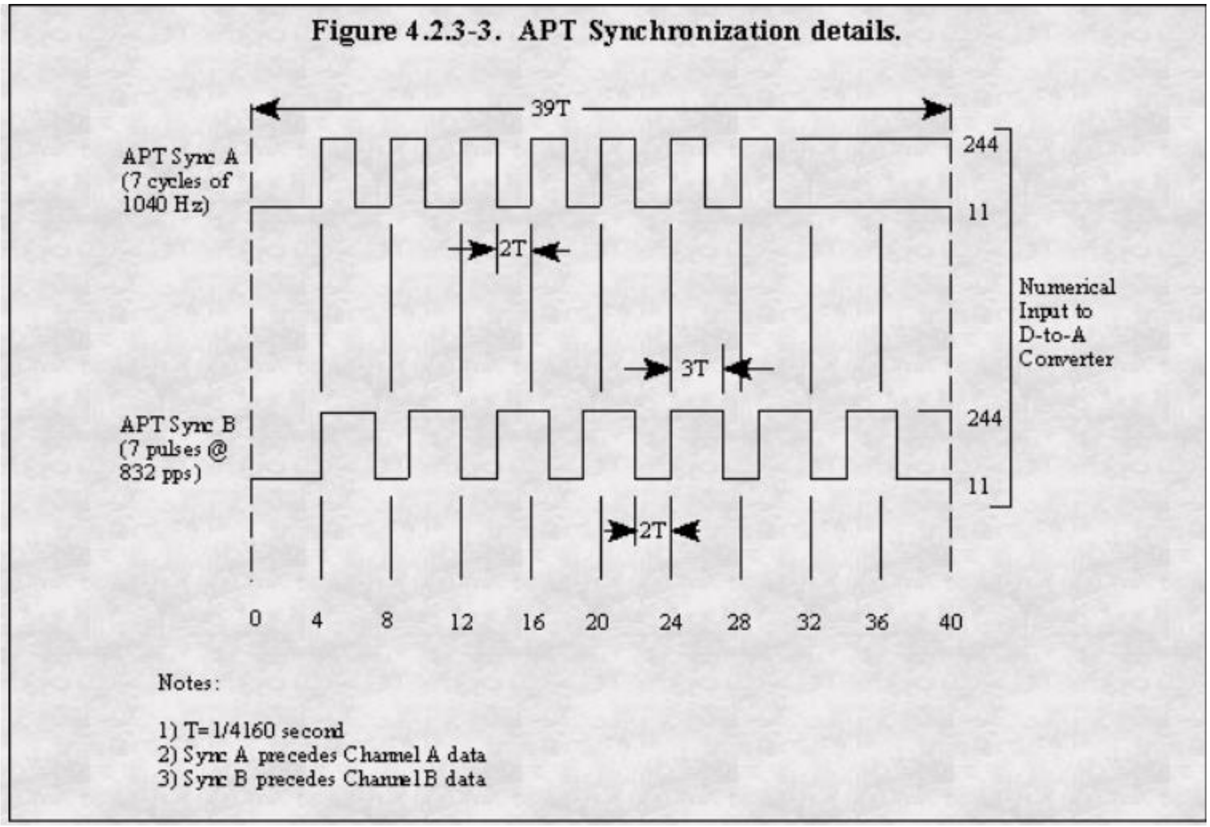

Figure 32: APT synchronization pattern
Source (Commerce, 2009)

7.3 Image Display using Software

There are many software's that can be downloaded to decode the images from the received signal. The data received is processed using techniques such as filtering, demodulation, image colors, overlapping the world map to the image. The signals were decoded using different software and the images are documented as below.

7.3.1 WXtoIMG

APT and WEFAX can be decoded using this software. It can be installed on all versions of Windows, Linux and Mac OSX. The signals can be recorded, decoded, edited and viewed using this software. The features of WXtoImg are real-time decoding of images, color images, temperature display, overlay maps to standard maps. Wide range of enhancements in image quality. WXtoImg is a freeware that can be downloaded from website (Anderson, 2015). Three recorded files were decoded using this software and images are as below

