PRL-TN-2014-105

Technical Note

Development of a new GNU Radio Beacon Receiver (GRBR) system for Total Electron Content (TEC) measurements using 150 and 400 MHz transmissions from Low-earth Orbiting Satellites

by

Smitha V. Thampi, Y. B. Acharya, M. B. Dhadania, Kedar A. Phadke, Mala S. Bagiya, Sachin, Panchal, Nidhi Kotecha, Chaitalee Patel
(Space & Atmospheric Sciences Division)

भौतिक अनुसंधान प्रयोगशाला, अहमदाबाद
Physical Research Laboratory, Ahmedabad

Published by
The Dean's office, PRL.

PRL Technical Note
PRL-TN-2014-105

Development of a new GNU Radio Beacon Receiver (GRBR) system for Total Electron Content (TEC) measurements using 150 and 400 MHz transmissions from Low-earth Orbiting Satellites

Smitha V. Thampi, Y. B. Acharya, M. B. Dhadania, Kedar A. Phadke, Mala S. Bagiya [1], Sachin Panchal [2], Nidhi Kotecha [3], Chaitalee Patel [4]

Abstract
In this report, we present the technical details of the new GNU Radio Beacon Receiver (GRBR) system for Total Electron Content (TEC) measurements using 150 and 400 MHz transmissions from Low-earth Orbiting Satellites. The GRBR system is originally designed by Yamamoto [2008] using the open-source software toolkit for the software radio, GNU Radio and the Universal Software Radio Peripheral. Using this design, we have fabricated a GRBR system, which has been tested and installed at Ahmedabad (23.04°N, 72.54°E geographic) to obtain routine TEC measurements. In this report, we present the details of the hardware and the software of the GRBR system and the first samples of the TEC observations from Ahmedabad.

[1] *Indian Institute of Geomagnetism, Navi Mumbai, 410218, INDIA*
[2] *BSNL, Gandhinagar*
[3] *Sardar Vallabh Bhai Patel Institute of Technology, Vasad, 388306, INDIA*
[4] *SAL Institute of Technology & Engineering, Ahmedabad- 380060, INDIA*
[*] **Corresponding author**: smitha.v.thampi@gmail.com

Contents

1. Introduction

The successful launch of the first artificial satellite Sputnik-I provided the first useful data of the electron content of the ionosphere and its spatial structure [Garriot, 1960]. The receiving system included a simple dipole antenna and an analog radio receiver recording the Faraday fading of the signals. This technique was utilized later by a large number of stations after the launch of BE-B and BE-C satellites, transmitting coherently linearly polarized radio beacons of 20, 40 and 140 MHz. Since then, there were many low-earth orbiting satellites (LEOS), for example, the Navy Navigational Satellite System, which could give information on the spatial variability of the ionosphere using on-board instruments like Langmuir probe for *in situ* measurements, as well as beacons for remote sensing and navigation. The satellite beacon contributions to the studies of the structure of the ionosphere have been reviewed by Davies [1980]. Over the Indian region, radio beacon studies of the latitudinal distribution of the ionospheric Total Electron Content (TEC) were initiated in the early 1960s with the recording signals from the orbiting explorer (BE-B and BE-C) satellites. The beacon from BE-B satellite was used for studying the latitudinal variations of TEC. Rastogi and Sharma [1971] have described the results of TEC measurements over Ahmedabad. Further, the latitudinal variations of TEC were obtained by combining the data from satellite passes recorded over Kodaikanal and Ahmedabad to investigate the strength of the Equatorial Ionization Anomaly (EIA) as well as its day-to-day variability [Rastogi et al 1973, 1975]. A major improvement in measuring the TEC was by providing phase coherent radio beacons at 40, 140 and 360 MHz onboard ATS-6, which is a geostationary satellite, which basically gives the temporal variation of electron density, when observed from a particular ground station. The signals were received by short backfire antenna for each frequency and fed to a complicated receiver measuring group delay between different frequencies. Later, TEC observations using Transit beacons (also known as Navy Navigational Satellite System) were done during the total solar eclipse event of 16 February 1980 from Rangapur in the totality zone, and Ahmedabad and Rajkot, away from totality zone. [Deshpande et al 1982 a, b]. This was the only campaign when the 150 and 400 MHz signals from LEOS were recorded over Ahmedabad. With the emergence of tomographic imaging as a powerful tool [Austen et al. 1988] to address the spatial variability of the ionosphere, there is a renewed interest on TEC measurements using the beacons on LEOS. Thus there is a need for developing simple receiving systems for recording beacon signals. The TEC data from LEOS is often obtained using the differential Doppler or differential phase measurements between two coherent frequencies. The most commonly used frequencies are 150 and 400 MHz- in the ratio of 3:8-generated from a common oscillator signal at 50 MHz. The most important beacon satellite constellation, presently operational is the Russian COSMOS Navigation Satellite System. Beacon receivers developed in the past have been mostly analog receivers for 150 and 400-MHz signals, and some of them are commercially available.

