Onboard and Ground Station Telemetry Architecture Design for a LEO Nanosatellite

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Abstract— **This paper details the communication system architecture for a 3U hyperspectral imaging cubesat. The paper begins with discussions on objectives of and requirements from the communication system. Based on these, an architecture has been proposed. The architecture has been designed to ensure that the system works even in the case of emergencies, including, but not limited to antenna deployment failure or other component failures. This has been done by introducing multiple redundancy provisions. The architecture is broadly classified into three sections - Uplink, Downlink and Beacon transmission. The satellite implements a full-duplex UHF-VHF architecture using Gaussian Minimum Shift Keying (GMSK) modulation scheme for data downlink and uplink, while a Morse coded, simplex, On-Off Keying (OOK) scheme is used for beacon transmission. Onboard the satellite, a single monopole antenna is used for receiving uplink, while the other antenna doubles as a turnstile and dipole for downlink and beacon transmissions respectively. All the components to be used in the system, both onboard the satellite and at the Ground Station (GS) have been discussed. The reasons for selecting and details regarding interfacing of these components have been elucidated. The paper also describes the flight plan for TTC and how the microcontroller switches between the modes of operations. Entry and exit conditions for each mode are defined. Discussions on terrestrial testing of individual modules and architecture of the system have been included. All of the conducted tests were satisfactorily passed and the proposed architecture was proven to be a viable option for use in the satellite.**

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1. INTRODUCTION

Over the past decade, CubeSats have created new avenues for researchers, students and amateur space enthusiasts. Because of the ease of development and realization of this form factor, it is a low-cost alternative to testing new technologies. The use of global standards in the development of these missions enables the development of modular systems which furthers the cost efficiency of CubeSats. However, CubeSats come with their own problems of low power generation capabilities, limited mass budgets and size constraints [1].

This paper details the work done by students of Team Anant, the student satellite team of Birla Institute of Technology and Science, Pilani, India. This work was done towards the development of a 3U CubeSat under the Student Satellite Program of Indian Space Research Organization (ISRO). The primary payload of the mission is a hyperspectral imager and the secondary payload is a System-on-Chip (SoC) with Field Programmable Gate Array (FPGA) which will be used for compression and processing of the primary payload data.

The paper primarily focuses on the communication system architecture design for the satellite. It further expounds on the qualitative and quantitative reasoning for the selection and placement of onboard antennas along the satellite body, along with a detailed description of the deployment circuit used for its deployment [2]. This is followed by the description of the flight plan for TTC and the scheme with which the microcontroller will switch between the modes of operations. Entry and exit conditions for each mode have been specified. Besides uplink and downlink, the beacon transmission is another crucial part of a successful satellite communication system. The beacon control is shared between the EPS, and TTC, and this resource sharing is explained in the flight plan of Section 6.

The architecture has been designed, so as to ensure that the system works even in the case of emergencies, including but not limited to the antenna deployment failure or other component failures. This is achieved by introducing numerous redundancies in the system.

Finally, Section 8 of the paper describes the ground station architecture; including the GS antennas used, the implementation of decoding methodology, and the auto-tracking with rotor control mechanism using HAMLib and open source software such as GPredict on GS-PC.

2. SUBSYSTEM REQUIREMENTS

The high-power requirements of the communication subsystem, and the low power generation capability of the nanosatellite are important considerations for the design of the nanosatellite. The size constraints also pose problems in positioning of onboard antennas.

Student satellites are recommended to operate at unlicensed amateur radio frequencies called HAM bands [3]. However, use of amateur frequency requires proof of frequency coordination from the International Amateur Radio Union (IARU).

This section details provisions and constraints of other subsystems of the satellite that bear consequences on the conceptualization, design and functionality of the communication system.

Structural and Thermal

- The communication board should be placed away from the magnetorquers to reduce RF interference.
- The antennas are to be wrapped and packed inside the nanosatellite until 30 minutes after on-orbit deployment. The doors are to be wound with nylon wire wrapped around nichrome and are opened using nichrome burn wire release mechanism [2].

Electrical Power Subsystem

- Power consumption of all on-board components is specified in table 1.
- For the antenna deployment circuit, a one-time power requirement of about 6.4 Watts for short bursts of 6 seconds is required.

On-Board Computer (OBC)

- Housekeeping data needed for the advanced beacon is to be collected by the OBC and sent for encoding, modulation and subsequent transmission.
- The image data from the payload is to be compressed and supplied by the OBC.
- To support a full-duplex architecture, with simultaneous uplink and downlink, the uplink data: which includes retransmission requests for erroneous packets and the TLE, is to be handled by the OBC subsystem.
- OBC has to exercise control over the various modes of operation of the nanosatellite.

Table 1: Power consumption for on-board communication components

Component	Nominal Power Consumption (mW)	Standby Power Consumption (μW)
CC1101 Transceiver (Tx - UHF band)	96.36	0.66
MAX1472 OOK Modulator (Beacon - UHF Band)	19.06	6.12
PE4259- RF switch	0.066	----
THS9001 High Power Amplifie	463	----
MSP430F5529 MCU	0.9	0.3
ADF7021 Transceiver (Rx - VHF Band)	79.2	----

Attitude Determination and Control System (ADCS)

- Appropriate stabilization should be achieved by ADCS to reduce pointing loss during data transmission.

3. ONBOARD TELEMETRY ARCHITECTURE

System Design

Table 2 describes the operating frequency and modulation schemes to be used in the satellite.

This section highlights the considerations for system design and finalised parameters for the onboard architecture.

Nanosatellites have strict power constraints. Given the high-power consumption by the Telemetry subsystem, it is essential that the system parameters are chosen so as to reduce the power consumption while not compromising much on the data transmission/reception fidelity. Keeping this in mind, during data transmission mode, an upper limit of power of 2 Watts is considered for the two communication systems, namely, on-board beacon and payload data transmission.

Table 2: Key Specifications of the System Configuration

Link	Operating Frequency	Modulation Scheme	Baud Rate
Downlink (Telemetry)	433 MHz (UHF)	GMSK (Gaussian Minimum Shift Keying)	9600 bps
Uplink (Telecommand for Software Update and TLE)	144 MHz (VHF)	GMSK (Gaussian Minimum Shift Keying)	1200 bps
Beacon	433 MHz	On-Off Keying	9600 bps

Modulation Scheme

The modulation scheme depends on the following factors:

- Bit error probability
- Intersymbol interference
- Transmission power
- Bandwidth
- Circuit complexity

Generally, for CubeSat communication, FSK or PSK (and their special cases) modulation techniques are used. While PSK is more bandwidth efficient (can transmit a larger number of bits in a given bandwidth) when compared to FSK, it does so at the expense of power efficiency. FSK also has better noise rejection for the same data rate and has a simpler implementation than PSK. Hence, some form of FSK will be used. MSK is a special type of FSK which has a continuous phase, as compared to a normal FSK which has discontinuities when switching between the “mark” and ”space” frequencies, producing wideband frequency components. Due to this, it has a better spectral efficiency than a standard FSK and has lower sideband power. Applying a Gaussian low pass filter to MSK further lowers the sideband extension into the other frequency bands. Hence, GMSK modulation technique will be used.

Onboard Components

Keeping in mind budgetary constraints, the components of the onboard circuit are to be Commercial-Off-The-Shelf (COTS) components. However, care has been taken that each component conforms to industry-grade standards with respect to operating and storage temperature range. More importantly, it has been ensured that all the components possess space heritage. A comprehensive overview of the selection and specifications of all COTS components that make up the on-board architecture is presented briefly in Table 6. Detailed studies and comparative analyses for component selection are expounded in the relevant sections [5].

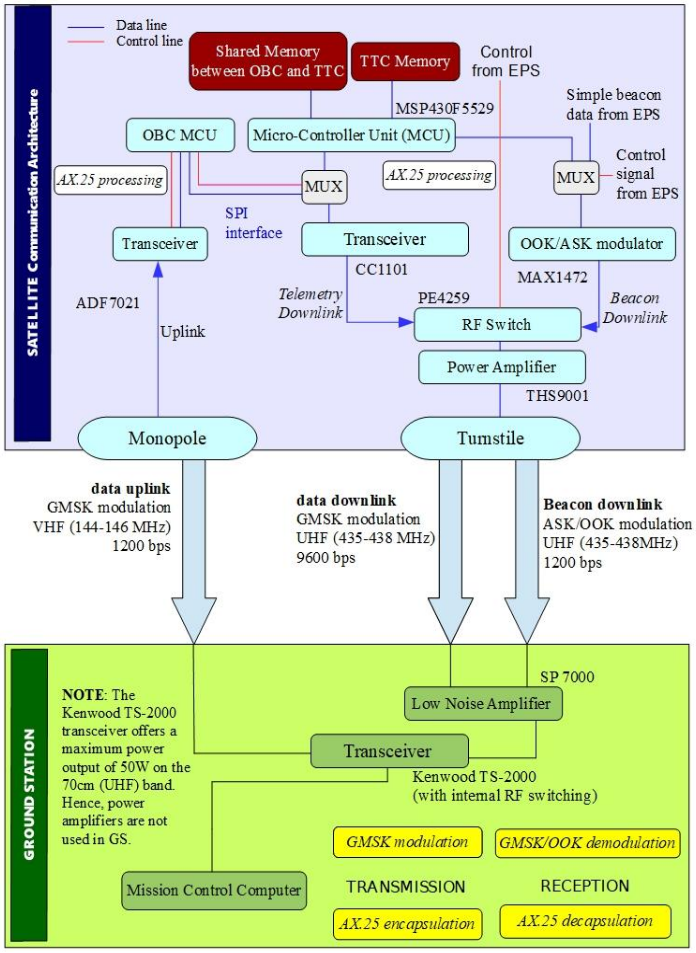


Figure 1: Block diagram of on-board communication architecture

Transceiver:

Requirements: The mission objective of downlinking a hyperspectral image requires an efficient modulation scheme, high data rate and minimum error to ensure high throughput. Also, this must be done with the limited power available on a CubeSat. So, the transceiver must be able to accommodate all these functionalities and be operational in the VHF/UHF bands.