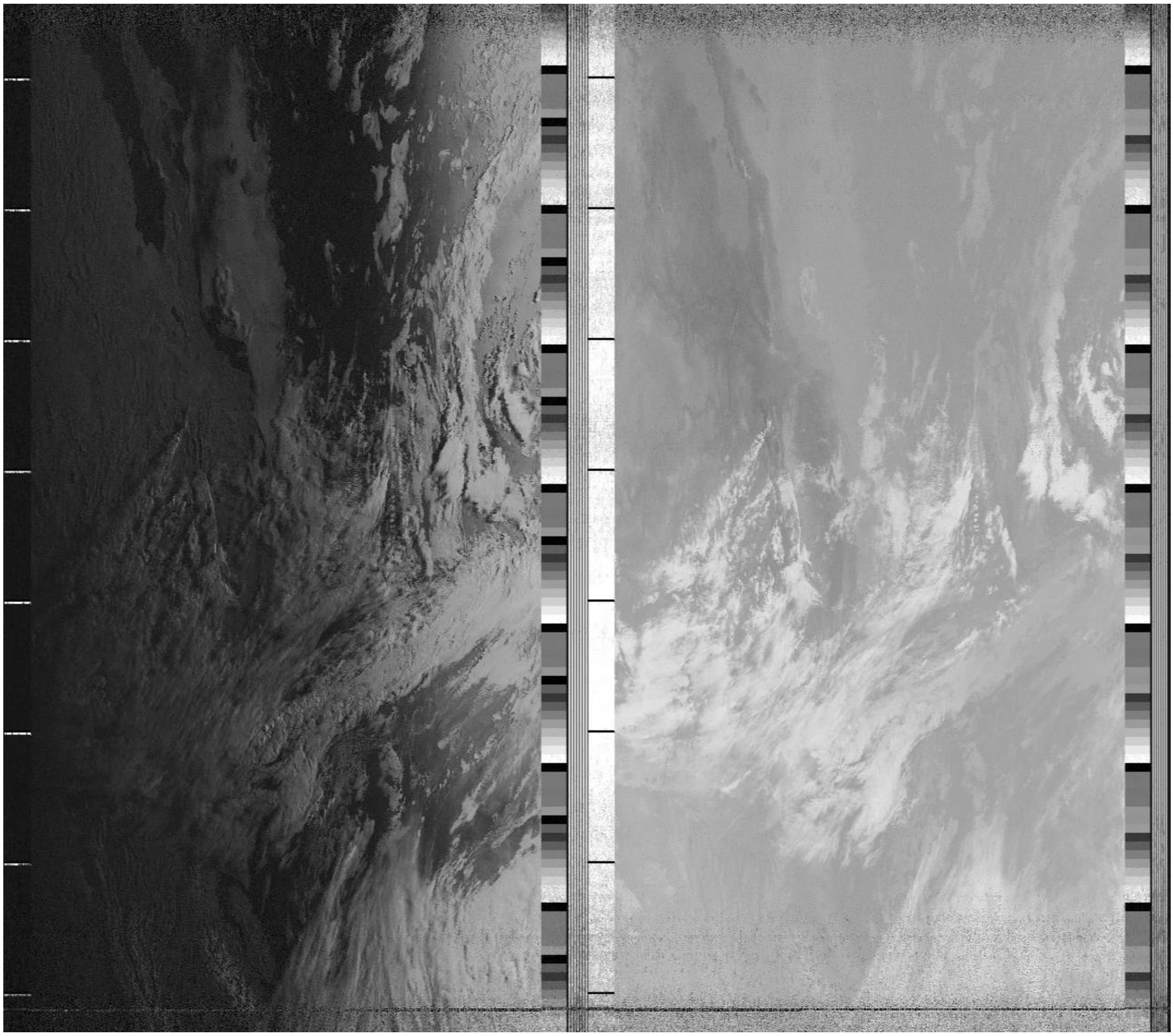

Figure 33: Image decoded using WXtoIMG

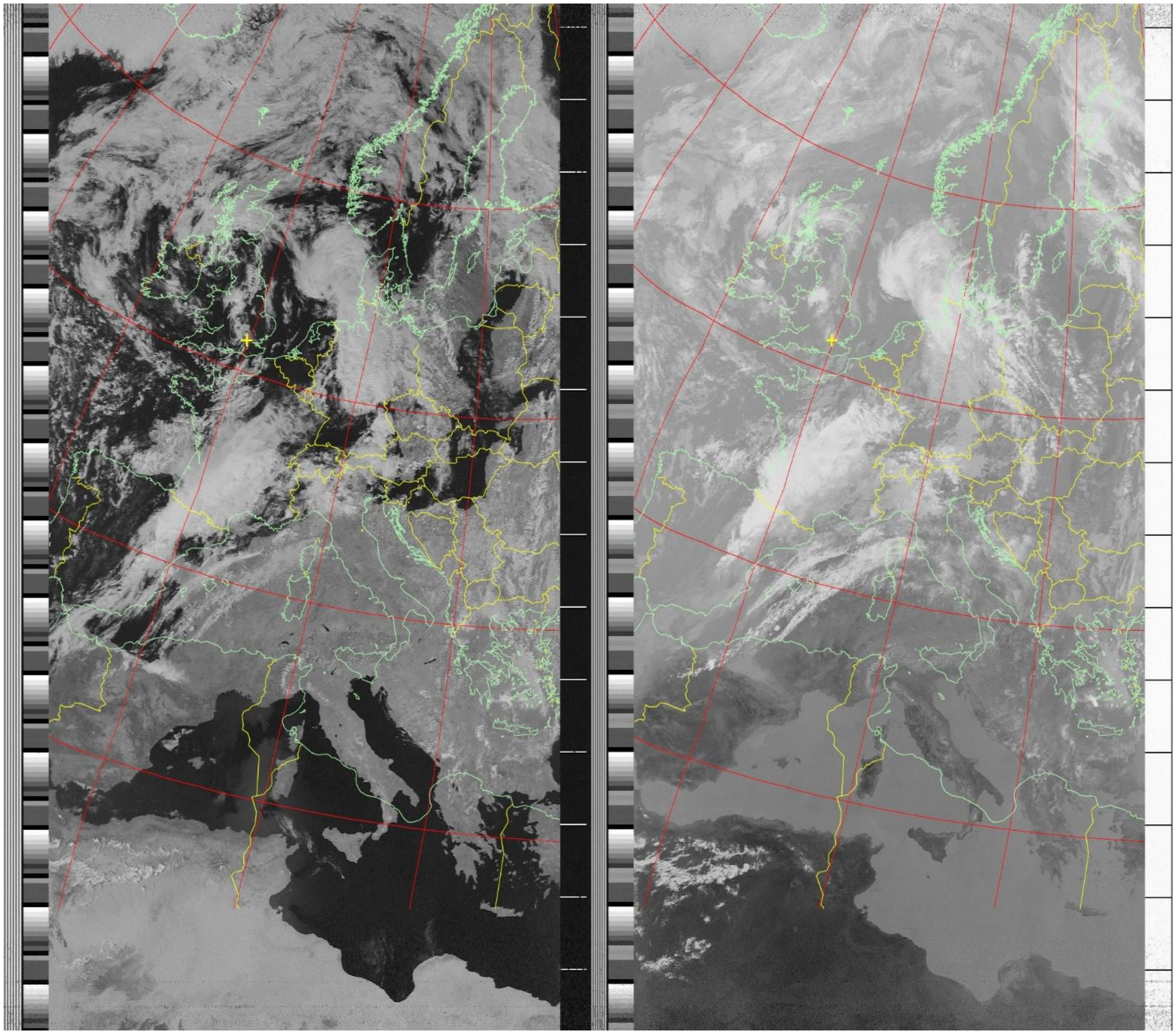

Figure 34: An image of Europe from NOAA 18

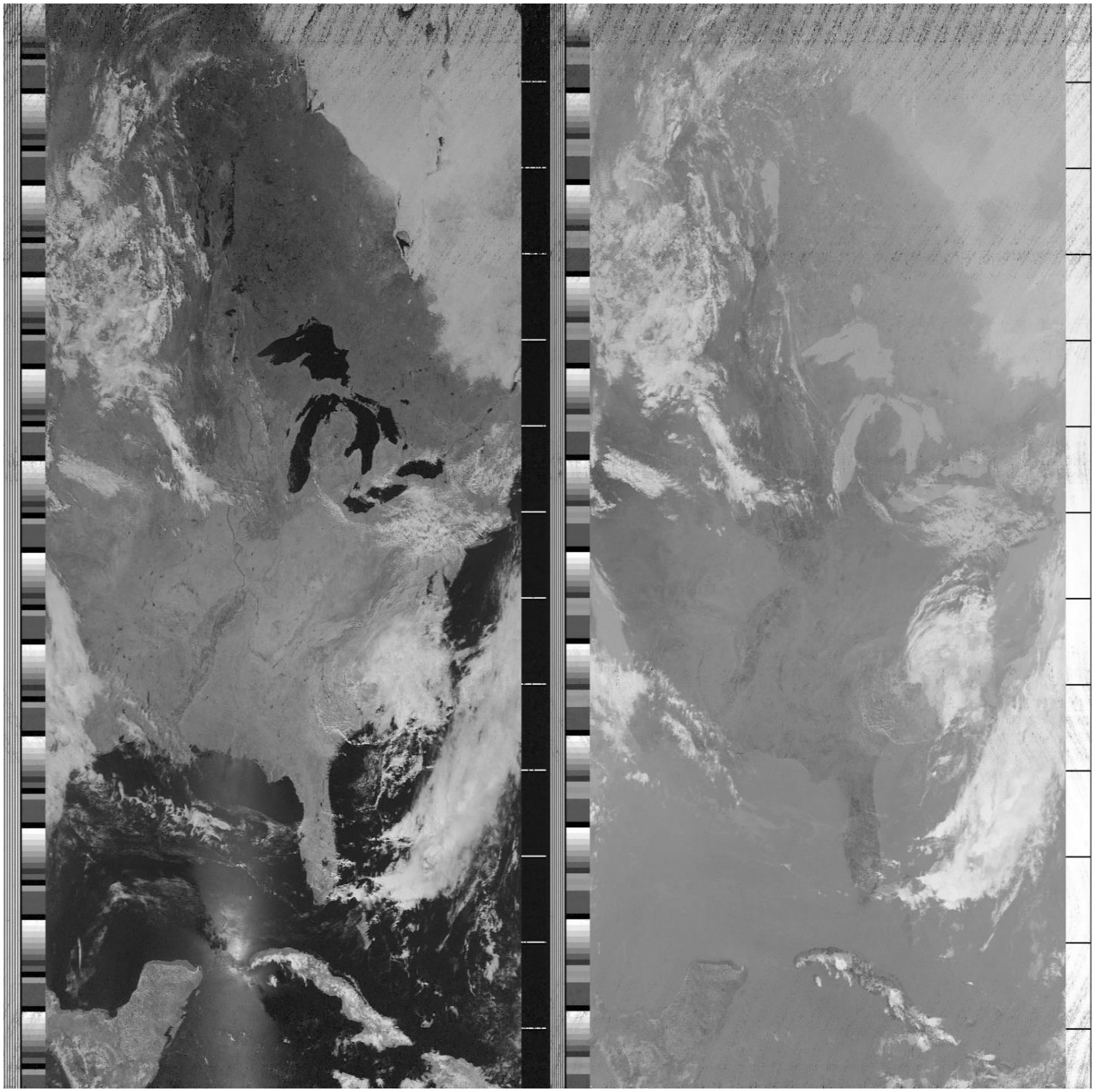

Figure 35: Image of USA decoded using WXTOIMG

3.2 APT Decoder

Another freeware available online to decode the APT images. APT decoder captures the NOAA signals as an audio file. The file can be converted to images, the images can be improved by adding color, reducing noise and many more. (Tast, 2017)

