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Engineering Reports

A cost effective receiver for meteorological balloon telemetry application using RTL-SDR and LabVIEW

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Abstract

In this paper we present design of RTL-SDR based low cost receiver for meteorological balloon telemetry. In developed receiver all the demodulation processes are performed in software developed in LabVIEW. Design and fabrication of Quarter Wave Monopole Antenna and Quadrifilar Helix Antenna (QHA) is also presented for use with the receiver. Antennas are selected such that the combined beam pattern provides optimum coverage in both low and high elevation angles. This system is designed to operate in meteorological-aids frequency band of 400-406 MHz. Paper presents bit error rate performance of developed receiver. Performances of the RTL-SDR receiver using both the antennas are assessed by processing the signals received from the radiosonde flights at Gadanki (13.46°N, 79.17°E). Finally it is shown that RTL-SDR based receiver can receive signals up to the range of about 75-80 Km.

KEYWORDS

RTL-SDR, Radiosonde receiver, LabVIEW demodulator, Radiosonde antenna.

1. INTRODUCTION

A case of DVB-TV [1] tuner based software defined radio as a ground receiver for meteorological balloon borne sensor instrumentation, often termed as radiosonde [2] [3], is presented. These tuners DVB-TV are based on Rafael Microelectronics make R820T and Realtek make RTL2832U chipsets and popularly known as RTL-SDR[1]. Proprietary hardware receiver or universal software radio peripheral (USRP) are commonly used as meteorological balloon telemetry receivers. Most of these receivers are expensive and are suitable for bench-top applications. In addition a small, mobile, low power and low cost ground receiver is desirable for remote location radiosonde launch campaigns. Further a mobile receiver can be of great use if tracking and recovery of expensive radiosonde payload such as Ozonesonde, frost point Hygrometer etc. is required. Often recovered payloads are reused to cut down the launch cost.

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In this paper an affordable low cost receiver for hobbyist and student community is presented. Figure 1 shows the block diagram of the proposed RTL-SDR based receiver system. Radiosonde transmitter parameters and characteristics are well defined in ITU-R SA.1165-1, 2004 [5]. Typical parameters of the telemetry system for radiosonde application are as given in Table 1. Most of the present day radiosonde uses Gaussian Frequency Shift Keying (GFSK) to transmit the sensor data in the frequency range of 400.15-406 MHz. Often Reed-Solomon error detection and correction technique is also applied to improve the link performance.

Table 1: Radiosonde Telemetry specifications

Frequency range	400.15-406 MHz
Modulation	GFSK
Data rate	1200 -4800 bps
Transmit power	+20dBm
Error correction and detection	Reed Solomon and CRC
Range coverage	Up to 100 Kms.

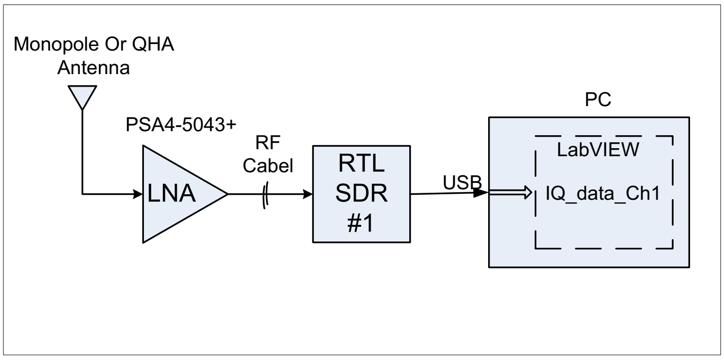

Figure 1: RTL-SDR based meteorological balloon ground receiver

In this paper, we first give receiver hardware details in section 2. In section 2.1 design details of quarter-wave monopole and quadrifilar helical antennas are given. Beam pattern of these two antennas complement each other in sky. Both the antennas are fabricated and tested in lab. Description of RTL-SDR hardware architecture is given in section 2.3. In meteorological balloon application, the balloon borne transmitter typically transmit one packet every second. As given in Table 1 transmitted signal is GFSK modulated with data rate between 1200-4800 Kbps. Receiver first tunes to the centre frequency of transmission and then demodulates the signal and recovers the message. Description of RTL-SDR interface with LabVIEW, demodulation method and processes are given in section 3. In section 4, we evaluated the following parameters to prove the case of RTL-SDR based receiver for radiosonde application:

1. Sensitivity of receiver in terms of SNR and bit error rate.
2. Expected link coverage of the receiver.

In order to assess the sensitivity of RTL-SDR based receiver, IQ data is fetched from RTL-SDR and processed in real time using LabVIEW. Synthesized modulated signal from a vector signal generator is used to evaluate BER at different SNR levels and modulation parameters

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Further to estimate the link coverage of the receiver, routine soundings of radiosonde at NARL are used. SNR of the signal received receiver with respect to the radial distance of the GPS radiosonde are recorded and analysed. Section 5 concludes the paper.