Study: Initially transceiver AX100 was chosen. The transceiver IC had integrated power amplifier as well as RF switching and hence was best suited for our application. However, this idea was discarded due to budget constraints. Texas Instruments’ CC1101 was the second choice as it has a rich component heritage, is used in many nanosatellite missions and offers compatibility in interfacing with the microcontroller It’s a very low power transceiver and gives a considerable gain of 10 dB. Unlike the AX100, the CC1101 requires external high power amplifier and RF switch. All its other specifications were in line with the mission parameters, except for the fact that it doesn’t operate in the 144-148 MHz VHF range, which is to be used for uplink. It was therefore decided that CC1101 will be used for only Tx in UHF. And for uplink in VHF band, another transceiver ADF 7021, a transceiver IC manufactured by Analog Devices was finalised. It was found suitable for our uplink requirements and was hence finalised as the Rx transceiver. This design came with an added benefit of redundancy: in case CC1101 (Tx) fails, the ADF 7021 can take over as main transceiver in VHF(Rx)/UHF(Tx) in a half-duplex (Time Division Duplex) contingency mode. Similarly, in the event that ADF 7021 fails, CC1101 can take over as main transceiver in VHF/VHF half-duplex mode [11].

Components Selected:

1. CC1101 (Texas Instruments) for Downlink and Beacon transmission in UHF band.
2. ADF7021 (Analog Devices) for Uplink Reception in VHF band

Some important features of CC1101 that suit our mission are:

1. Efficient SPI interface; All registers can be programmed with one burst transfer.
2. Programmable output power up to +12 dBm for all supported frequencies.
3. High sensitivity, -116 dBm at 0.6 kBaud, 433 MHz, 1% packet error rate.
4. Automatic Frequency Compensation (AFC) can be used to align the frequency synthesizer to the received signal centre frequency.
5. Can be used in conjunction with IC TPS62730 (step down converter, also manufactured by Texas Instruments) to reduce power consumption.
6. Operational Temperature range: -40C to +85C.
7. Storage Temperature range: -50C to +150C.

ADF7021 is a high performance, low power, narrow-band transceiver. It's salient specifications are mentioned below [8],[18].

1. Operational Frequency bands using external VCO: 80 MHz to 960 MHz.
2. Programmable IF filter bandwidths: 9 kHz, 13.5 kHz, and 18.5 kHz.
3. Modulation schemes: 2FSK, 3FSK, 4FSK, MSK.
4. Spectral shaping: Gaussian and raised cosine filtering.
5. Data rates: 0.05 kbps to 24 kbps.
6. Power supply: 2.3 V to 3.6 V.
7. Leakage current in power-down mode: 0.1µA.
8. Programmable output power: −16 dBm to +13 dBm in 63 steps.
9. Receiver sensitivity -125 dBm at 250 bps, 2FSK and -122 dBm at 1 kbps, 2FSK.
10. Operational Temperature range: -40C to +85C.
11. Storage temperature range: -65C to +125C.

Microcontroller Unit:

Requirements and Study: The primary requirement from the telemetry MCU was low power consumption. MSP430F5529, from Texas Instruments [7], was considered over ARM Cortex-A9 as the MCU IC because of its high power efficiency, as well as considerable nanosatellite heritage, as elucidated in Table 3.

Table 3: Space Heritage for MSP microcontroller series

Nanosatellite	Micro-Controller used	Reasons for selection
Parikishit (Manipal Univerity, India)	MSP430	Easy compatibility with CC1101
CubeCAT-1 (Universititat Polytechnnica De Catalunya)	MSP430	1. Least power consumption. 2. Has flown in space successfully. 3. Maximum code efficiency. 4. Wake-up from low-power modes to active mode in less than 6 µs. 5. Debugging and programming through easy to use development tools.
EST-Cube1 (University of Tartu)	MSP430FR5969	1. Low power consumption 2. Radiation tolerant
SwissCube (University of Switzerland)	MSP430F1611	1. Ease of interfacing. 2. Radiation tolerance.
Aalto -1 Aalto -2	MSP430F2274	Easy compatibility with the transceiver.

OOK Modulator:

Requirements: The chosen modulation scheme for beacon transmission from the satellite is On-Off Keying (OOK). The downlink architecture is designed for operation in the 434.79-438 MHz band (UHF) and this is the first consideration for the selection of a suitable modulator. Although the transceiver used for telemetry data downlink can also be used for beaconing of housekeeping data, the use of separate modulators was preferred so as to introduce redundancy in the system. Desirable parameters considered for OOK modulator selection include power consumption, operating temperature range, voltage rating and simplicity in interfacing.

Study: Introducing another CC1101 transceiver for the beacon is possible, but due to the complexity in interfacing and control, simpler modulators were considered; RF 2516 from RF microdevices, MAX 1472 from Maxim and TWS-BS-3 from delta electronics were compared on the basis of requirements. Based on component heritage and specifications, RF2516 was initially chosen but the component has become obsolete. So, a final comparative study was done between MAX 1472 and TWS-BS-3. A parametric comparison is presented in table 4. With respect to cost, power efficiency as well as heritage, MAX1472 was selected. MAX1472 has space heritage for being used in IIT Kanpur's nanosatellite Jugnu.

Component Chosen: MAX 1472 (Maxim Integrated).

Specifications: MAX 1472 is an OOK/ASK transmitter operating in the 300 MHz to 450 MHz frequency range. The device can also be placed into a 5nA low-power shutdown mode. Depending upon the frequency of operation, the input voltage varies between 2.1 V and 3.6 V. The stand-by current consumption of the device may shoot up to 350 nA if the temperature goes to 125^o C. The typical power output fluctuates between 6 mW and 13.7 mW, depending upon the temperature.

Table 4:Comparison between MAX1472 and TWS-BS-3 OOK modulators

Criteria	MAX 1472	TWS-BS-3
Range of operational frequency	300 MHz to 450 MHz	433.67 MHz to 434.17 MHz
Maximum data rate	100 kbps	8 kbps
Peak output power (at 25◦C)	10.3 mW	10 mW
Operating supply range	2.1 V to 3.6 V	3 V to 12 V
Temperature	−40◦C to 125◦C	−20◦C to 85◦C

Power Amplifier:

Requirements: The power amplifier needs to provide an amplification of at least 11 dB to keep up with link budget requirements. Another important requirement is that the frequency of operation should be in the UHF range. To allow for flexibility, a cascadable amplifier is preferred because any changes in amplification requirement can be incorporated in the system by simply cascading another such amplifier. The linearity of the amplifier, its frequency response in the desired frequency range and supply voltage are other specifications that were considered.

Study: On the basis of the above parameters and the space heritage of components, the search narrowed down to two amplifiers: THS9001 from Texas Instruments and RF5110G from Qorvo. A comparative study is presented in table 5. While RF5110G shows superior gain performance, sufficient gain is also provided by THS9001 in the desired frequency range of operation. THS9001 is also a cascadable amplifier. In terms of cost, accessibility and relatively simpler printed circuit specifications, it was decided that THS9001 would be preferable over RF5110G.

Specifications: THS9001 is a 50 MHz to 750 MHz cascadable amplifier chip from Texas Instruments. It has a low noise figure of 4.5 dB and design only requires two dc-blocking capacitors, a power-supply bypass capacitor, a RF choke and a bias resistor as additional components. The datasheet of THS9001 recommends an operating voltage of 2.7V to 5V. The operating free-air temperature agrees with industrial-grade component temperature specifications i.e. −40C to 85C. The typical frequency response for VS = 3V and 5V , L(COL) = 470 nH at room temperature.

Table 5: Comparison between THS9001 and RF5110G Power Amplifiers

Parameter	RF5110G	THS9001
Operating frequency range	150MHz to 960MHz	50MHz to 750MHz
Input Impedance matching	50Ω	50Ω
Gain	32dB	15 to 15.8 dB
Supply Voltage	-0.5V to +6V	2.7V to 5V

RF Switch:

Requirements: To switch between beacon downlink and payload data downlink, an RF switch is required. On the ground station transceiver Kenwood TS-2000 has internal RF switching capability. Hence, an external RF switch is required only for the onboard circuit. An RF switch design should achieve a low insertion loss, high isolation, and high linearity. Cost and space heritage are the other parameters considered.

Study: PE4259, manufactured by Maxim Integrated, has been chosen for switching between onboard transceiver CC1101 and OOK modulator MAX1472. This RF switch is space-proven in SwissCube nanosatellite.

Component Chosen: PE4259 (Peregrine Semiconductor).

The PE4259 UltraCMOS RF switch is designed to cover a broad range of applications from 10 MHz through 3000 MHz. This reflective switch integrates on-board CMOS control logic with a low voltage CMOS-compatible control interface and can be controlled using either single-pin or complementary control inputs. Using a nominal +3V power supply voltage, a typical input 1dB compression point of +33.5 dBm can be achieved [9].