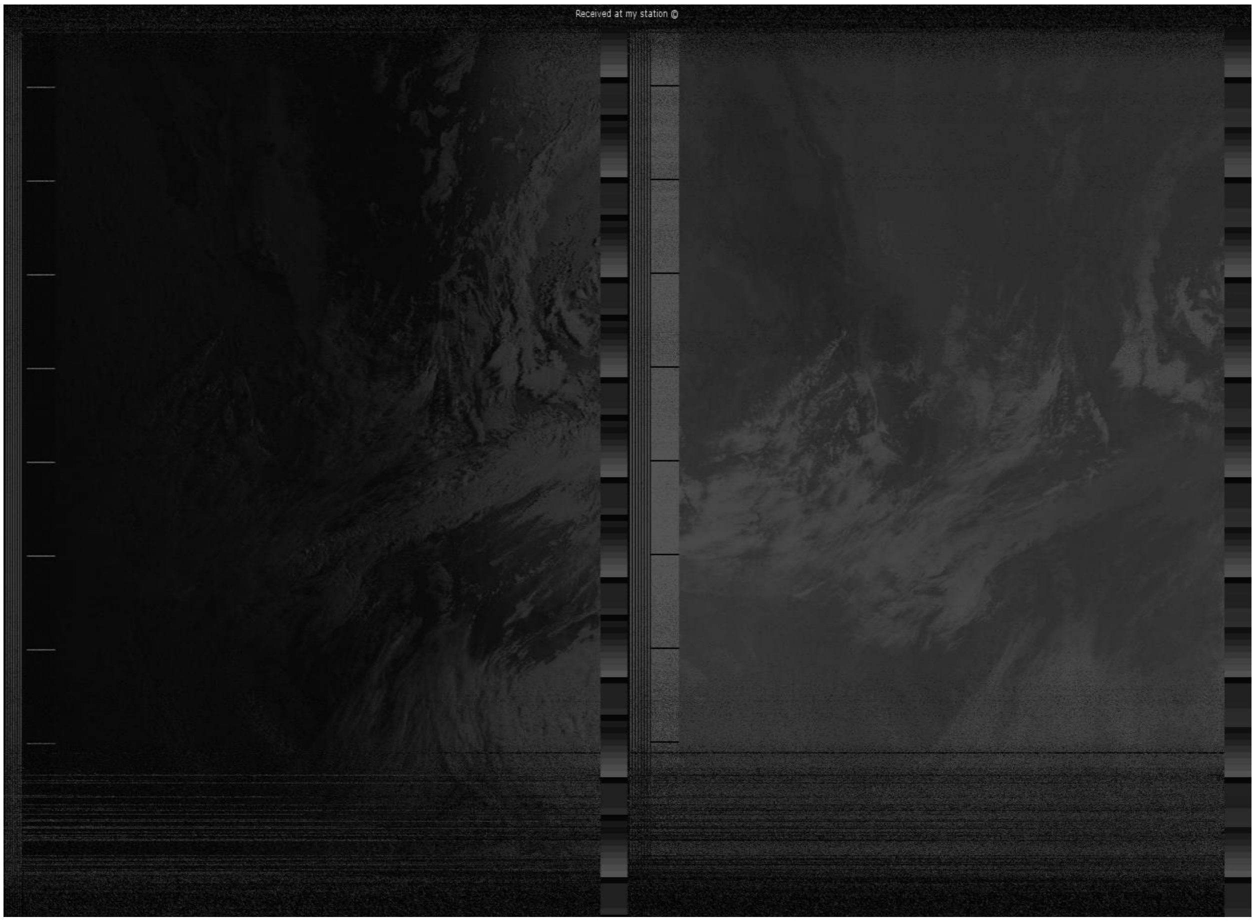

Figure 36: Image decoded using APT Decoder

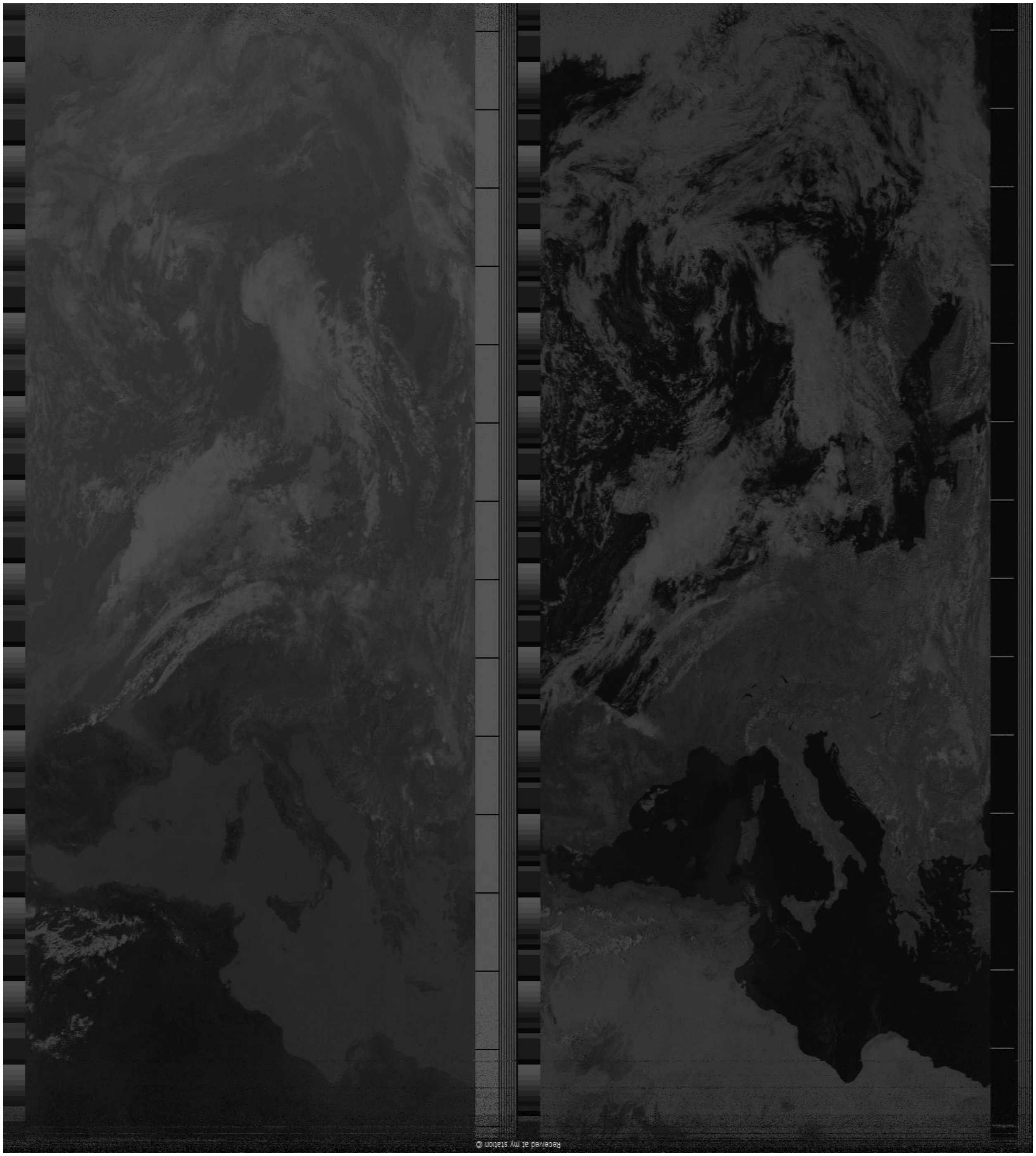

Figure 37: Europe image decoded using APT decoder

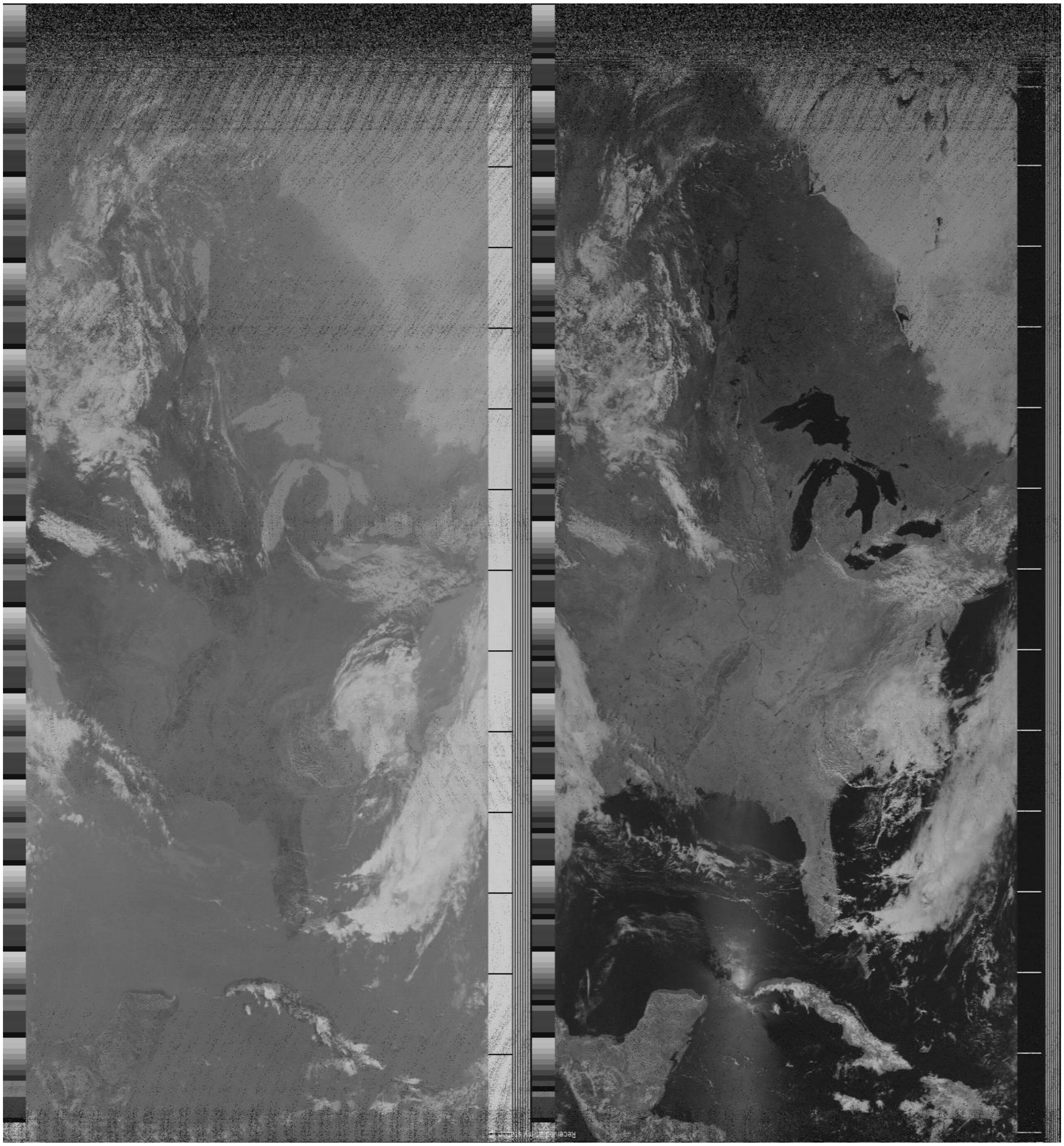

Figure 38: Image of USA decoded using APT Decoder

7.3.3 Wxsat

The simplest software available for NOAA APT decoding. It uses soundcard as the demodulator. Wxsat is a freeware that can be installed on any version of Windows. Real time image decoding is also available in Wxsat. It saves