2. HARDWARE DESCRIPTION

This section describes the details of the three main components of the receiver system used in design viz. software defined radio comprising of a PC and RTL-SDR USB dongle, Antenna and LNA block.

2.1 RECEIVER ANTENNA

Two antennas- Quarter-wave monopole and Quadrifilar Helical Antenna (QHA) are selected such that the combined beam pattern provides optimum coverage in both low and high elevation angles. Design parameters such as return loss and beam pattern of both the antennas are first simulated and optimized using software called 4NEC2 which can be obtained from website http://www.qsl.net/4nec2/. This software is based on Numerical Electromagnetic Code version two (NEC-2). The Numerical Electromagnetics code (NEC-2) is a computer code for analyzing the electromagnetic response of an arbitrary structure consisting of wires and surfaces in free space or over a ground plane. The analysis is accomplished by the numerical solution of integral equations for induced currents[6]. 4NEC2 is a simple yet powerful tool which comes with an optimizer which can be used to optimize various parameters of the antenna under design.

a. Qurter-wave monopole Antenna

Using the Image theory monopole antenna can be modeled as a half the size of dipole antenna. It is always mounted above some ground plane. The ground plane prevents the radiation below the ground plane and therefore its radiation pattern is equivalent to the radiation pattern of a dipole in upper hemispere[7][8][9]. Four numbers of radials having length of the order of $\lambda/4$ are used to realize the ground plane. Futher the dimension of radiator and radials are optimized to obtain the beam pattern and refelction coefficients as shown in Figure 2. To achive the impedance matching with 50Ω co-axial feeder, radials are bent about 45° from the horizontal plane. Theoritical dimenstions, dimenstions after optimisation and actual dimentions of radiator and radials are tabulated in Table 2.

Table 2: Monopole antenna dimenstions

Dimenstions	L1 (mm)	L2 (mm)	Ø (deg)
Theoritical	186	186	0
After Optimization	179	215	45
Actual	178	215	45

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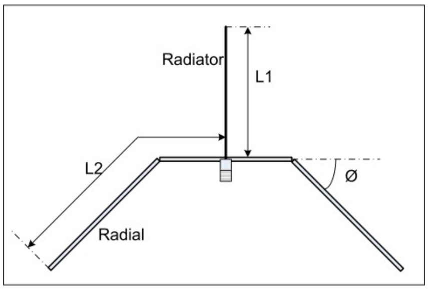
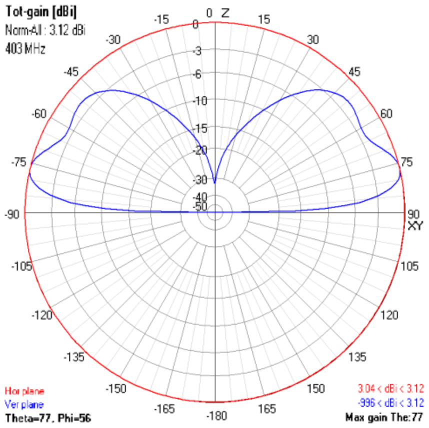
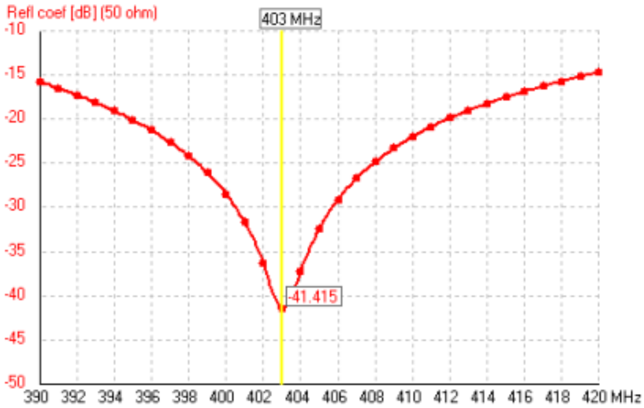


(a)