Table 6: Summary of component selection

Components	Reasons for selection
Microcontroller MSP430 F5529 (Texas Instruments)	1. Highly power efficient. 2. Proven space heritage. 3. Extensive documentation on programming and development available.
UHF Transceiver CC1101 (Texas Instruments)	1. Proven space heritage. 2. Compatibility with the TI microcontroller MSP430
VHF Transceiver ADF7021 (Analog Devices)	1. Low power consumption. 2. One of the few transceivers to offer 144 MHz VHF operation (in RF divide-by-2 mode). 3. Proven space heritage.
OOK Modulator MAX1472 (Maxim Integrated)	1. Proven space heritage (IIT-Kanpur's student satellite Jugnu, for instance). 2. Offers higher data rate. 3. Offers ultra-low power consumption during shutdown mode.
High Power Amplifier THS9001 (Texas Instruments)	1. Consumes less than half the power as compared to other considered. 2. Cascade-able amplifier. 3. Desired linearity and response in the frequency range of interest
RF Switch PE4259 (Peregrine Semiconductors)	1. Proven space heritage (SwissCube nanosatellite). 2. Parameters required for Isolation, Insertion losses, linearity range and operating frequency are met.

4. ONBOARD INTERFACING AND TESTING

The testing of the on-board circuit consisting of the MSP430F5529 microcontroller, MAX 1472 OOK modulator, PE 4259 RF switch and CC1101 transceiver was successfully implemented using evaluation boards and breadboard circuits of the components. A dedicated block diagram of this implementation is shown in figure 2 along with actual implementation in figure 3 for cross-referencing. All the components were successfully interfaced and their working was verified using an RTL-SDR

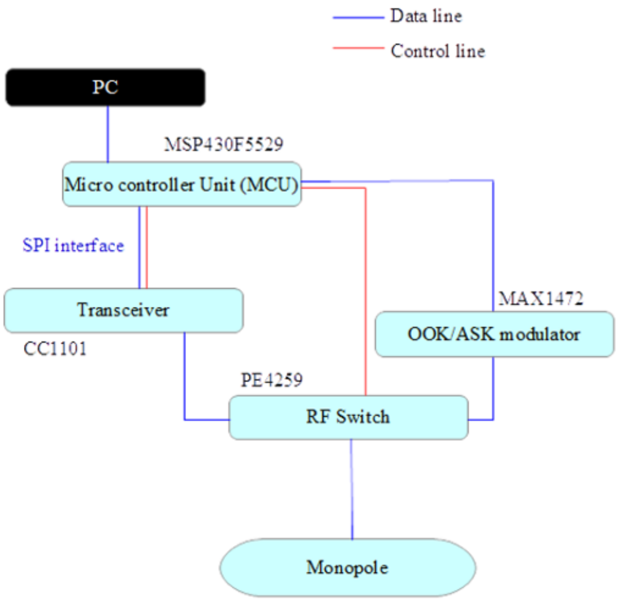


Figure 2:Block Diagram of the testing circuit for onboard components

Microcontroller to Transceiver Interfacing

For interfacing CC1101 to MSP430F5529 an SPI bus was used, with MSP430 as the master and CC1101 as the slave.

The SPI transfer is responsible for writing the optimum register settings for the RF link into CC1101 through a single burst transfer. These settings are calculated beforehand with the help of SmartRF studio and then uploaded in the code on the MSP [16].

Code Composer Studio (CCS) was used to program the telemetry MCU. CCS is an Integrated Development Environment (IDE) that supports TI's Microcontroller and Embedded Processors portfolio. It a suite of tools used to develop and debug embedded applications [3].

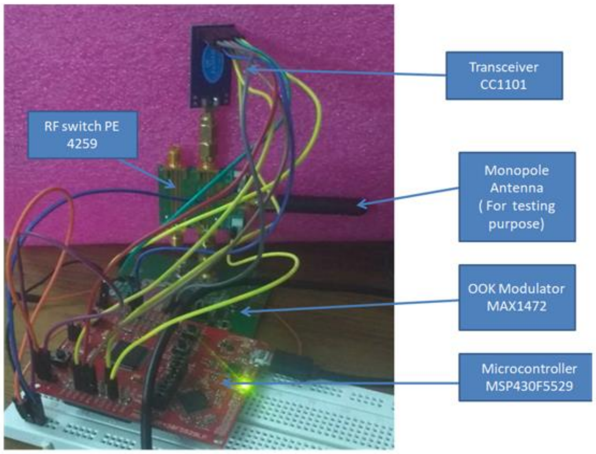


Figure 3: Testing circuit for onboard components

It includes an optimizing C/C++ compiler, source code editor, project build environment, debugger, profiler, and many other features. Code Composer Studio combines the advantages of the Eclipse software framework with advanced embedded debug capabilities from TI resulting in a compelling feature-rich development environment for embedded developers.

CC1101 Registers and SmartRF Studio

The following points are relevant when interfacing CC1101 [6]:

1. There are 49 8-bit registers.
2. All registers can be programmed with one burst transfer.
3. After chip reset, all the registers have default values initially. The optimum register setting might differ from the default value. After a reset, all registers that shall be different from the default value, therefore, need to be programmed through the SPI interface.
4. CC1101 is configured via a simple 4-wire SPI compatible interface (SI, SO, SCLK and CSn) where CC1101 is the slave. This interface is also used to read and write buffered data.
5. All transfers on the SPI interface are done MSB first.
6. All transactions on the SPI interface start with a header byte containing an R/W bit (B), and a 6-bit address (A5 A0). bit, burst access.
7. The CSn pin must be kept low during transfers on the SPI bus. If CSn goes high during the transfer of a header byte or during read/write from/to a register, the transfer will be cancelled.

Table 7: RF link parameters for ASK/OOK modulation at 433 MHz, 9600 bps and 10 dBm gain

Parameters	Value
Base Frequency	432.99 MHz
Channel Number	0
Channel Spacing	49.98 kHz
Carrier Frequency	432.99 kHz
Xtal Frequency	26 MHz
Data Rate	9.59587 kBaud
RX Filter BW	101.5625 kHz
Modulation Format	ASK/OOK
Deviation	2.38 kHz
TX Power	10 dBm

The register value of CC1101 determines its operational parameters. For eg. FREQ1, FREQ2, FREQ3 together determine the frequency. Firstly, in this experiment we tried to configure our device to transmit at a frequency of 433 MHz using On-Off Keying modulation scheme. Table 7,8 with parameters that represent a beacon signal with ASK/OOK modulation at 433 MHz, 9600 bps and 10 dB gain.

Table 8:Changed Register's values (CC1101); Other register settings are kept as their default values

Register	Changed Value
IOCFG0	06
FIFOTHR	47
PKTCTRL1	05
PKTCTRL0	05
FSCTRL1	06
FREQ2	10
FREQ1	A7
FREQ0	62
MDMCFG4	C8
MDMCFG3	83
MDMCFG2	37
MDMCFG1	00
DEVIATN	04
MCSM1	0C
MCSM1	18

Software for SPI using TI CCMSP library

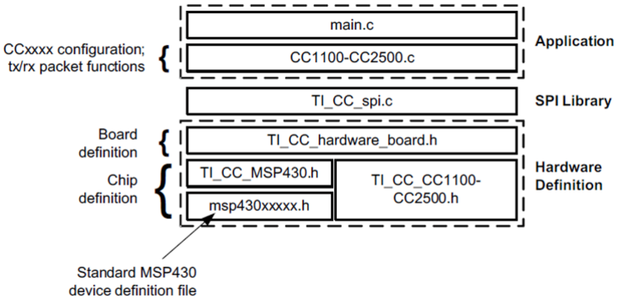


Figure 4: Code Library stack

The software for SPI between CC1101 and MSP430F5529 was written with the help of TI CCMSP Library [4]. To aid in interfacing these devices, Texas Instruments has produced this code library, which eliminates the need to write low-level interface functions. This library is designed to be used with any MSP430 device. Since an SPI master can be implemented using one of many peripherals within the MSP430 family, and since the peripherals available may differ by device and application, library calls are provided for each of these interfaces. The library has been implemented with modular hardware abstraction. There is a header file specific to each of the hardware components (CCxxxx, MSP430, and the board). Figure 4 shows the code library stack.

To test the register settings, a signal was transmitted from CC1101 and detected with the help of a Software Defined Radio (SDR) dongle using GQRX software based on UBUNTU. The block diagram of the setup is shown in figure 5. The received signal corresponding to ASK/OOK at 433

MHz is shown subsequently in figure 6. From the figure it could be concluded that signal is received at the central frequency of 432.934 MHz. The signal strength at this frequency is -20 dB. Signals received at other bands are noise.

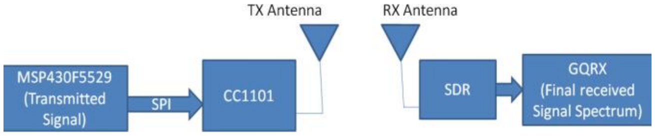


Figure 5: Interfacing Experiment Block diagram

GMSK signal Detection with SDR on GQRX

Signal was also transmitted using GMSK modulation through CC1101. CC1101 supports GFSK and GFSK with modulation index 0.5 gives GMSK. So, RF link settings and corresponding register values are shown in Table 9,10. Figure 7 shows the output received by SDR. Central frequency is at about 432.936 MHz, with the signal strength of -15 dB. Spectral density at other frequencies are present due to noise because of the surrounding environment and internal circuit.

Table 9:RF link parameters for GFSK modulation at 433 MHz, 9600 bps and 10 dBm gain

Parameters	Value
Base Frequency	432.99 MHz
Channel Number	0
Channel Spacing	49.98 kHz
Carrier Frequency	432.99 kHz
Xtal Frequency	26 MHz
Data Rate	9.59587 kBaud
RX Filter BW	101.5625 kHz
Modulation Format	GFSK
Deviation	2.38 kHz
TX Power	10 dBm

Table 10: Changed Register's values (CC1101); Other register settings are kept as their default values

Register	Changed Value
MCSM0	18
FOCCFG	16
AGCCTRL2	43
WORCTRL	FB
FSCAL3	E9
FSCAL2	2A
FSCAL1	00
FSCAL0	1F
TEST2	81
TEST1	35
TEST0	09

Microcontroller to RF Switch Interfacing

The RF switch has two data input pins, a supply voltage (VDD) pin and a GPIO CTRL pin. A combination of these inputs decides the switch path. The datasheet provides the control alternatives presented in table 7. Hence, RFC is connected to the test circuit antenna. RF1 and RF2 are RF outputs from the two transmitters, CC1101 and MAX1472.