The important elements include the conversion of VHF and UHF to IF range, the phase lock loop, the phase detector and the data acquisition system. In such receivers, the phase relationship between the two signals is detected by an analog circuit and the resultant phase signal is digitized. Tuning to new frequency offsets and simultaneous reception are difficult with such analog systems. In this context, a new idea of digital receiver using software-radio concept emerged. A digital receiver, named the GNU Radio Beacon Receiver (GRBR) was developed [Yamamoto, 2008] based on the open-source software toolkit named GNU Radio http://gnuradio.org/ and its open-source hardware called Universal Software Radio Peripheral (USRP) http://www.ettus.com/, for the dual band LEOS beacon reception. The GRBR has hardware based on off-the shelf units and parts and the open source software makes it easy to augment and make changes, including tuning to new frequency offsets. Another advantage of the digital receiver is that simultaneous multi-channel reception is possible, which enables us to track up to 3 satellites simultaneously.

Using the design by Yamamoto [2008], we have fabricated a GRBR, which is operational at PRL since May 2013. The presently operational high inclination satellites having a radio beacon payload include the Russian COSMOS Satellites, RADCAL and DMSP F15. GRBR system is capable of receiving signals from these satellites. In this technical note, a detailed description of the hardware and software of the new beacon receiver is provided.

2. Description of the dual beacon experiment

2.1 TEC Calculation – Theory

It is well known that while propagating through the atmosphere, the electromagnetic waves are affected by the troposphere as well as the ionosphere. The ionospheric effects are dispersive, whereas the effects of troposphere on radio signals are non-dispersive. When a radio wave travels through the ionosphere, it experiences a group delay and a phase advance proportional to the TEC between the transmitter and the receiver. As the ray passes through the ionosphere, phase speeds up and the ray bends in accordance with Snell's law, as a result of the changing index of refraction of the ionosphere. Ignoring bending and other higher order effects, we can find the TEC along the straight line between the transmitter and the receiver, because the phase change is directly proportional to the TEC along the line of sight.

The real part of the refractive index n scales with the inverse of the phase speed Vp of the radio waves $R(n) = c/Vp)$. The imaginary part is a measure of absorption. In the radio window we consider, there is practically no absorption and hence in the estimation of TEC we are only interested in the real part.

The tropspheric index of refraction is given by,

$$n_{trop} = 1 + 7.76 * 10^{-7}\frac{p}{T} + 3.37 * 10^{-3}\frac{P_{\omega}}{T^2} \tag{1}$$

Here T is the absolute temperature, p is the atmospheric pressure in Pascal and P_{ω} is the partial pressure of water vapor. At normal ground level conditions $P = 10^5$ Pa and T = 290 K; n_{trop} may vary from 1.00027 at zero humidity to 1.00036 at 100% humidity. With increasing altitude n_{trop} decreases to 1.

For the ionosphere, the complex index of refraction is given by the Appleton-Hartree formula [Rishbeth and Garriott, 1969]. This formula is based on a simple description of the cold plasma considering the electron motions only. Another important assumption is that the disturbances in the plasma induced by the electromagnetic wave are small and do not affect the propagation itself, i.e., the problem is linearized.