image in bitmap format and the raw data is store as wav file. The wav files can be used to decode and do some post processing on the images (Bock, 2017).

7.4 Decoding image using MATLAB

To obtain an image from the wav file it is necessary to process the signals received from satellite. A schematic of the decoding process is as shown in figure 38.

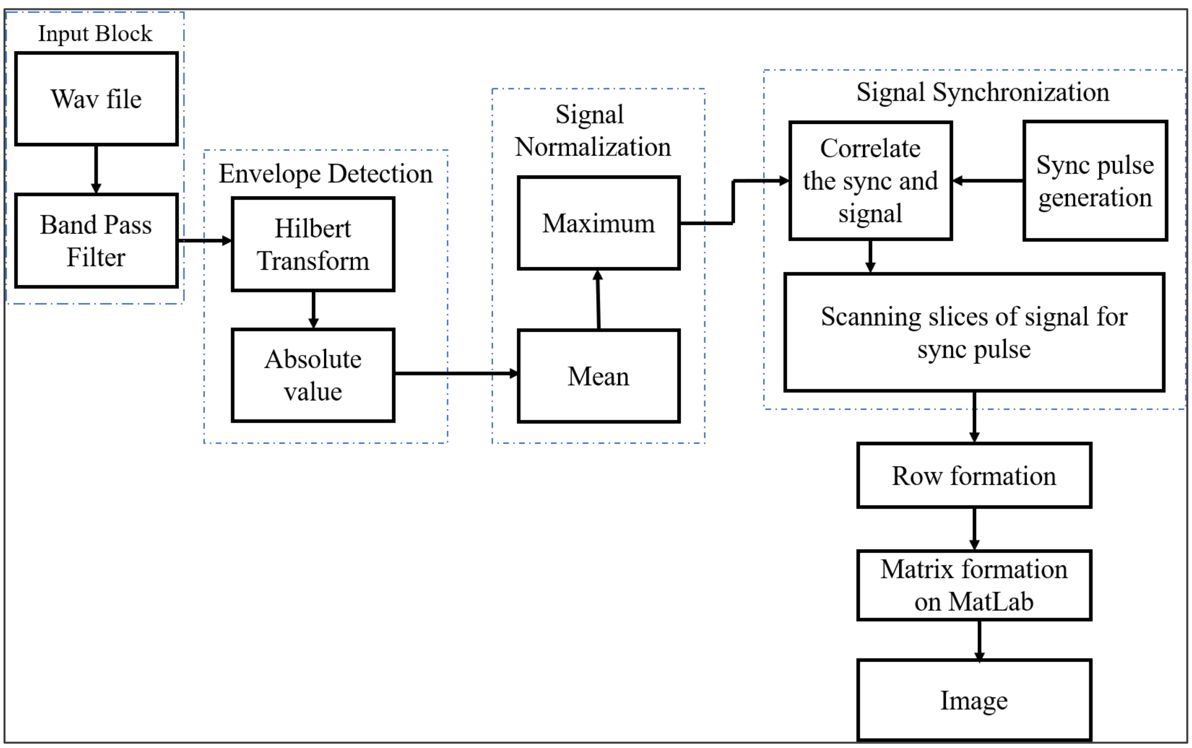

Figure 39: Block diagram of the image decoding process

The image decoding process can be explained in blocks:

Input block: The FM demodulated signal recorded by the HDSDR is saved as a wav file. This file is read on MatLab and then passed to through a band pass filter. Band pass filter is designed to pass through 500Hz -4300 Hz of frequencies and reject all other frequencies. The result of the low pass filter is as shown in figure 39.

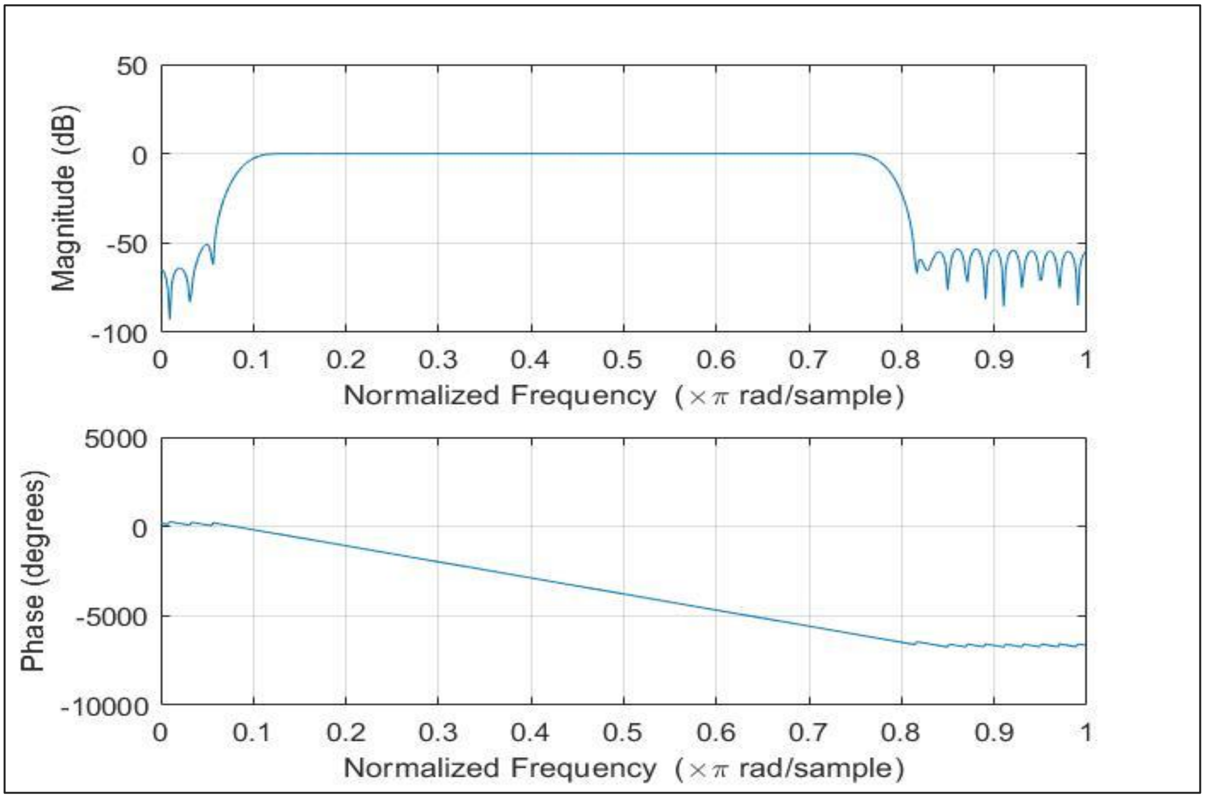

Figure 40: Band pass filtered signal

Envelope Detection: The APT signals are AM modulated. Envelope detection is opted as a method to demodulate the signals. Hilbert Transform is applied to the signals, Hilbert Transform calculates the instantaneous values of amplitude and frequency. After the envelope detection, the absolute value of the signal is calculated. The plot of the absolute value of the signal is as shown in figure 37

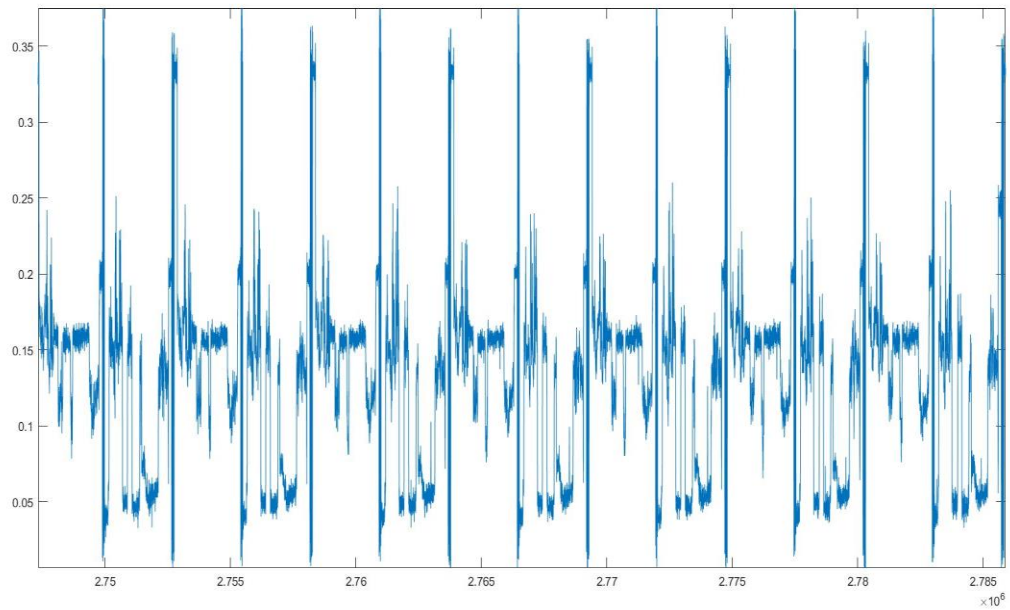

Figure 41: Envelope detected signal

Normalization: The AM demodulated signal is normalizing by calculating the mean, subtracting it from the value and dividing by the maximum value. This is done to remove the DC component.

Synchronization: The APT signals have sync pulses which denote the beginning and end of the image data. The synchronization is explained in Section 6.3. Each of the IR and visible range have sync pulses of seven 1’s and 0’s in it. The synchronization is achieved by correlating the normalized AM demodulated signal and the square sync pulse generated.

Sync pulse generation: the time-period ‘t’ is calculated for the IR frequency of 832Hz and the visible frequency of 1040Hz. Sync pulse is generated using MATLAB, figure 38 shows the sync pulse for 832Hz.