Table 11: Control Pin levels for RF switch

Control Voltages	Signal Path
Pin6 (Vdd)=Vdd Pin 4 (CTRL) = High	RFC to RF1
Pin6 (Vdd)=Vdd Pin 4 (CTRL) = Low	RFC to RF2

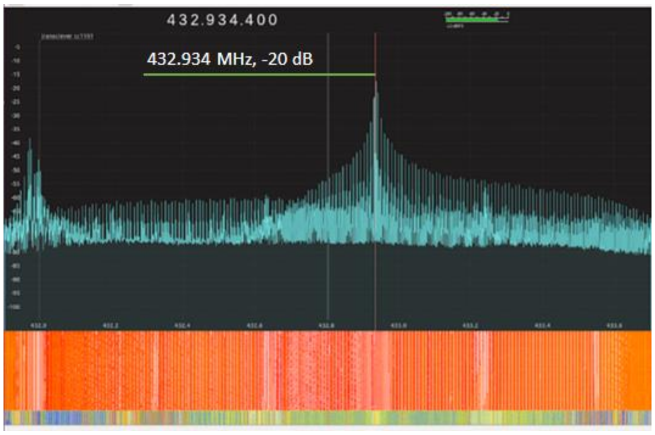


Figure 6: ASK/OOK modulated signal received at 433 MHz (using CC1101)

Microcontroller to OOK Modulator Interfacing

There are four connections of the OOK modulator which are:

1. RF OUT: Connected to the RF switch and subsequently to the antenna
2. DATA IN: Input data to be transmitted. This comes from one of the pins of the microcontroller.
3. VDD: Supply voltage
4. VSS: ground pin

These connections were made with the MSP430F5529 microcontroller and PE4259 RF switch and the evaluation kit of MAX 1472 OOK modulator. Figure 8 shows the results obtained for the signal received using SDR at 433 MHz from the OOK modulator. From figure 8, it is clear that the signal from the OOK modulator is received at SDR at the central frequency of 433.893 MHz, with a bandwidth from 433.88 MHz to 433.9 MHz. Signal strength at this frequency is about -12 dB. Given that the power spectral density has the same pattern as the OOK modulated signal transmitted using CC1101, the experimental results stand validated (i.e Pattern received in figure 6 and figure 8 are the same). Next step is packet-to-packet encapsulation, transmission and decapsulation along with the integration of uplink transceiver ADF7021 in the onboard circuit.

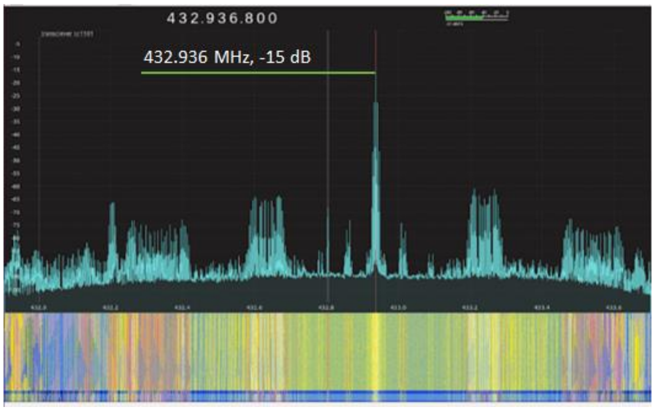


Figure 7: Signal received at 433 MHz with GMSK modulation settings (using CC1101)

Figure 8: Received Power Spectral Density after OOK modulator is turned on

High Power Amplifier (HPA) Interfacing and Testing

Testing of THS9001, the HPA used in the downlink circuitry, has been successfully completed using two methods, enumerated below:

1. Using a Mixed Signal Oscilloscope: A simple sinusoidal signal was supplied at the RF IN port of this HPA, and the RF OUT port of the HPA was directly connected to the MSO IN port. In other words, the output from the HPA was viewed on the MSO and a gain of 11 dB was achieved. From the datasheet it could be seen that in between 435 - 438 MHz band, the S21 response is somewhere between 14 to 15 dB. Further losses are presumed to occur due to connection and wire losses. The experimental setup is shown in Figure 9.
2. Interfacing OOK modulator with Power Amplifier: MAX1472, the onboard OOK modulator, was interfaced with power amplifier. The distance between the ground station transceiver (Kenwood TS-2000) and the OOK modulator interfaced with HPA was increased incrementally and then reception testing was performed which gave reliable and expected results.[22].

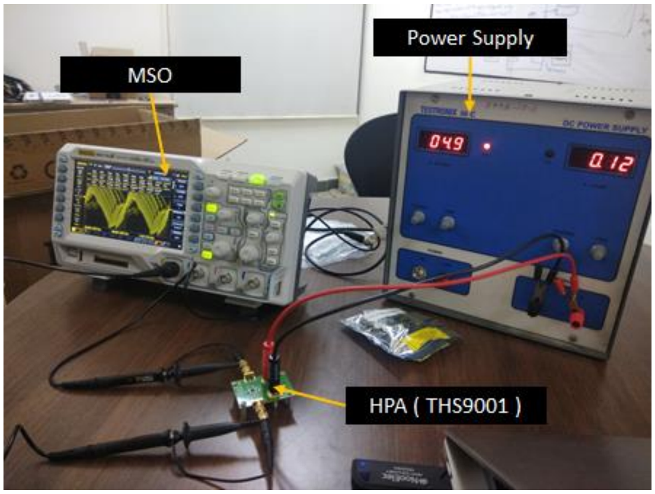


Figure 9: Experimental setup for HPA (THS9001) testing

5. ONBOARD ANTENNAS

The decision of on-board antenna types and configuration has been made to account for the following [10]:

1. Since the beacon antenna has to be continuously working, it is not feasible to use a directional antenna for the beacon, otherwise a continuous pointing is needed and the power budgets on nanosatellites generally do not permit that.
2. The advantage of using a turnstile antenna is that it gives a circularly polarized signal and hence it is not required to orient the satellite to prevent polarization mismatch. This, however, comes at the cost of increased power requirements in comparison to a simple dipole.
3. Approximately 70% of the CubeSats support Right Hand Circularly Polarized (RHCP) Ground Station.
4. Turnstile antenna usage also provides redundancy in the system, as one of the dipoles may also be used for reliable communication in an exigency mode.
5. A monopole is simple to construct. The radiation pattern for a monopole is not very directive.. Since there are no power constraints for the Ground Station, a monopole is an effective choice for receiving uplink.
6. Wire antennas are easy to integrate with a CubeSat because folding or looping of antennas is possible, thus achieving ease of compactness.

Turnstile

A crossed dipole turnstile antenna is a directive antenna that consists of two coplanar resonant dipoles placed at right angles to each other and is fed with voltages of equal amplitude and 90◦ phase shift to produce circular polarization. Circular polarization reduces the need of satellite to be oriented along its longer axis and gives better link margin, thus resulting in better data rate [12], [13].

The on-board turnstile antenna is assigned [14]:

- to transmit payload data (Downlink)
- to broadcast beacon data. As the beacon needs to be transmitted at all times, satellite pointing is not a viable solution due to power restrictions. Thus, the omnidirectional radiation generated by feeding only one pair of opposite antenna elements of turnstile, serves the purpose.
- to transmit the payload data through the deployed dipole, in a case of deployment failure where only the pair of dipole is deployed. The deployed dipole also acts as the uplink antenna for the system in case of failure of monopole deployment. The dipole will then work in half-duplex mode.

Because of magnetorquers placed near the center of the body of the satellite and the hyperspectral imager placed on one end, it has been decided to position the antennas on the other end of the satellite. This is due to electromagnetic compatibility issues. Figure 11 shows the directive radiation spectrum of the antenna in this position.

Ansys High Field Structural Simulator (HFSS) has been used for pre-verification of the design ideas. The basic modelling consists of mainframe of the satellite along with a thin epoxy layer on its surface. The optometric approach is applied after setting the element base length to 17 cm (lambda/4), and 18.2 cm is the length obtained for maximum impedance matching to the micro strip feed. Considering the normal mode of operation when all elements are deployed, the turnstile configuration has been simulated, i.e, both the dipole arms are fed [17].

The relevant results are presented in Table 12. The S11 dip of -33dBi is obtained at 435MHz as shown in figure 12, with a 3.273 dB gain (figure 11). The major benefit deduced from the radiation pattern shown in Figure 11 is that there is no need to employ 180◦ rotational actuation of the nanosatellite to focus the main lobe towards the earth, as it is automatically directed when the camera placed on the opposite face of the turnstile is earth-pointed. Thus pointing for down-linking of data is equivalent to pointing for image capture. Moreover, the antenna should maintain sufficient gain with 1 degree pointing relaxation according to ADCS, and our system is able to achieve this specification with multifold margin. The design also results in 0.93dB axial ratio which indicates a close to ideal circular polarization.

Table 12: Relevant Results for normal turnstile operation

Relevant Results	Simulated Value
S11 at 435.13 MHz	-33 dB
Antenna Bandwidth	40.85 MHz (416.5 MHz - 457.35 MHz)
Gain	3.273 dBi
Axial Ratio	0.93 dB

For further characterization and robustness check, the system performance was analyzed in case of deployment or feeding failure in a dipole pair. The simulation has been done by using the turnstile in a dipole configuration described in the previous sections. S11 plot in Figure 14(a) shows a sharp dip of about -28 dB at 433.23 MHz. The simulated antenna could work efficiently in between 399.25 - 482.28 MHz, and hence there is an available bandwidth of 83.03MHz. Also, the polar plot shows the omnidirectional behavior of turnstile antenna in this feed configuration with a gain of 3.72 dB (figure 13).