The Appleton-Hartree formula for the complex index of refraction is given by,

$$n_{ion}^2 = 1 - \frac{\tilde{X}}{1 - \frac{\tilde{Y}^2 \sin^2\theta}{2(1-\tilde{X})} \pm \sqrt{\tilde{Y}^2\cos^2\theta + \frac{\tilde{Y}^4 \sin^4\theta}{4(1-\tilde{X})^2}}} \tag{2}$$

Here q is the angle between the wave vector and the geomagnetic field. The tilde implies division by the absorption factor (1 + iZ). X, Y and Z are the ratios between the characteristic frequencies of the medium and the angular frequency of the signal ω,

$$X = \frac{\omega_p^2}{\omega^2}, \qquad Y = \frac{\omega_c}{\omega} \quad , \quad Z = \frac{\nu_e}{\omega} \tag{3}$$

Where n_e is the effective collision frequency, ω_p is the angular electron plasma frequency and ω_c is the gyro frequency given by,

$$\omega_p^2 = \frac{e^2 N_e}{m_e \varepsilon_0} \text{ and } \omega_c = \frac{eB}{m_e} \tag{4}$$

Here e is the electron charge, m_e the electron mass, N_e is the free electron density, e_0 is the vacuum permeability and B is the magnetic field.

For TEC measurements, we need a linearized relationship between the ionospheric index of refraction n_{ion} and the electron density N_e. As Z is very small, we can neglect the collisions since collisions mainly affect the imaginary part of the index of refraction and we are only interested in the real part. When Z is set to zero, refraction becomes real and equation [2] becomes,

$$n_{ion}^2 = 1 - \frac{X}{1 - \frac{Y^2 \sin^2\theta}{2(1-X)} + \sqrt{Y^2 \cos^2\theta + \frac{Y^4 \sin^4\theta}{4(1-X)^2}}} \tag{5}$$

As X and Y are small, the equation can be very well approximated as

$$n_{ion}^2 = 1 - \frac{X}{1 \pm Y \cos\theta} \tag{6}$$

Here, if we neglect the magnetic field altogether, the error would be still less than 1%. Consequently we can drop Y from Appleton-Hartree Formula. Now, as X << 1, we can write

$$n_{ion} = \sqrt{1-X} \cong 1 - \frac{X}{2} = 1 - \frac{e^2}{2 m_e \varepsilon_0} \frac{N_e}{\omega^2} \tag{7}$$

2.2 Differential Doppler

For TEC calculation, using differential Doppler technique, the phase path between transmitter and receiver is generally approximated as a straight line. The optical path length, L (which is the sum of L_0 (the geometric distance between transmitter and receiver) and ΔL (the range error due to refraction in the medium) is given by,

$$L = \int_t^r n ds \tag{8}$$

The contributions to L due to the characteristics of the medium are included in ΔL which is much less than L_0. From equations 7 and 8, DL due to ionosphere can be written as

$$\Delta L_{ion} \approx \int_{Line} (n_{ion} - 1)\, ds_0 = -\frac{e^2}{2 m_e \varepsilon_0 \omega^2} \int N_e\, ds_0 \tag{9}$$

To estimate TEC, we need the ΔL due to ionosphere. This can be achieved if the phase change of the radio signal as it travels through the ionosphere were known. The phase ϕ_t of the carrier wave is given by $\phi_t = \omega t$ where t is the time and at $t = 0$ the phase is assumed to be zero. The phase ϕ_r and the angular frequency ω_r both at the receiver are given by

$$\phi_r = \phi_t - \omega \frac{L}{c} = \omega t - \omega \frac{L}{c} \tag{10}$$

$$\omega_r = \frac{d\phi_r}{dt} = \omega - \frac{\omega}{c} \frac{dL}{dt} \tag{11}$$

Here c is the speed of light in vacuum and L is the optical path length. The contributions to L due to the characteristics of the medium are included in ΔL. To extract this information from phase shift measurements L_0 must be known and corrected for, since $L_0 >> \Delta L$, a small error in L_0 destroys the useful information. This problem can be solved by differential measurements, i.e., by using two well-separated frequencies and finding their phase difference. This also eliminates the effects due to troposphere, which are non-dispersive.

In the actual case, the differential Doppler compares the phases ϕ_1 and ϕ_2 of two widely separated frequencies when they are translated to a common reference frequency f_r such that $f_1 = p f_r$ and $f_2 = q f_r$. Normally, we use f_r = 50 MHz, p= 3, and q= 8, i.e., f_1 = 150 MHz and f_2 = 400 MHz.

The phase difference at f_r is given by,

$$\Delta\phi = \frac{\pi A}{f_r c} \left[\frac{1}{q^2} - \frac{1}{p^2} \right] \int N ds + \eta \tag{12}$$

where $A = \frac{e^2}{4\pi^2 m \varepsilon_o}$ and η is the phase bias [Davies, 1980].