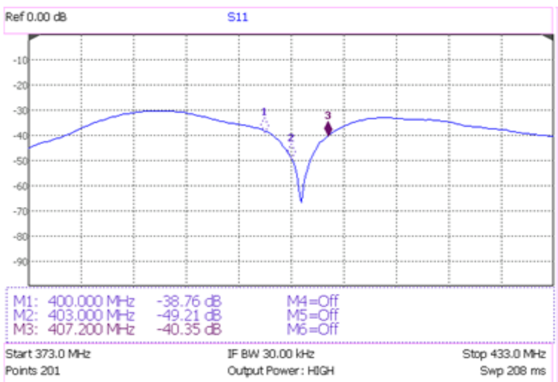


(b) (c)

Figure 2:Quarter-wave Monopole Antenna (a) Schematic (b) Simulated beam pattern (c) Simulated reflection coefficient.

The dimention of the quarterwave monopole antenna are optimized to obtain a peak gain of 3 dBi and half power beamwidth from 42° to 84° in vertical plane.

Figure 3(a) shows the fabricated antenna having dimensions obtained from simulation. Return loss of the fabricated antenna is measured using Keysight N9912A network analyzer. Retrun loss of better than 39 dB is achieved for the operating frequency range of 400-407 MHz.



(a) **(b)**

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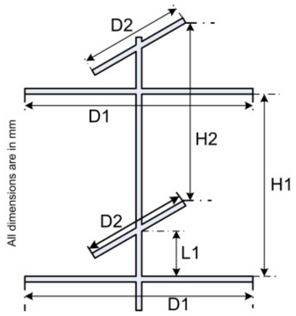
Figure 3:(a) Fabricated Quarter-wave antnnea and (b) measured S11 parameter

Designed monopole antenna provides maximum gain in the lower elevation region. At higher elevation angles between 45° to 90° its gain varies from 0 dBi to -30 dBi. This creates no coverage region or gap region overhead the antenna. Therefore another antenna was designed to provide the coverage in the overhead gap region of the fabricated quarter-wave monopole antenna.

b. Qurter-wave monopole Antenna

Quadrifilar Helix Antenna [10] is a good choice to provide the coverage in gap region of designed quarter-wave monopole antenna. Beam-width of greater than 100° was required in the vertical plane. Optimizer functionality of 4NEC2 was used to achieve beam pattern and reflection coefficient as shown in Figure 4. Final dimensions of the antenna obtained from the 4NEC2 are tabulated in Table 3.



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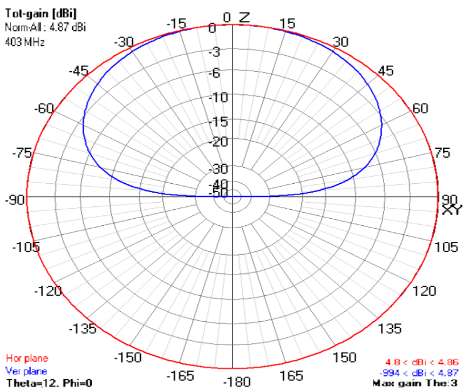

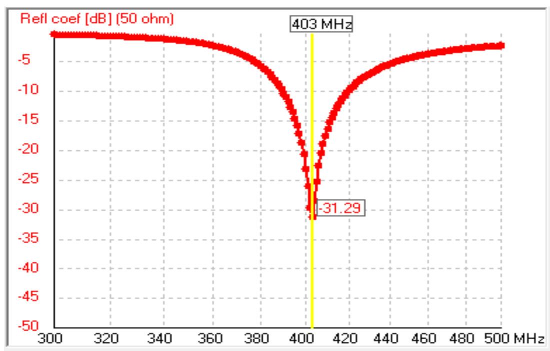

(b) (c)

Figure 4:Quadrifilar Helical Antenna (a) Schematic (b) Simulated beam pattern (c) Simulated reflection coefficient.

Simulation results shows that designed QHA has maximum gain of about 5 dBi at 0° elevation angle. It has a hemispherical beam pattern above ground plane with 3 dB beam width close to 120°. Figure 5 shows the fabricated QHA and its measured S11 parameter.

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Centre frequency of 402 MHz and return loss of better than 45 dB is obtained for the fabricated QHA.