Beacon is an integral part of any satellite system. To prevent failure in reception of beacon, turnstile antennas would be used in dipole configuration, i.e., only one antenna pairs would be fed. Result should be omnidirectional which we can see from Figure 15 with a gain of 4.286 dB. S11 plot remains almost similar to that of turnstile antenna with a dip of 33 dB at 435 MHz.

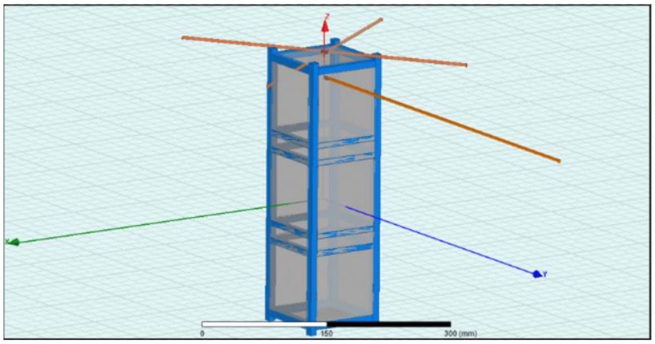


Figure 10: Turnstile antenna and monopole antenna positioned on top of the satellite [17]

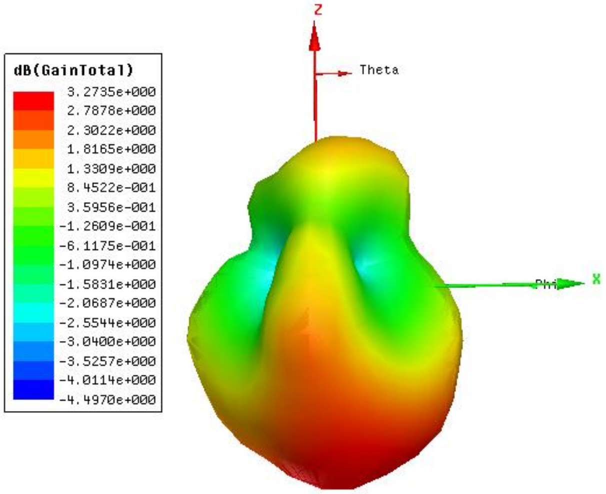


Figure 11: Polar radiation plot pattern for the turnstile antenna

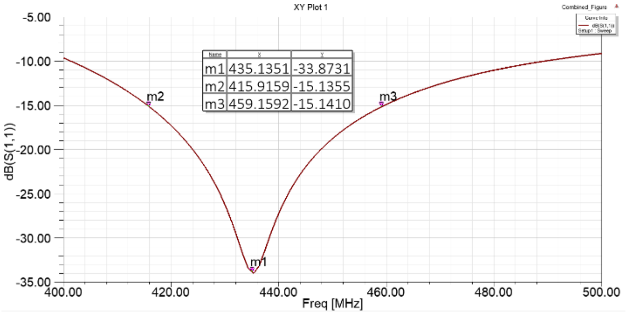


Figure 12: S11 dip for turnstile antenna

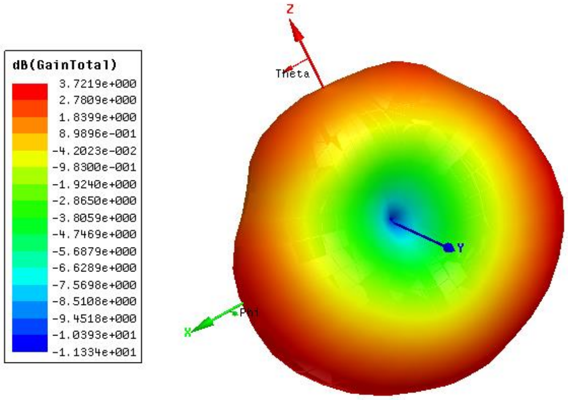


Figure 13: polar radiation pattern for dipole antenna

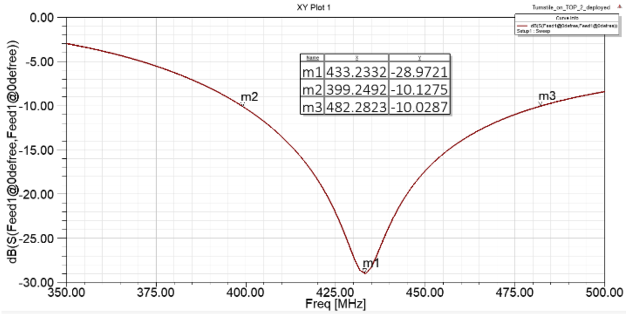


Figure 14: S11 dip for dipole antenna

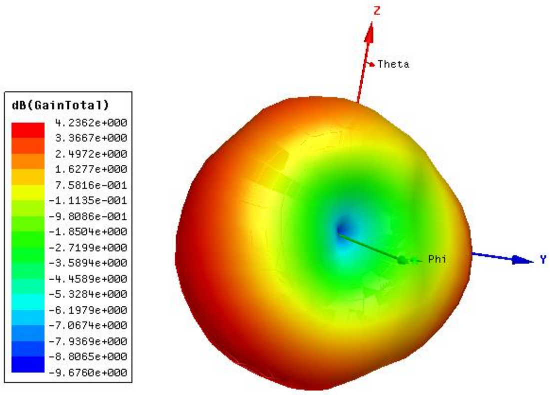


Figure 15: polar radiation pattern for turnstile fed as dipole

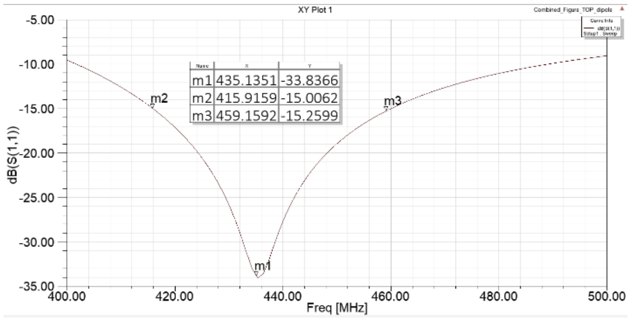


Figure 16: S11 dip for turnstile fed as dipole antenna

Monopole

One of the targets of TTC is to enhance the data throughput and minimize packet errors, which is necessary due to the large imaging payload data. Full duplex is one way to achieve a higher data rate. However, implementing a full-duplex system on a nanosatellite creates space constraints and might result in huge interferences. So, we choose a simple, more compact, monopole antenna to receive the uplink data to enable full-duplex operation. Also, the issues regarding linear polarization of monopole are mitigated because the ground-station is assumed to have very precise pointing. A similar rationale for positioning of the turnstile has been followed for deciding the placement of monopole antenna at the end of CubeSat. In order to avoid mutual coupling of the two antennas along with larger metal ground area availability to the monopole to increase radiation gain, the position as shown in figure 10 has been selected [17].

Figure 17 shows the omnidirectional radiation of monopole in this configuration at 144MHz frequency. The operable frequency ranges from figure 18 is 138.67 MHz to 149.67MHz, and the design's maximum S11 dip is -28.5 dB at 146.2 MHz, perfect for fabrication. The gain obtained is 2.04dBi as depicted in figure 17, and the deviation from the literature maxima of 5.15 dB gain for monopole on a ground plane occurs due to practical limitations of the maximum conductive ground area availability.

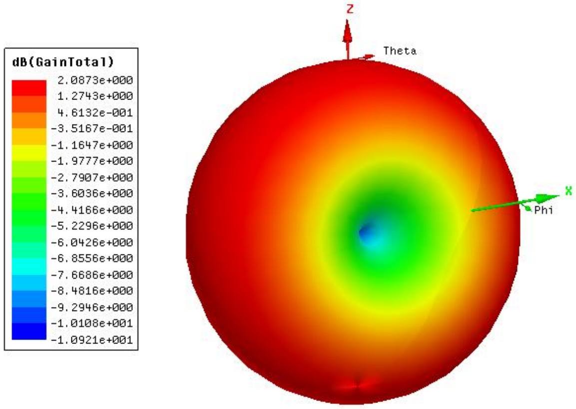


Figure 17: polar radiation pattern for monopole antenna

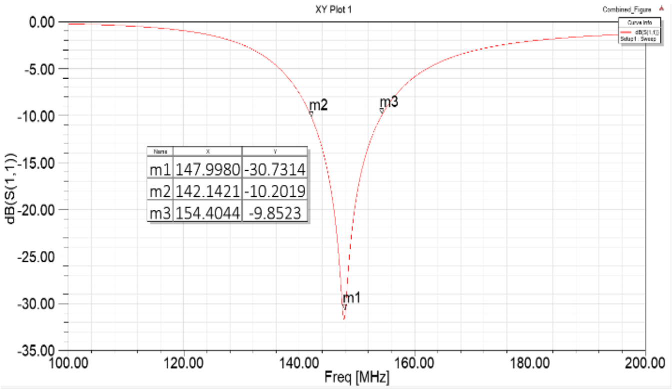


Figure 18: S11 dip for monopole antenna

6. DEPLOYMENT CIRCUIT

The requirements from the deployment circuit are:

1. Should be actuatable with standard CubeSat power bus.
2. Should Use Commercial-Off-The-Shelf (COTS) components.
3. Should Have space-proven heritage
4. Should be Inexpensive.