However, we can also estimate the phase at the frequency of the least common multiple of two frequencies, i.e, at 1200 MHz [Yamamoto, 2008]. In this case,

$$\Delta\phi = \frac{\pi A}{f_r c} \left[\frac{p}{q} - \frac{q}{p} \right] \int N ds + pq\eta \tag{13}$$

This method is employed in the GRBR system, as described in section 5.

3. System Description of the Receiver

There are two different families of satellites that can be used for TEC measurements, low earth orbit VHF/UHF dual frequency beacon satellites (LEOS) and GPS/Geostationary satellites. In the most optimal case, a receiver should be

capable of observing both of these types of satellites. This type of a receiver is only realistically feasible using a software defined radio (SDR), which basically means that most of the signal processing is performed with software on a general purpose computer instead of custom-designed signal processing hardware. In practical cases, antenna and the other RF front end circuits make it difficult to receive both low earth orbiting and GPS satellites simultaneously. However, it is easy to tune the receiver system for both LEO and GPS/Geostationary signal reception. GNU Radio is an excellent software toolkit for implementing the SDR systems. Its front-end is based on the script language Python, while the performance-critical engine of the digital signal processing is written in C++. The advantage of the GNU Radio is enhanced by its user-friendly hardware for data acquisition, called the USRP. The USRP is connected to a host computer through the USB 2.0 interface. It can be operated as a two-channel receiver and a two-channel transmitter simultaneously. All analog signals are fed through daughter boards that can be attached to the main board, and some daughter boards can down-convert the signal frequency by analog circuitry. An FPGA (field programmable gate array) on the USRP main board is used for fast digital processing. By selecting specific daughter boards, the USRP is applicable to various radio systems in the frequency range from near DC to several GHz.
A software defined beacon satellite receiver consists of the following parts:

1. RF frontend (antennae, amplifiers and filters).
2. USRP and Daughterboards.
3. Linux PC with GNU radio.
4. Satellite ephemeris program that provides the geometry, satellite pass schedules and frequency offsets.
5. Data acquisition software, which records the dual-band signals from satellites at given times and stores them to disk.
6. Phase/TEC estimation software which calculates the relative phase of two beacon frequencies and TEC.

This approach has several advantages compared to the traditional analog type solutions as the software is more easily customizable and in most cases results in less/less expensive hardware.
A simple block diagram of the GRBR developed at Physical Research Laboratory is given in Figure 1. The following subassemblies are described in detail in the following sections.

- Antenna –Quadrifilar Helix.
- Pre-amplifiers.
- Filters.
- Low-Noise Amplifiers.
- Basic Rx (for 150 MHz) and WBX (for 400 MHz) daughterboards, with USRP-1 motherboard.
- GNU Radio Software on host PC with Linux.

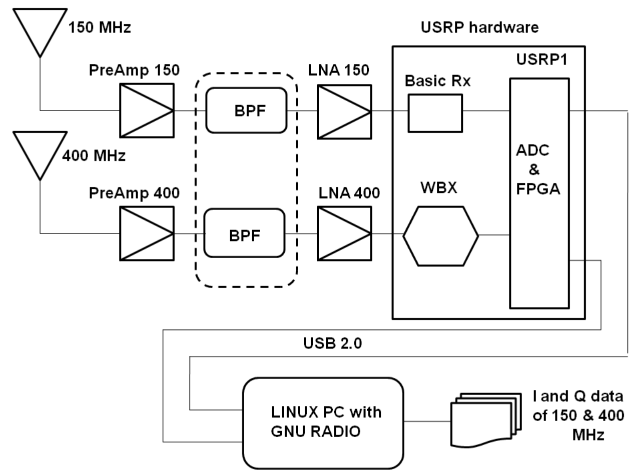

Figure 1. Simple Block diagram of GRBR system, showing its components

3.1 Antenna

We use simple Quadrifilar Helix (OFH) antennae for both 150 and 400 MHz. The QFH antennae is a unique antennae that has a quasi omni-directional beam pattern of circularly polarized radio wave and is suitable for low earth orbiting satellite beacon experiments. The QFH antenna for each frequency comprises four conductive elements arranged to define two helical loops one slightly differing in electrical length than the other. The two helical loops are connected to each other, and instead of a conventional balun, the antenna is fed at a tap point on one of the conductive elements which connects the antenna to a transmission line. The 400-MHz antenna element is nested inside the 150-MHz element; this coaxial mounting provides the same phase center at the two frequencies. Figure 2 shows the nested configuration.
The dimensions are calculated using an online design tool (http:/ /www.jcoppens.com/ ant/qfh/calc.en.php), and are summarized in Table 1.