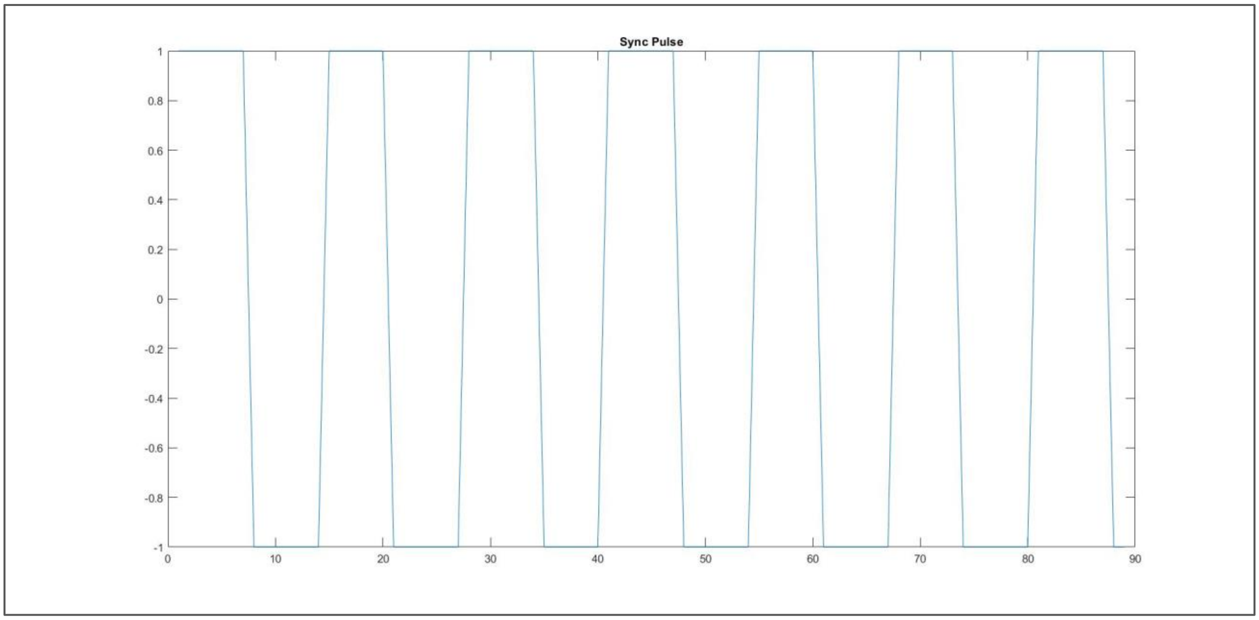

Figure 42: Square sync pulse generated for IR range

Correlation: the image data is in frames separated by the sync pulses. The sync pulses are located to know the start and stop of the image data frames. Cross correlation is done to locate the sync pulses, its location and the maximums. The correlated output of image signal and the sync pulse is as shown in figure 39.

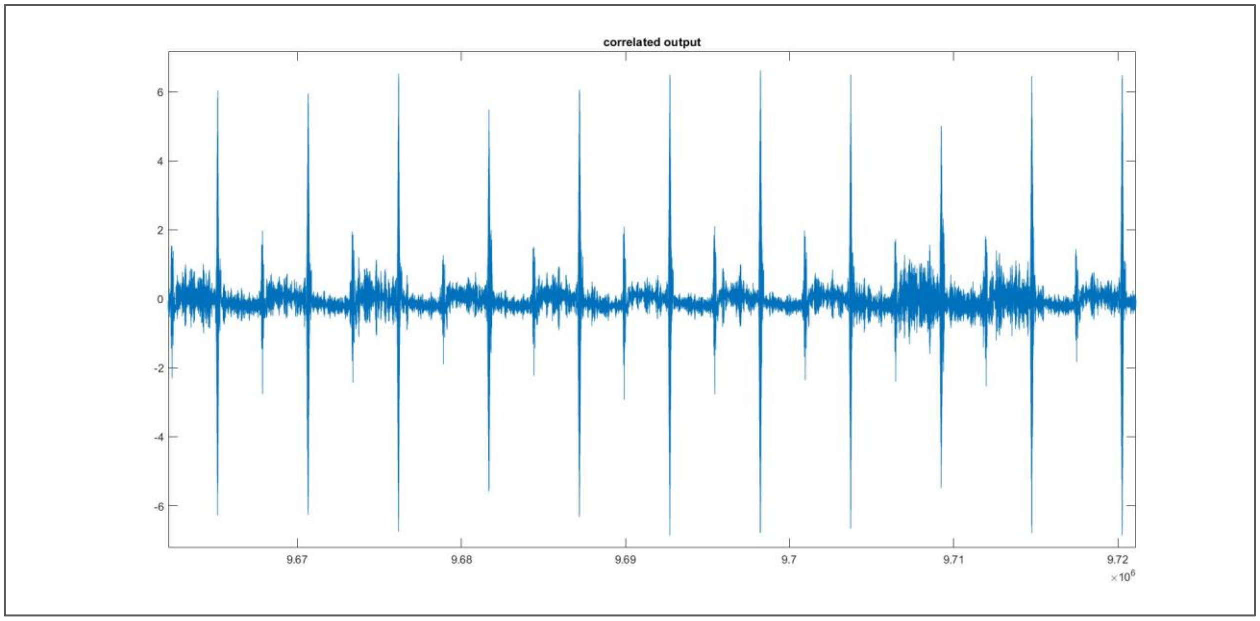

Figure 43: Correlated signal

Finding the first sync pulse: the image data lies between the sync pulses, thus locating the sync pulses in the signal plays an important role in decoding the image. The MATLAB program takes a small portion/slice of the signal and scans through this slice to find a sync pulse. The length of slice is considered as half of sampling frequency (f_s). For the NOAA signals, sampling frequency of the recorded signal is 11025Hz. The slice of the signal is scanned, the sync pulse is located, and the value of the pulse is compared to the threshold value set. The location is considered as the start of the next slice, the slice is approximately $f_s/2$. This slice is scanned for sync pulse and the threshold, the data/samples between the first and second sync pulse is stored as the row of the image.

This process is followed throughout the signal and the rows are stored in the memory. If there are no sync pulse found, the slice is not considered as a row and is omitted from the row formation.

Forming rows and columns (Indexing): The rows are formed by screening samples and finding the sync pulses. The columns are fixed for NOAA APT images as 5513 (fs/2). Thus, the rows and columns are formed.

Image Decode: Once the matrix is formed, it is simple to convert the matrix to an image on MATLAB. The image decoded is documented. Figure 40 displays the image decoded using MATLAB and is compared with the images decoded using software such as the WXtoIMG and the APT Decoder.