Keeping the above factors in mind, nichrome burn-wire release mechanism was selected. The circuit designed for deployment is shown in figure 19. It uses IRF540N, an NMOS power MOSFET which acts as a switch. On receiving deployment instruction in the form of a gate pulse, a current of about 0.64 A flows through the ceramic drain resistance of 5.6 Ω, producing sufficient heat to burn the Nylon wire, wound across the antenna doors. Figure 20 (a), (b) shows the experimental setup of the given circuit. In the figure it can be clearly seen that the antenna has been deployed from the deployment module when the nylon wire was burnt.

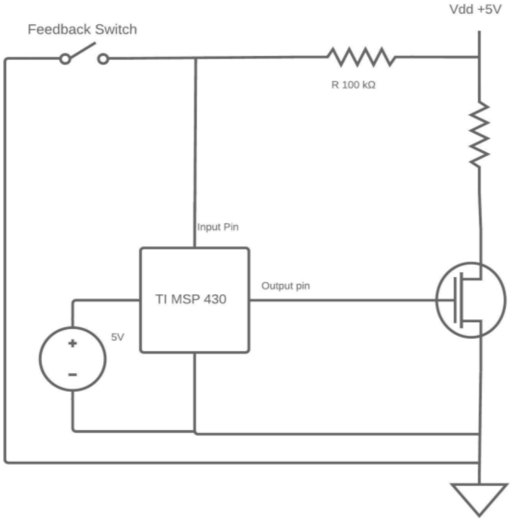


Figure 10: Deployment Circuit

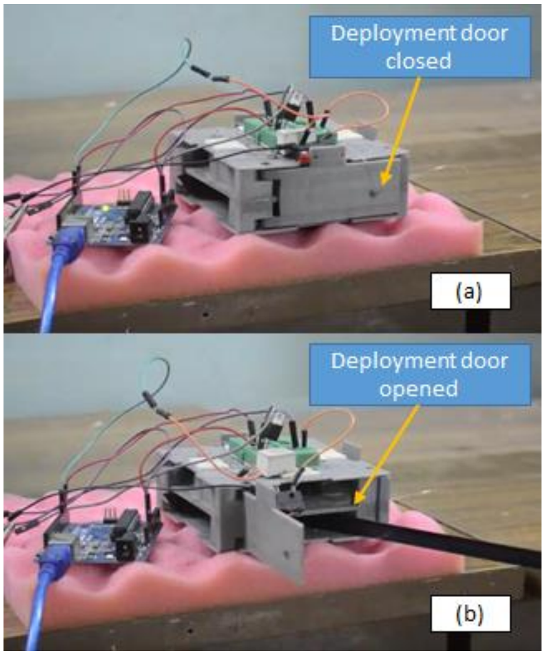


Figure 11: Prototype of deployment circuit

7. FLIGHT PLAN AND EMERGENCY MODES

The sequence of modes on the following page provides an overview of sub-system tasks and operation sequence for the on-board communication system. The terminology of the modes is consistent with the overall modes of operation of the nanosatellite.

There are three types of antenna configurations possible as posed by Structural and Thermal Subsystem due to the structure of the deployment module which is shown in the following figure 21.

If the antenna is deployed as in Figure 21 (a) and Figure 21 (b) then the microcontroller will be operating in the full duplex mode whereas if it follows the Figure 21 (c) then it will be operating in Half Duplex Mode [15].

Different modes of telemetry microcontroller operations:

1. INIT Mode: Whenever Onboard Computer switches ON the Telemetry microcontroller then it will first goes into the INIT Mode where it will do the following operations:
    - Retrieve Antenna configuration packet from the Onboard Computers.
    - Beacon control which is initially in the hands of Electrical Power Subsystem microcontroller will be transferred to the Telemetry microcontroller and advanced beacon transmission will start.
    - First pass condition will be tested once advanced beacon starts

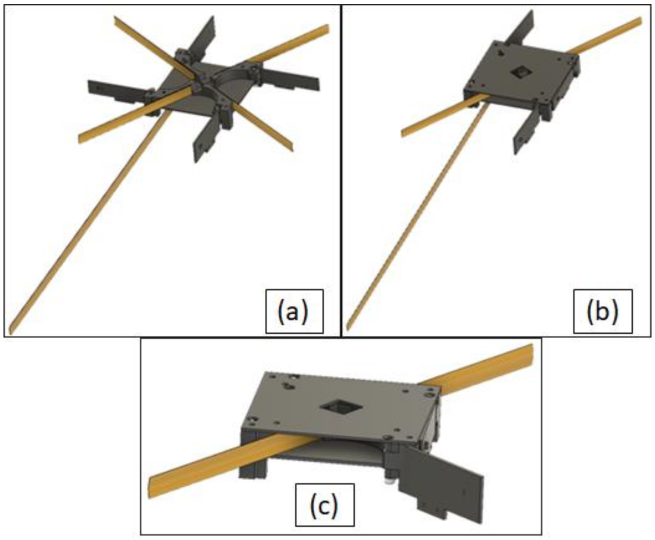


Figure 12: a) All elements of the turnstile and monopole antenna open. (Full-Duplex Mode); b) Two elements of Turnstile and monopole antenna open (Full-Duplex Mode); c) Only two elements of turnstile open (Half Duplex Mode)

2. First Pass Mode: If the satellite is having its first pass in its orbit, then following operation will be performed.
    - Turnstile antenna will be fed in the dipole format as explained in section 4.5 for beacon transmission and uplink reception. Because in the first pass mode, the first link will be established with the satellite's onboard computer through UHF band using CC1101 and MUX. (Refer Fig.3.1).
    - In this mode, Beacon transmission will occur in one minute intervals i.e. for the first one minute the beacon transmission will take place and for the next one minute, the satellite will be awaiting for uplink reception (First TLE) from the ground station.
3. Idle Mode: If the satellite is not in the first pass mode then it will enter in this mode where the following operations will be performed:
    - The microcontroller will retrieve data from the shared memory and save it in telemetry's memory after AX.25 packetization of payload data.
    - Continuous beacon transmission will take place through dipole fed turnstile.
4. Handshake Mode-A: In the First pass mode it will keep checking if the link between the satellite and the ground station has been established or not. If yes, then it will enter into this mode and will perform the following operations:
    - Uplink from the ground station will be received through UHF band using dipole fed turnstile antenna and CC1101.
    - It will then send an acknowledgement packet back to the ground station.
5. Handshake Mode-B: After the execution of the idle mode the microcontroller will keep checking if the pass is near or not. If yes, then it will check the antenna configuration. If it is Full Duplex, then uplink reception will take place through the Monopole antenna otherwise, it will take place in UHF band through turnstile fed as a dipole.
6. Downlink Mode: When the satellite comes in the field of view of the Ground station, then after Handshaking it will go into the downlinking mode where the following tasks will be performed:
    - Payload data downlink through Turnstile antenna in UHF Band.
    - Beacon transmission will stop.
    - Turnstile will be fully fed.
7. Re-Transmission Mode: Telemetry microcontroller will enter into this mode as it will receive Retransmission request from the ground station.

Onboard System Architecture Redundancies

- Turnstile antenna as two independently operable dipoles.
- CC1101 as an OOK Modulator redundancy.
- ADF7021 as CC1101 transceiver redundancy.
- CC1101 as ADF7021 transceiver redundancy.
- Onboard Computer as Telemetry microcontroller redundancy.

Emergency Modes

- CC1101 fails and Telemetry MCU is operating: In this case, Telemetry MCU continues to carry out the packetization operation but ADF7021 will be used for transmission of payload data.
- Telemetry MCU and/or CC1101 fail: In this case, OBC becomes the only active processing unit but ADF7021 will be used for data transmission.
- ADF7021 fails: In this CC1101 is used for uplinking of data.
- OOK Modulator fails: CC1101 will be used in its place.

8. GROUND STATION

A dedicated ground station needs to comprise of both robust hardware and software to transmit and receive data reliably. The target is to build a truly autonomous GS, which can communicate with the satellite without any human intervention. The GS needs to receive data from the satellite and send some predetermined commands including the Two Line Element (TLE), retransmission requests and other data, to the satellite. Therefore, the components in the GS architecture include the transmitting and receiving antennas, a computer with orbital-prediction software, compatible with the hardware for auto-tracking, and a transceiver to transmit and receive data [19].

Ground station Antennas

Yagi-Uda antennas and helical antennas are commonly used for ground stations. Yagi-Uda antennas are known to be more directional than helical antennas, having beam widths more than 90°, but compromises on pointing accuracy in comparison to helical antennas. Moreover, dish antennas cannot be used because they are not feasible at low frequencies at which operation is planned. Crossed Yagi antennas, being more efficient owing to their circular polarization, will be used for the ground station design.

The antenna to be used for downlink reception at the ground station is a crossed Yagi antenna operating at a frequency of 436 MHz [25]. Simulations of the antenna have been done to optimize the gain. A gain of 17.96 dB has been obtained in the simulations performed in the open-source electromagnetic modelling software 4NEC2 (National Electromagnetics Code). Figure 22 shows the gain pattern in φ as well as θ planes.

The antenna was thus constructed physically in-house as per the parameters obtained from the simulation. The elements are attached on an aluminum boom. Phase quadrature between the excitations to the two driven elements was obtained by virtue of quadrature wavelength distance between them. The antenna was finally tested by using Vector Network Analyzer for determining reflection coefficient and VSWR versus frequency. Several constraints from a structural and physical perspective including soldering on aluminum and feeding, make the task of crossed Yagi construction challenging. Similarly, another crossed Yagi antenna is used in the 144 MHz VHF band for uplink from the ground station to the satellite.