3.1.1 Link Calculation

The intensity of the beacon signals is estimated by assuming the transmission of 1 W from a LEO satellite, the maximum propagation distance of 4000 km, and the use of omnidirectional antennas at both ends. Power and voltage into a 50 Ω load induced at the receiving antenna are 1.58×10^{-15} W and 2.8×10^{-7} V at 150 MHz, and 23×10^{-16} W and 1.1×10^{-7} V at 400 MHz, respectively. The smallest detectable voltage of the ADC is about 0.5 mV, considering its 12-bit resolution to the 1 V input. Hence, the necessary amplification from antenna to the ADC is about 65 dB and 74 dB for 150 and 400 MHz, respectively. For this system,

Figure 2. Photograph of the Quadrifilar Helix antennae for 150 MHz and 400 MHz (nested inside).

Table 1. Important dimensions of the QFH antennae for 150 and 400 MHz

	150 MHz	**400 MHz**
Conductor diameter	3 mm	3 mm
Wavelength	2000 mm	750 mm
Compensated wavelength	2128 mm	798 mm
Bending correction	6.4 mm	6.4 mm
Larger Loop Dimensions		
Length	2183.3 mm	818.7 mm
Total Compensated Length	2209 mm	844.5 mm
Antenna Height	667.1 mm	255mm
Horizontal Separation	293.5 mm	112.2 mm
Smaller Loop Dimensions		
Length	2074.7 mm	778 mm
Total Compensated Length	2100.5 mm	803.8 mm
Antenna Height	634.3 mm	242.7 mm
Horizontal Separation	279.1 mm	106.8 mm

pre-amplifiers are located at the bottom of the antennas. Additional amplifiers are used for both the signals. The daughter board for 400 MHz also has some amplification on its own. Table-2 provides the summary of the link calculations.

Table 2. Link Budget for 150 MHz & 400 MHz Beacons

Parameter	**150 MHz**	**400 MHz**
Transmitter Power, dBm	+30(1 W)	+30(1W)
Transmitter Antenna Gain,(dB)	+2	+2
EIRP,(dBm)	+32	+32
Cable Loss,(dB)	-2	-2
Free Space Loss,(dB)	-148	-156.5
Receiver Antenna Gain,(dB)	+2	+2
Polarization Loss,(dB)	0	0
Margin,(dBm)	+16.5	+10.5
Signal at Receiver,(dBm)	-116	-124.5
Required Signal,(dBm)	-132.5	-135
Receiver Noise Temperature,(°K)	600	1590
Antenna Noise Temperature,(°K)	4000	1200
System Noise Temperature,(dBK)	+36.6	+34.5
Boltzman Constant, dBm	-198.6	-198.6
Receiver Bandwidth,(Hz)	25	25
Receiver Bandwidth,(dBHz)	14	14
Receiver Noise Power,(dBm)	-148	-150.1
Signal to Noise Ratio,(dB)	+32	+25.6

3.2 Pre-Amplifiers

The preamplifiers are connected in series between the antenna and the receiver to effectively reduce the noise figure of the RF front end, allowing weaker signals to be received. We have used the LNK-450 (tuned to 400 MHz) and LNK-146 (tuned to 150 MHz) preamps from Hamtronics Inc. (http://www.hamtronics.com/). This provides $\sim$ 18 dB gain for each signal. Typical Noise figure is 0.6 dB for the LNK-146 and 0.8 dB for the LNK-450 preamps. +12V DC power is required for the preamps.

3.3 Band Pass Filters

The band pass filters are custom-made, for both 150 and 400 MHz centered at these frequencies. We have implemented the third order capacitive coupled resonsator band pass filters for both the frequencies. The band pass filtering cause a loss of $\sim$10dB for both the signals. For 400 MHz, the pass-band is $\sim$20 MHz, whereas for 150 MHz, the pass-band is $\sim$15 MHz. The response of the filters is shown in Figure 3 and 4.