Table 3:QHA Dimensions

Parameter	Value
Frequency	403 MHz
No. of turns	0.5
H1	150 mm
D1	130 mm
H2	150 mm
D2	120 mm
L1	25 mm

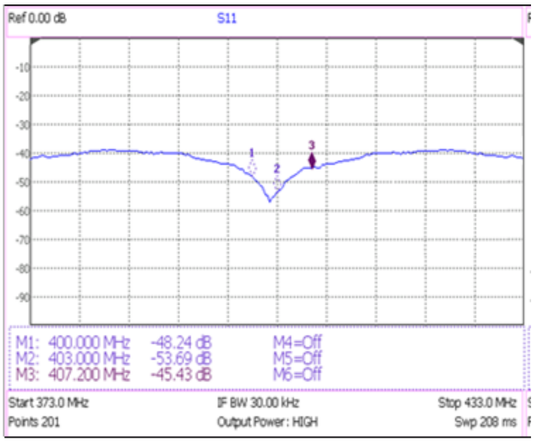

Figure 5: Fabricated QHA (left) and its S11 parameter (right)

2.2 LOW NOISE AMPLIFIER

Maximum transmit power of radiosonde is limited to 20 dBm [5]. Free space path loss for operating frequency of 406 MHz and path length of 100 km will be about 124 dB. Therefore to Mini-Circuits ultra-low noise PSA4-5043+ LNA is used to amplify the received signal. Key specifications are given in Table 4. More details can be found in part datasheet.

Table 4: Specification of LNA

Parameter	Specifications
Frequency band	50-4000 MHz
Gain	+23dB @403MHz
Noise figure	<1 dB

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2.3 **RTL-SDR RECEVER**

A simplified functional block diagram and a photograph of the used RTL-SDR are shown in Figure 6.

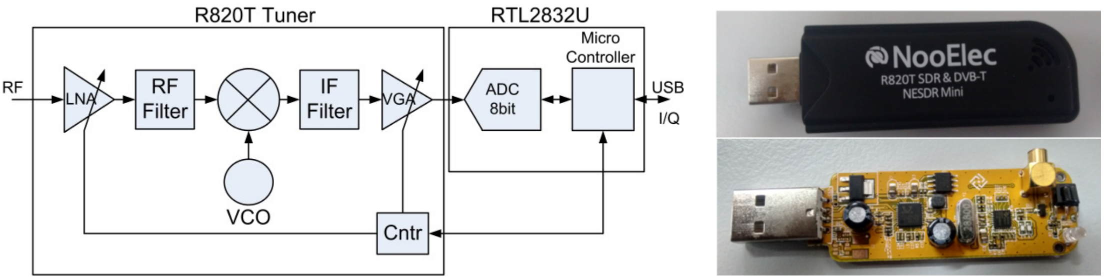

Figure 6: Functional block diagram (left) and photograph (right) of RTL-SDR.

It gets its RF functionality from Rafael Microelectronics make R820T chip. R820T is a RF tuner IC which consists of a mixer and digitally controlled VCO along with variable gain amplifier and filter stages before and after the mixer stage. VCO oscillator frequency, amplifiers gain and filter bandwidth of R820T are controlled by the Realtek RTL2832U chipset over I2C serial bus. RTL2832U also digitize the down converted baseband IF signals using inbuilt DDC and sends 8 bit IQ data over USB bus to the PC for further processing. Key specifications of RTL-SDR are tabulated in Table 5. More details of RTL-SDR hardware can be obtained from [1].

Table 5: RTL-SDR Specifications

Parameter	**Specifications**
Frequency range	42-1002 MHz
Return loss	-10 dB
Noise Figure	3.5dB
Max. input power	+10dBm
Phase noise	-96dBc @10Khz
Image rejection	65 dBc
IQ data resolution	8 bit
Max sample rate	3 MSps

3. RECEIVER SOFTWARE

Receiver software is developed in LabVIEW. The receiver software performs the following tasks:

1. RTL-SDR parameters configuration and signal acquisition from RTL-SDR.
2. Frequency offset correction and decimation.
3. Demodulation, decoding, packet formation and data log.
4. Received data analysis and bit error rate computation.

RTL-SDR drivers for LabVIEW are not available therefore USB to TCP pipe is used to communicate with RTl-SDR as given in [11]. Once communication with RTL-SDR is

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established its centre frequency, amplifier gains and sample rate can be controlled from the receiver software. Since occupied bandwidth of most of the digital radiosondes is typically less than 20 KHz therefore IQ data is sampled at lowest possible sample rate of 250 KSPS.