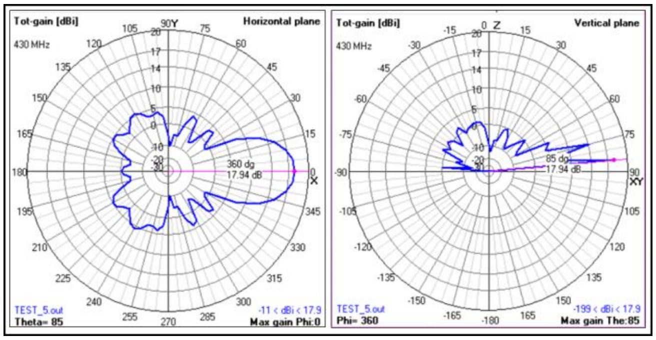


Figure 22: UHF Crossed Yagi Gain pattern in φ and θ planes

The VHF antenna was also simulated using 4NEC2, and a gain of 14 dB was obtained, meeting the link budget requirements. The VSWR is 1.67 at 146MHz and good impedance matching was achieved in the desired frequency range of operation. Figure 23 and 24 shows the gain pattern versus phi and antenna parameters respectively.

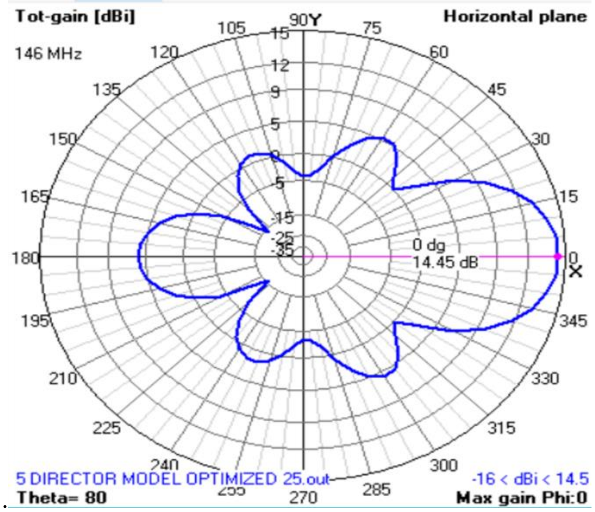
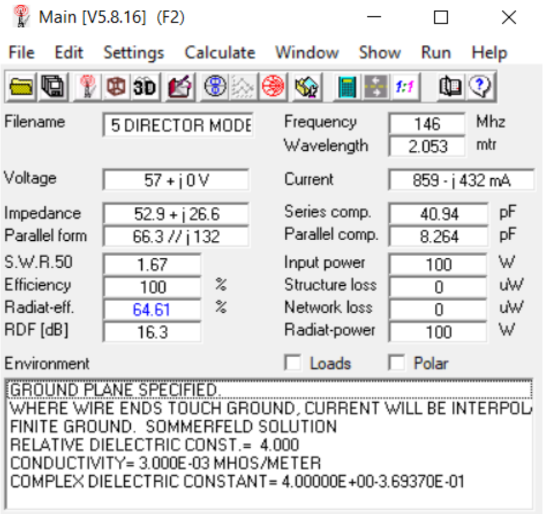


Figure 13: VHF Crossed Yagi Gain pattern in φ plane



Filename 5 DIRECTOR MODE
Frequency 146 Mhz
Wavelength 2.053 mtr
Voltage 57 + j 0 V
Current 859 - j 432 mA
Impedance 52.9 + j 26.6
Parallel form 66.3 // j 132
Series comp. 40.94 pF
Parallel comp. 8.264 pF
S.W.R.50 1.67
Efficiency 100 %
Radiat-eff. 64.61 %
RDF [dB] 16.3
Input power 100 W
Structure loss 0 uW
Network loss 0 uW
Radiat-power 100 W
Environment ☐ Loads ☐ Polar

```
GROUND PLANE SPECIFIED.
WHERE WIRE ENDS TOUCH GROUND, CURRENT WILL BE INTERPOL
FINITE GROUND. SOMMERFELD SOLUTION
RELATIVE DIELECTRIC CONST.= 4.000
CONDUCTIVITY= 3.000E-03 MHOS/METER
COMPLEX DIELECTRIC CONSTANT= 4.00000E+00-3.69370E-01
```

Figure 24: Antenna parameters (Snapshot of the main window of 4NEC2)

Ground Station Components

Low Noise Amplifier (LNA)

For LNAs, the primary parameters are noise figure (NF), gain and linearity. On satellite ground stations, an LNA, or low noise amplifier, is often placed close to the antenna. Power consumption and efficiency in the LNA are generally no the primary concern. The function of the LNA is to sense the extremely weak from the antenna, usually of the order of microvolts or under 100dBm and amplify it to a more useful level. SP-7000 has been selected as low noise amplifier for our ground station. SP-7000 is powered from the radio through its coaxial connection with a DC voltage at 13.8 volts applied to the center conductor. This eliminates the need for an additional power cable [23].

Transceiver

The transceiver used for the ground station is a Kenwood TS-2000 [20]. It is an all-band VHF/UHF transceiver with versatile connectivity options. There are two operation modes: main and sub, which can be used for UHF and VHF respectively allowing us to listen/transmit on both channels without having to switch manually. There are two important interfaces: one for frequency control and the other for received baseband audio signals (containing telemetry and housekeeping data). There is a COM port provided in the transceiver which allows serial connection with PC. The PC running a radio control s/w (like ARCP from Kenwood) can be used to set the transmission frequency and Doppler shift remotely as well as change other settings.

The other interface is audio output from the transceiver external speaker jack that is inserted into the Line In of the ground station PC. This audio data is processed by a satellite decoding s/w using the PC's sound-card.

To ensure proper connection, a sound card interface circuit may be designed. This will protect the soundcard from the high current that may flow from the transceiver and provide isolation from the transceiver, although they can be directly connected.

An experiment was set-up and successfully conducted for demonstrating reception via Kenwood TS-2000. Kenwood receives data sent from a transmitter (tested separately for both transceivers, CC1101 and MAX1472) interfaced with THS9001 High Power Amplifier by using a monopole that was fabricated for 435 MHz frequency. Figure 25 shows the transmission end of the experiment. Interfacing protocols as mentioned in section 4, have been used to construct this transmission end. A monopole antenna has been attached with the HPA, which was connected to the OOK Modulator, which was interfaced with the on-board MCU.

Data is sent through MSP430, the onboard microcontroller, whose output was also tapped on a Mixed Signal Oscilloscope (MSO). To verify that the data sent was at the desired frequency range, the same signal was also received on a PC using Software Defined Radio (SDR) and associated HSDR software. Figure 26 shows the complete experimental setup. This experiment successfully tested the reception capabilities and operation of the Kenwood TS-2000 transceiver in the UHF band. Kenwood received the signal at the desired frequency of 433 MHz with a BER of approximately 10^{-8} (calculated using DIREWOLF). The discrepancy in the calculated and the observed BER was attributed to the differences in the transmission environment of space and ground where the experiment was performed.

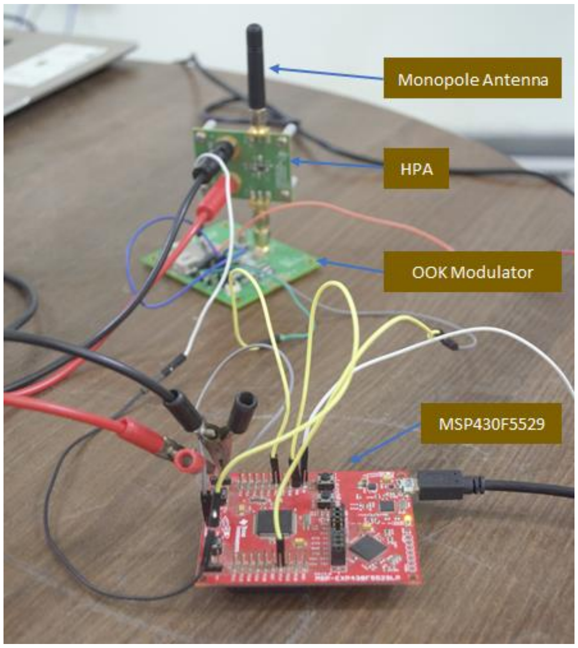


Figure 25: The transmission circuit of the experimental setup

RTL-SDR, one of the most popular receivers used by HAM Radio enthusiasts was used for an independent test of our fabricated monopole antenna (435 MHz) to be used with Kenwood TS 2000 for the final experiment. Data was sent through OOK Modulator (MAX1472) and received by RTL-SDR using the software HSDR. Figure 28 shows a snapshot of the power spectrum of the signal received by the RTL-SDR as part of reception testing. The peak of +22 dB occurs at around 434.97 MHz, thus verifying that the antenna's frequency band of operation is as intended.