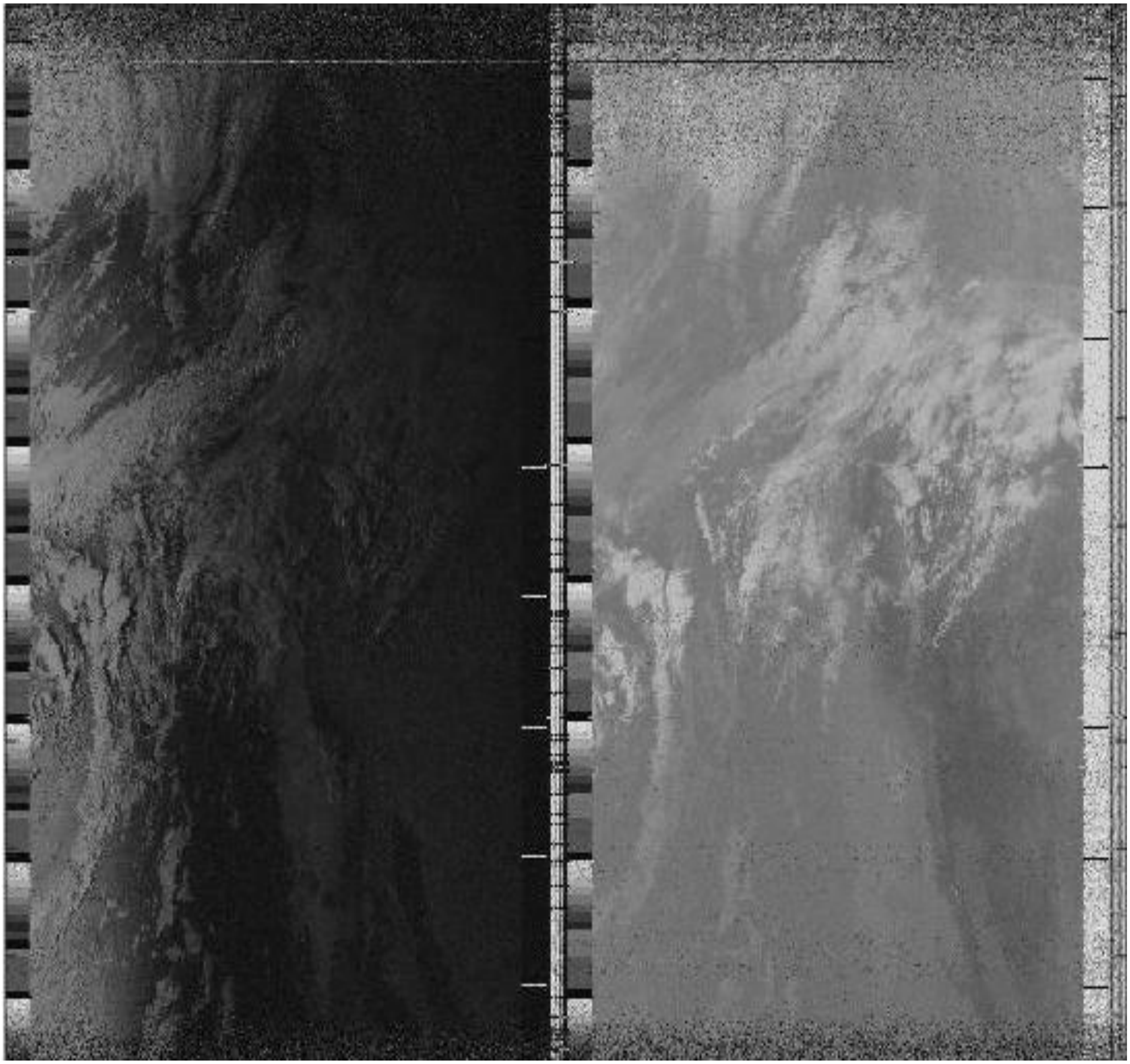

Figure 44: Image from NOAA 15 decoded using MATLAB

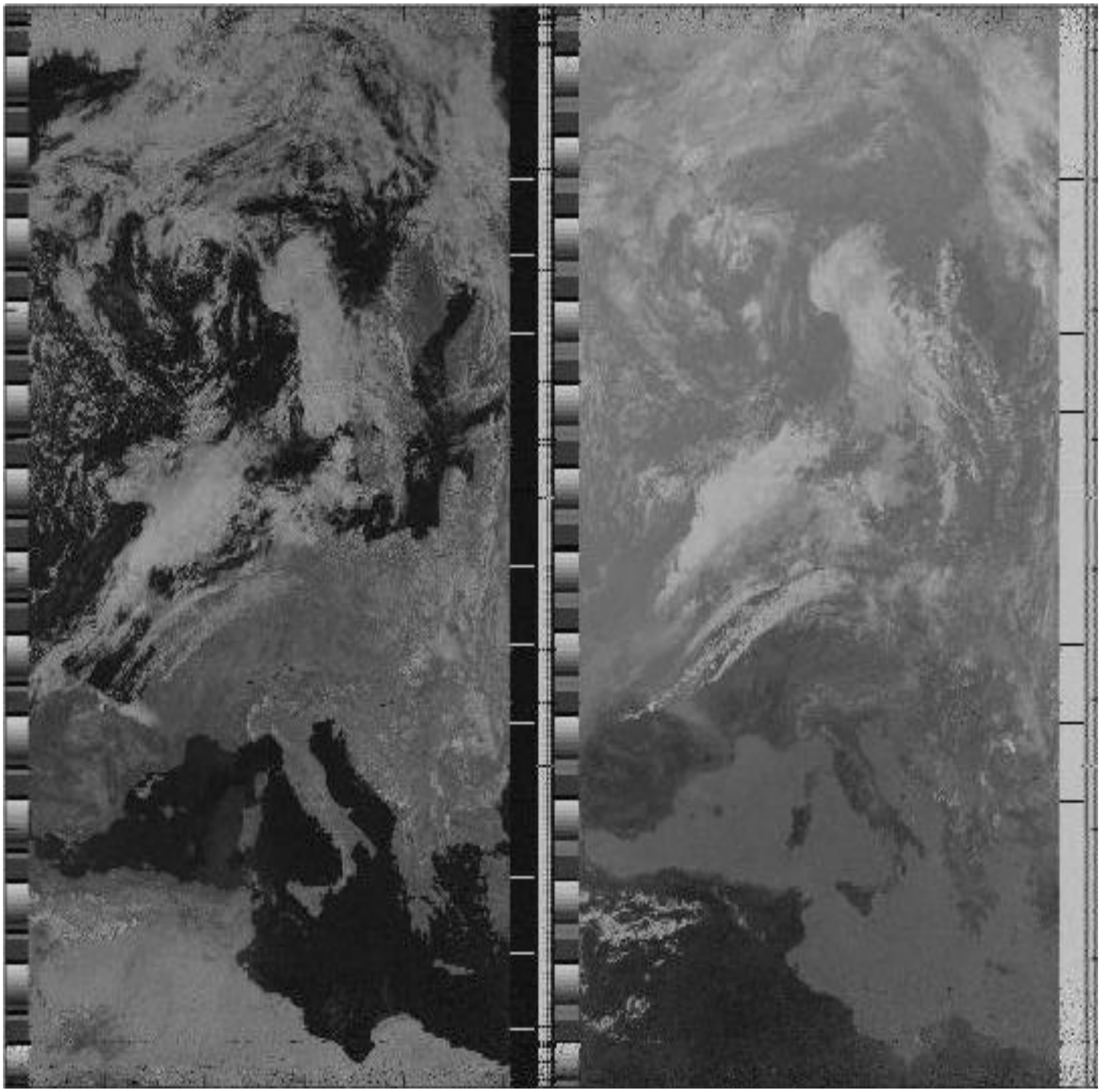

Figure 45: Image of Europe decoded using MATLAB

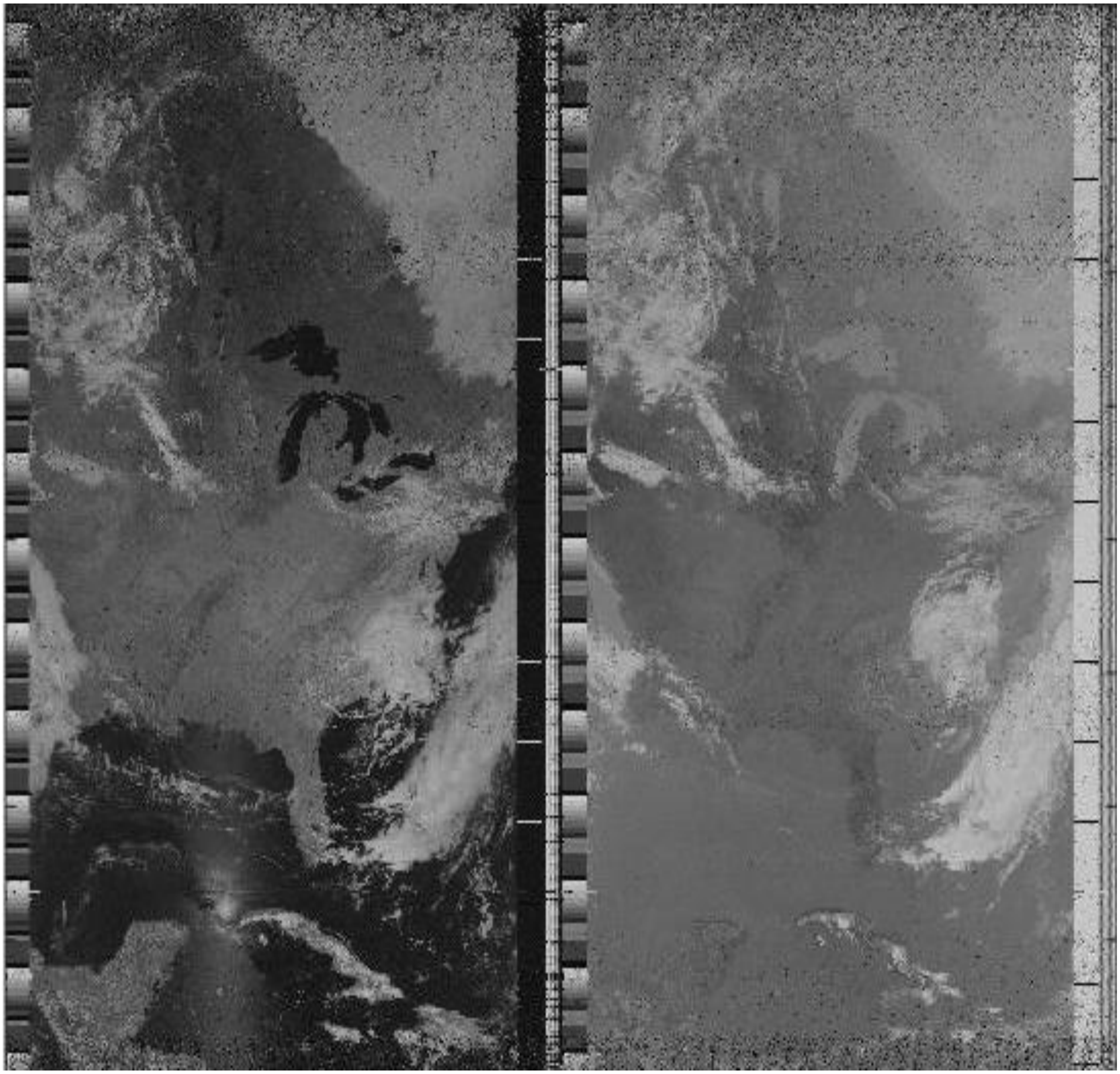

Figure 46: Image of USA decoded using MATLAB

Two wav files (baseband file of NOAA 15 and file that decoded image of Europe) were downloaded by NOAA website as examples of the NOAA files. The wav file that decodes the USA map was received by the GS we set up, Comparing the images decoded by two popular software's and the MATLAB program we have created; the images look very similar and technique is verified to decode the APT images.

Conclusion

In this thesis, we have implemented a ground station using COTS components at relatively small investment. The ground station is capable of tracking and receiving data from satellite operating in VHF frequency band. The study on satellite, satellite orbits, satellite communication, link margin was performed. The highlights of this research are:

(i) Cost: The relative low cost of the components makes this project certainly affordable for a research or an educational institution or even an individual to have access to satellite and space communications.

(ii) Portability: the small size and the light weight of its hardware makes it attractive as it no longer needs expensive equipment, high maintenance and large space to set up the station.

The ground station was analyzed for its link margin to establish the communication link, software needed for tracking and communicating was studied beforehand, components were purchased, the components were individually tested for its performance and system was implement within a stipulated time. Satellites such as FUNcube (A0-73), International Space station, NOAA satellite series were tracked. The signals received was recorded and the post processing of the signals were done and documented. The images of the Earth from NOAA satellites were decoded using MATLAB and the images are documented. The objective of including the satellite communication in existing wireless communication course was accomplished. It has laid a platform to increase the student motivation and learning in the field of wireless communication, software defined radio and image processing. We believe that real time processing of signals will excite the engineering students.

Future Work

This research and its finding have paved way for new ideas that would improve the existing ground station