Demodulation is performed as shown in Figure 7. Plot-A in Figure 8 shows the spectrum of the received modulated signal. Following two characteristics of the received signal can be observed from the spectrum- first, there is a frequency offset of about 25 kHz in received signal due to imperfection in crystal oscillator used in tuner. Second, presence of DC noise due to IQ imbalance. These problems are rectified by first applying a bandpass filter centered at offset frequency of 25 KHz to remove DC noise and then shifting centre frequency to zero hertz. These functions are performed using *Downconvert Passband* VI available in modulation toolkit of LabVIEW. This VI is also used to limit the signal bandwidth to 15 KHz to remove out of band noise. Frequency spectrum of output of these functions is shown in plot-B of Figure 8. Further to reduce the computational load of the demodulator processes complex baseband signal is resampled. Resampling rate is computed by multiplying symbol rate with required sample per symbol. Required samples per symbol are chosen as 16. An even number of samples per symbol is required because timing recovery process in demodulator is optimized for four or more samples per symbol.

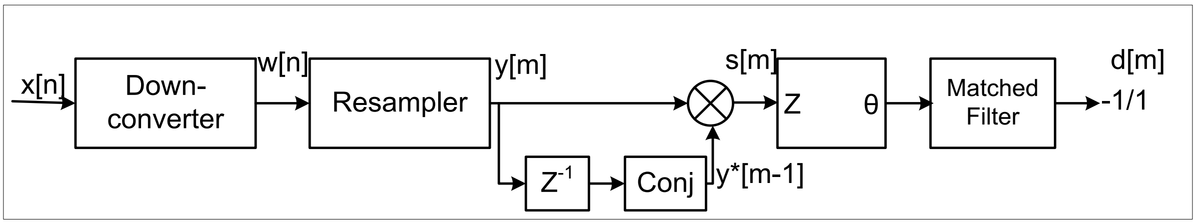

Figure 7: Frequency estimation and demodulation of 2FSK modulated signal.

Demodulation of the resampled complex baseband signal is performed by FSK *demodulator* VI. After resampling, signal s[m] is computed as given in equation-1 below:

$$s[m] = y[m]y^*[m-1] \tag{1}$$

For the FSK y[m] will be of the form $Ae^{-jm\omega_0}$, where $\omega_0 = \pm 2\pi\Delta f/f_s$, Δf is frequency deviation and f_s is sampling frequency. Therefore s[m] will be reduced as given in equation-2.

$$s[m]=(Ae^{-jm\omega_0})(A^*e^{-j(m-1)\omega_0}) = A^2e^{j\omega_0} \tag{2}$$

Phase of complex signal s[m] provides ω_0. Recovered frequency ω_0 is then compared with the expected frequency $\widehat{\omega}_0$ using a matched filter. Matched filter determines whether recovered frequency is close to Δf or -Δf . Output d[m] of matched filter varies from -1 to +1. Since the sample per symbol is set as 16, each bit of encoded massage is represented by group of 16 samples of d[m]. It is required to find the location of optimum sample location at which SNR is highest to determine the corresponding bit. An estimate of decoded bit b[*l*] at sample location *l* is defined as:

$$b[l] = \begin{Bmatrix} 0 \; when \; d[l] \geq 0 \\ 1 \; when \; d[l] < 0 \end{Bmatrix} \tag{3}$$

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FSK *demodulator*.vi uses Mod_Max_Eye.vi to estimate the optimal sample location l at which SNR is highest. A transmitted packet consists of preamble bit sequence of [101010…], byte synchronization word followed by message bits. Synchronization word is used to lock to the start of massage and parse the information bits. Once information bits are extracted bit error rate is computed by comparing the obtained bit sequence with the actual modulated bit sequence. Developed graphical user interface of RTL-SDR receiver is shown in figure-9**.**