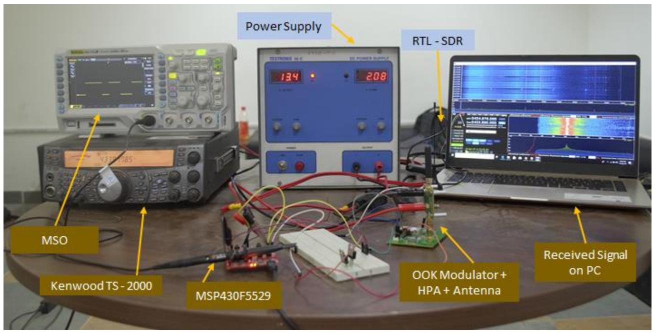


Figure 26: The complete experimental set-up

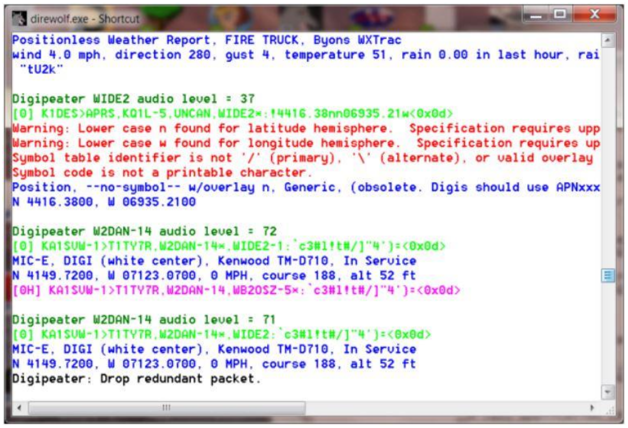
AX.25 implementations on Ground Station Computer

For participation in a network via the AX.25 protocol, a Terminal Node Controller (TNC) is generally used. It is a combination of a microcontroller with software to encode and decode AX.25 packets, modem and an antenna. Its functions are [22]:

1. Assembling a packet from data received from the computer.
2. Computing an error check (CRC) for the packet.

3. Reverse the process.

a virtual TNC will be used as it gives better results and reduces costs compared to its hardware counterpart. A virtual TNC works by connecting the radio to the soundcard interface of a computer and using software to decode the bit stream. The software used is Decoded Information for Radio Emissions for Windows and Linux (DIREWOLF), which was used on Windows OS. It is an open-source software[21].the functionalities of this software have been worked out. This includes configuring of AX.25 ports, logging and decoding of packets etc. Figure 27 shows Direwolf running on Windows and receiving packets. Information is colour-coded. The green colour represents received packets, blue represents decoded version of the received packets and red represents errors.



```
Positionless Weather Report, FIRE TRUCK, Byons WXTrac
wind 4.0 mph, direction 280, gust 4, temperature 51, rain 0.00 in last hour, rai
 "tU2k"

Digipeater WIDE2 audio level = 37
[0] K1DES>APRS,KQ1L-5,UNCAN,WIDE2*:!4416.38nn06935.21w<0x0d>
Warning: Lower case n found for latitude hemisphere.  Specification requires upp
Warning: Lower case w found for longitude hemisphere.  Specification requires up
Symbol table identifier is not '/' (primary), '\' (alternate), or valid overlay
Symbol code is not a printable character.
Position, --no-symbol-- w/overlay n, Generic, (obsolete. Digis should use APNxxx
N 4416.3800, W 06935.2100

Digipeater W2DAN-14 audio level = 72
[0] KA1SVW-1>T1TY7R,W2DAN-14*,WIDE2-1:`c3#l!t#/]"4'}=<0x0d>
MIC-E, DIGI (white center), Kenwood TM-D710, In Service
N 4149.7200, W 07123.0700, 0 MPH, course 188, alt 52 ft
[0H] KA1SVW-1>T1TY7R,W2DAN-14,WB2OSZ-5*:`c3#l!t#/]"4'}=<0x0d>

Digipeater W2DAN-14 audio level = 71
[0] KA1SVW-1>T1TY7R,W2DAN-14*,WIDE2:`c3#l!t#/]"4'}=<0x0d>
MIC-E, DIGI (white center), Kenwood TM-D710, In Service
N 4149.7200, W 07123.0700, 0 MPH, course 188, alt 52 ft
Digipeater: Drop redundant packet.
```

Figure 27: Direwolf simulations

Rotor control and Satellite Tracking

A rotor assembly is needed in order to point the antenna directly towards the satellite. The hardware, as well as software aspects of the rotor drive and control, are detailed in this section. Figure 29 is a block diagram of the rotor control circuitry.

Rotor Hardware

The Hardware Setup comprises the rotor controller and the circuitry to support it. The rotor was decided to be built in-house as the commercially available one is expensive. Two stepper motors will be used for this purpose - one for the azimuth rotation and the other for elevation. Worm gears were used for torque magnification and reducing the step size of the stepper motor. Worm gears were chosen as they provide mechanical locking [24].

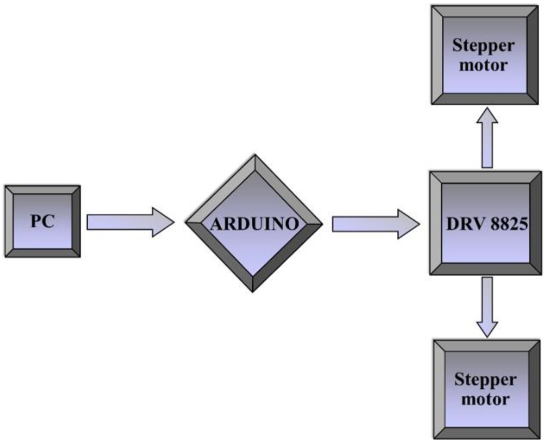
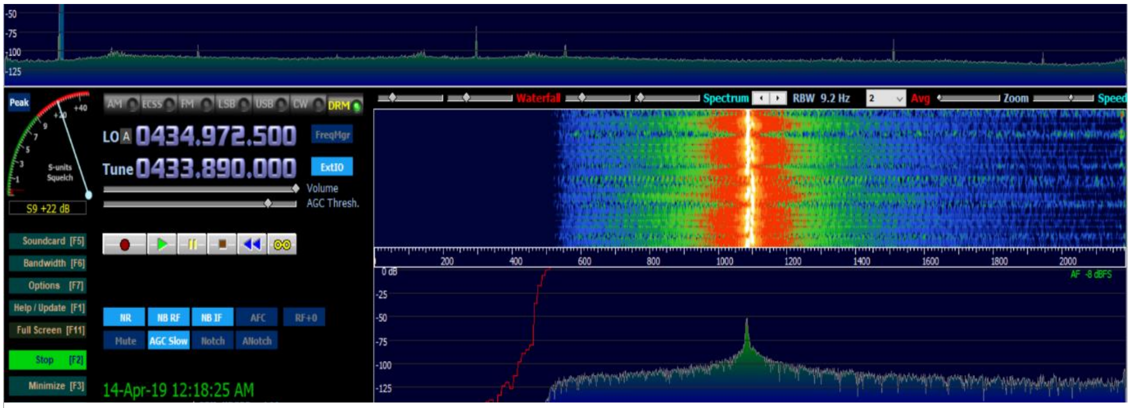


Figure29: Block diagram for the rotor control

The hardware components and specifications are listed below:

1. An indigenously designed gearbox. Construction has been built and is being tested.
2. DRV8825 is a motor driving shield intended for driving a bipolar stepper motor.
    - 8.2 V to 45 V Operating Supply Voltage Range
    - 2.5 A maximum drive current at 24V
    - Ambient temperature = 25 Degree Celsius
3. Arduino Uno is used which is a microcontroller board based on ATmega328. It has one I2C interface for interfacing the driver.



S9 +22 dB
LO A 0434.972.500
Tune 0433.890.000
RBW 9.2 Hz
2
14-Apr-19 12:18:25 AM

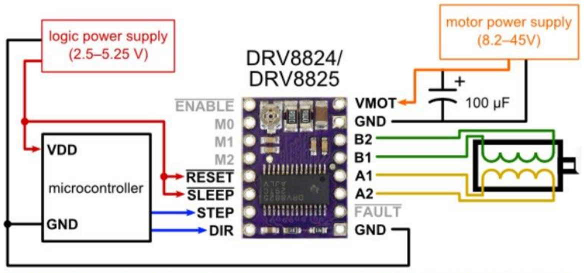
Figure 28: Testing with RTL-SDR as receiver

4. Two NEMA 23 stepper motors have been used. One motor is for elevation and the other one is for azimuthal of the antenna.
    - Voltage: 12-36V
    - Current: 3.2 A DC
    - Torque: 10.1 Kg-cm
    - Step Angle: 1.8 deg / step
    - Shaft Diameter: 6.3mm

Rotor Software

Gpredict: A free, open-source software for Linux/Ubuntu: GPredict was found to be commonly used among the amateur community. It also supports radio and antenna control for autonomous tracking and many such project details, videos were found showing how to use the same. GPredict works with Hamlib library. This library includes commands which take input from other programs and use them to control antennas. A rotator interface has been created on it specifying the limits of azimuthal and elevation angle, the port number used for the antenna control. With the help of an Ubuntu terminal command, the serial baud rate, serial port (the one with which Arduino is connected from before) and the protocol used to configure it with the Hamlib have been specified. Now the antenna control module of the Gpredict and can be used to start tracking of the satellite. Easycomm 2 serial terminal supported by Hamlib has been used. The initial testing for rotor control has been done by using GPredict and implementing code on Arduino.

Rotor Control Code: The code always has the current location of the rotor which it calculates based on previous movements of the motor, so in this way, no sensors are required to locate the rotors current position. Initially, including an accelerometer and a magnetometer in the rotor was planned, but this was no longer required. To prevent possibilities of error. The code locks the motor when it is not under any command to move. Based on the distance to move from the current position it determines the optimum speed and acceleration with which the antenna should be moved to achieve the target position. This prevents any damage due to jerks to the antenna.



Minimal wiring diagram for connecting a microcontroller to a DRV8824/DRV8825 stepper motor driver carrier (full-step mode).

Figure 30: Detailed connection of Driver Circuit DRV8825

Arduino IDE: the Arduino IDE is used for compiling and uploading the code to the Arduino Board. , The Accelstepper Library was used for running the rotor control code. Although there was some timing mismatch, it was observed that the rotation of the stepper motors (AZ and EL) was in accordance with the input provided by Gpredict in the antenna control module. Figure 30 shows the circuit diagram of the rotor mechanism.

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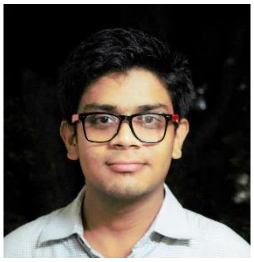

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