- Ground Station Architecture: Implementing a band pass filter after the antenna such that the signals are band pass filtered before passing through the LNA. The filtering at this stage will eliminate the unwanted frequencies received even before the LNA.
- Link Analysis: The link analysis can be analyzed for the effect of atmospheric losses more in detail as the link analysis done is for the best weather conditions.
- Receiver Design: many projects such as automatic modulation detection codes, error correction algorithms, noise reduction algorithms, carrier, bit, frame synchronization, demodulators can be implemented.
- Signal processing: more powerful tools such as GNU radio can be used to build a receiver design to characterize the noise on image signals, doppler shift correction etc.
- The ground station can be used to connect to astronauts on the International Space Station (ISS) and speak with them as an outreach activity.
- Station can also be used as a HAM radio station.

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APPENDIX A

MatLab code for the image processing of NOAA satellite

```
%% Read wav file

%[y,fs] = audioread('NOAA15-baseband.wav');
[y,fs] = audioread('D:\Downloads\090729 1428 noaa-18
8bit.wav');
fn = fs/2;  %nyquist frequency
%% Band pass filtering
bpf = fir1(100,[500 4300]./fn,'bandpass');
env = abs(hilbert(filter(bpf,1,y)));
env = env./max(env);  % normalize
%% Sync Pattern
t=0:1/fs:1/125;
sync = (square(832*t*(2*pi)));
%% Correlation threshold
th = 6; % if correlation is larger than th, we're good
%% Find first sync pulse
row = 1;
% A row has approximately 5540 samples
% slide through the signal until we find a correlation
larger than th
wbegin = 1;
step = 4000; % slice size includes only one sync pulse
wend = wbegin + step;
while 1
    [correl, lags] = xcorr(env(wbegin:wend),sync);
    [M,I] = max(abs(correl));
    if M > th
        lag = lags(I);  % found it
        break;
    end
    wbegin = wend + 1;
    wend = wbegin + step;
end
image(row,:) = env(wbegin+lag:wbegin+lag+5499);
row = row + 1;
%% Find remaining rows
wbegin = wbegin + lag;
wend = wbegin + step;
```

```
while 1
    if wend < length(env)
        [correl, lags] = xcorr(env(wbegin:wend),sync);
        [M,I] = max(abs(correl));
        if M > th
            lag = lags(I);  % found it
            image(row,:) = env(wbegin+lag:wbegin+lag+5499);
            row = row + 1;
        else
            disp('Warning: no good sync pulse found');
        end
        wbegin = wend + 1;
        wend = wbegin + step;
    else
        break
    end
end
imagesc(image)
colormap('gray')
```