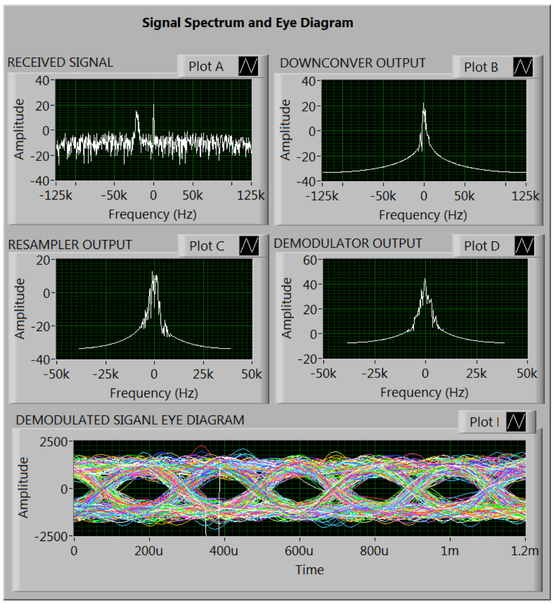
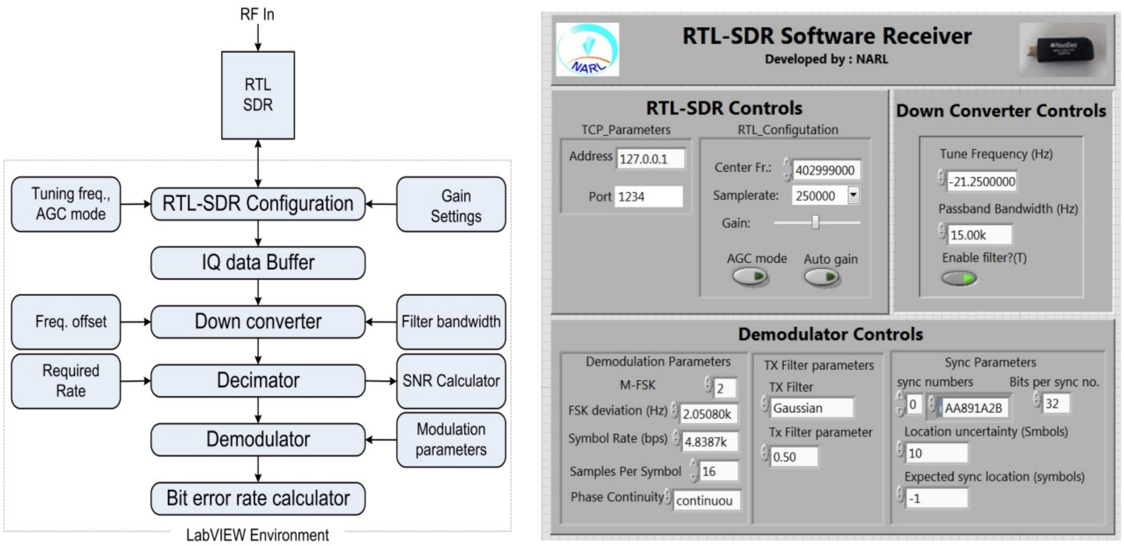


Figure 8: Spectrum of the signal at the output of various signal processing blocks and the eye diagram of the demodulated signal indicating the quality of the received signal.



(a) (b)

Figure 9: (a) Receiver software processing steps and corresponding input parameters (b) User Interface to set the receiver parameters.

4. RECEIVER SENSITIVITY AND LINK COVERAGE

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For given modulation scheme and propagation medium the desired Bit Error Rate (BER) gives the required SNR at the receiver input. In this work BER of 10^{-4} is considered and sensitivity of the receiver is defined by the minimum SNR of the input signal for which BER of the receiver becomes 10^{-4}. Agilent N5182A mixed signal generator is used to generate GFSK modulated signal of known bit sequence. The bit sequence consists of six bytes of preambles, four bytes of synchronization word and 256 bytes of information. Modulated signal is fed to RF input of RTL-SDR using RF cable. Received signal is then demodulated by the receiver as given in section-3 and BER is computed. Power of modulated signal is decreased in steps and corresponding BER are obtained. SNR for which BER is of the order of 10^{-4} is then recorded as receiver sensitivity.

Measured sensitivity of the receiver for various modulation parameters are given in Table 6.

Table 6: Receiver sensitivity for different modulation parameters

Data rate(bps)	Fr. Deviation(Hz)	SNR(dB)@BER=10^{-4}
1200	1000	14
2400	1200	15
2400	2000	15
4800	2400	16

Considering 4 dB of margin SNR of 20 dB or more will be required at the receiver input to achieve BER of 10^{-4} or better. Further to establish that developed receiver will be able to receive the data from long distance, tests are carried out to estimate the maximum radial distance up to which RTL-SDR based receiver system can be used to receive and demodulate the signal from the radiosonde flight. For this launches of radiosonde at NARL are used. To collect vertical profile of meteorological parameters such as Pressure, Temperature, Relative humidity, Wind Speed and Wind Direction GPS radiosondes are launched at NARL every day at 1730 LT. During the tests Meisei RS-11G radiosonde were launched. This radiosonde transmits modulated signal at 1200 baud rate to ground receiver in the frequency band of 400-406 MHz. The transmit signal power this radiosonde is 20dBm.

The data format of this radiosonde is unknown and cannot be used for the computation of the BER. Since the minimum SNR of 20 dB at the input of RTL-SDR receiver is required to achieve the BER of 10^{-4} therefore received signal SNR can be used to approximate the maximum radial distance for which RTL-SDR receiver system will be able to decode the receive signal. Maximum radial distance for which received signal SNR remains lower than 20 dB is defined as receiving range of developed receiver. Block diagram of the test setup is given in Figure 10. LabVIEW program is used to log the SNR of the received signal with corresponding time stamp for whole duration of the radiosonde flight. Time interval between two readings was set to one minute.

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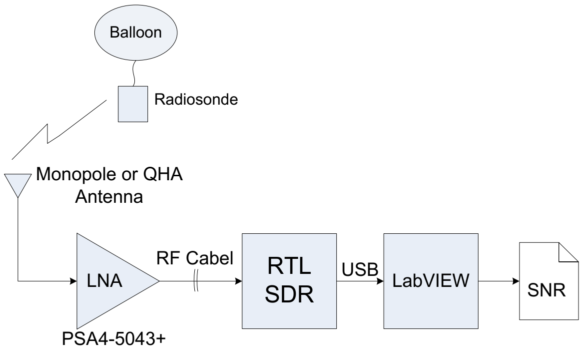

Figure 10: Block diagram of measurement setup for logging SNR of received signal from the fabricated antennas.

A separate ground receiver Meisei RD-06G-006 is used simultaneously to receive and log the data from the RS-11G. Along with other parameters it also provides geolocation of the radiosonde flight. This geolocation is used to obtain the radial distance of the radiosonde from the ground receiver with respect to the time. SNR of the received signal from the RTL-SDR receiver system are then time synchronized and correlated with radial distance of radiosonde. Four numbers of profiles of SNR with respect to radial distance as given in Figure 11, for both the antennas, are generated by repeating the test on different days. These measurements confirms that the RTL-SDR can be used to receive the radiosonde signals up to a distance of about 65-80 kms.

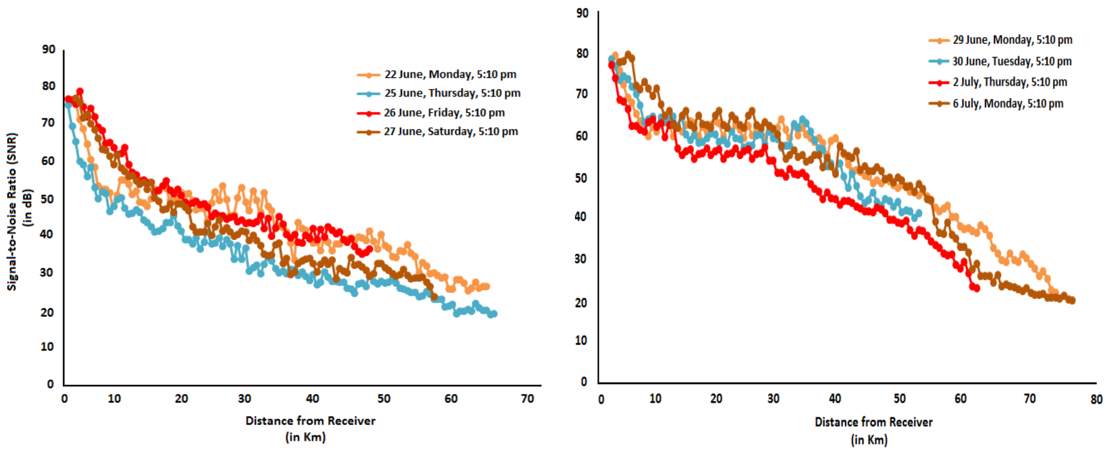

Figure 11: SNR vs Range profiles on four different days for Quarter-wave molopole antenna (left plot) and QHA antenna (right plot).

Further one year of radiosonde flights over NARL for the year 2015 are examined to find the histogram of maximum radial distance of the flights. This exercise is carried out to know if the distance coverage of RTL-SDR receiver is sufficient for the proposed application. Figure 12 shows the histogram of the radiosonde distance for one year of flights. Total 339 numbers of radiosonde profiles are used for the analysis.

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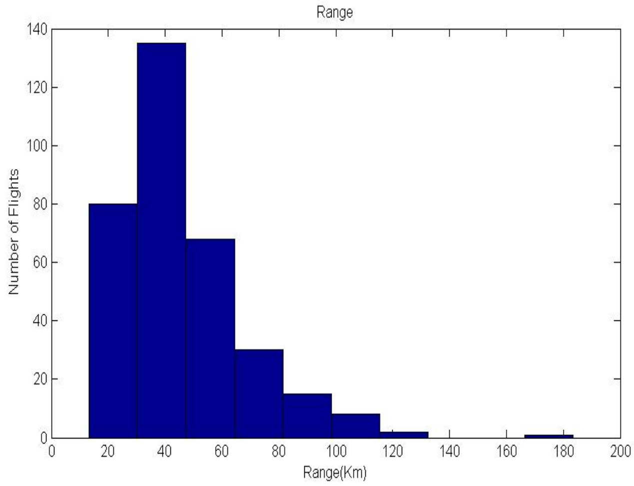

Figure 12: Range histogram of radiosonde over Gadanki for duration Jan-Dec 2015.

It is found that median range of radiosonde flight from Gadanki is only 40 km and few flights only went beyond 80 Kms.

5. DISCUSSION AND CONCLUSION

We have shown how a software defined receiver for radiosonde application can be built with the help of commercially available RTL-SDR and LabVIEW. The advantages of the developed receiver are quick development time, modularity and mobility. Design of Quarter-wave monopole and QHA antennas to be used in receiver system is also discussed to help the researchers and hobbyist to establish their own receiver for radiosonde application. The sensitivity of the RTL-SDR based receiver is evaluated for different data rate and frequency deviation values. Further to establish the maximum distance for which receiver can receive the data, real time radiosonde flights are used.

Results showed that minimum SNR value of 20dB is required to achieve BER of 10^{-4}. SNR measurements with respect to radial distance of transmitter shows that when RTL-SDR receiver is coupled with monopole antenna it can receive the data up to about 65-70 Km. and when coupled to QHA data could receive up to the range of 75-80 Km. Further from the analysis of one year of radiosonde flights at NARL it can be confirmed that RTL-SDR based receiver is a good contender to implement a low cost receiver for meteorological balloon telemetry system. However few improvisations such as inclusion of Reed-Solomon decoder, metallic enclosure for RTL-SDR, a band pass filter at front end and use of low loss RF cable etc. can be used to make the receiver system further robust and reliable. Further it is possible to implement that two channel receiver using two RTL-SDR devices fed with monopole and QHA for hemispheric coverage with little modifications in software.

6. CONFLICT OF INTEREST

Authors have no conflict of interest relevant to this article.

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7. REFERENCES

[1] R. W. Stewart *et al.*, “A low-cost desktop software defined radio design environment using MATLAB, simulink, and the RTL-SDR,” *IEEE Commun. Mag.*, vol. 53, no. 9, pp. 64–71, 2015.
[2] F. Flores *et al.*, “The life cycle of a radiosonde,” *Bull. Am. Meteorol. Soc.*, vol. 94, no. 2, pp. 187–198, 2013.
[3] W. F. Dabberdt and H. Turtiainen, “OBSERVATIONS PLATFORMS | Radiosondes,” *Encycl. Atmos. Sci.*, pp. 273–284, Jan. 2015.
[4] M. B. Sruthi, M. Abirami, A. Manikkoth, R. Gandhiraj, and K. P. Soman, “Low cost digital transceiver design for software defined radio using RTL-SDR,” *Proc. - 2013 IEEE Int. Multi Conf. Autom. Comput. Control. Commun. Compress. Sensing, iMac4s 2013*, pp. 852–855, 2013.
[5] International telecommunication union-radiocommunication study group, “Technical Characteristics And Performance Criteria For Radiosonde Systems In The Meteorological Aids Service,” 2004.
[6] A. J. P. G. J. Burke, “Numerical Electromagnetic Code-Method of Moments, Part I: Program Description, Theory.” Naval Electronics System Command (ELEX 3041), 1977.
[7] Melvin M.Weiner, *Monopole Antenna*. Marcel Dekker Inc., 2003.
[8] K. A. S. Kraus J. D., Marhefka R. J., *Antennas and wave Propagation*, 4th ed. Tata McGraw Hill Publication, New Delhi, 2010.
[9] Cheng D K, *Field and Wave Electromagnetics*, 2nd ed. Addison-Wesley Publishing Company Inc, 1983.
[10] Wen-Yi Qin, Jing-Hui Qiu, Qi Wang, “A novel multi-frequency quadrifilar helix 1 antenna,” *IEEE Soc. Int. Symp. Antennas Propag.*, vol. 1B, pp. 467–470, 2005.
[11] [Online]. Available: https://github.com/ha7ilm/sdrlab