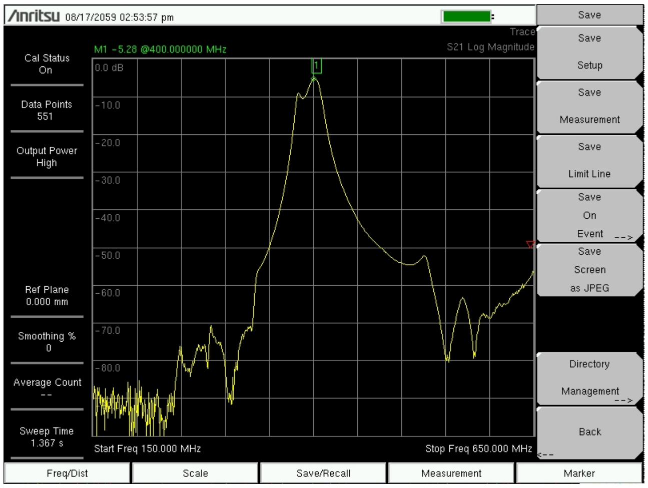

Figure 3. Response of the 400 MHz Band Pass Filter

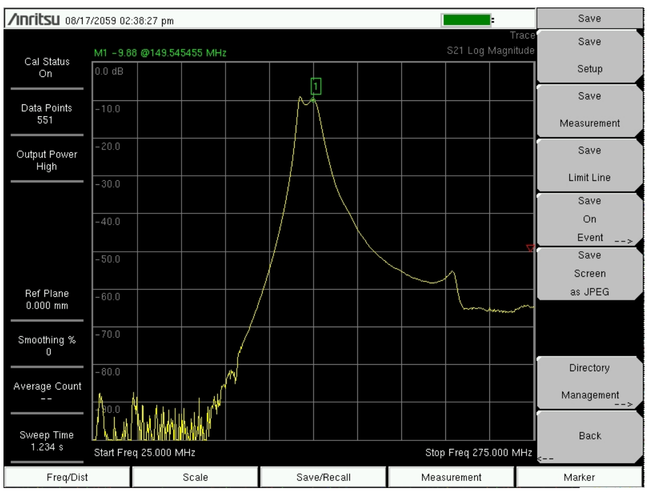

Figure 4. Response of the 150 MHz Band Pass Filter

3.4 Low Noise Amplifiers

Wide-band low-noise amplifiers (ZFL-500 LN+) are used for both 150 and 400 MHz, to obtain a further gain of ∼21 dB. The typical noise figure of this LNA is ∼6dB. +15V DC power is required for the LNAs. The LNAs are from Mini-Circuits (http://www.minicircuits.com/). It must be mentioned here that, in the original design [Yamamoto, 2008], the LNA was used only for 150 MHz. After observing the actual satellite signals we implemented this additional LNA for 400 MHz in the final GRBR system. However, we are considering the use of ZRL-700+ in the next version of GRBR, which can provide a gain of 32 dB with a noise figure of 2dB, both at 12 V.

3.5 Basic RX daughterboard

The Basic Rx (USRP daughterboard from Ettus Res.) is used as the RF front end for 150 MHz. This is a low cost daughterboard that provides a direct access to the ADC (Analog to Digital Convertor) inputs. The board can accept real mode signals from 1-250 MHz and is ideal for applications using an external front end, providing relatively clean signals within the bandwidth. The basic Rx does not include a local oscillator or a down converter. This just provides an entrance for the signal to the USRP main board, without altering the signal. The ADC inputs of the USRP main board are directly transformer-coupled with no mixers, filters, or amplifiers, using the BasicRx.

3.6 WBX Daughterboard

The WBX (USRP daughterboard from Ettus Res.) is used as the RF front end for 400 MHz. The WBX is a wide bandwidth transceiver that provides up to 100 mW of output power and a noise figure of 5 dB. The WBX provides 40 MHz of bandwidth capability within its range 50 MHz to 2.2 GHz. A gain of 30 dB is provided by the WBX daughterboard. Analog down conversion of the 400 MHz signal is done by the WBX. PLL on the daughter board is synchronized with the master clock of the USRP main board. Converted signal of about 10MHz is sampled on the USRP board.

3.7 USRP1 main board

The USRP1 is the original Universal Software Radio Peripheral hardware (USRP) that provides entry-level RF processing capability. The architecture includes an ALTERA Cyclone FPGA, 64 MS/s dual ADC, 128 MS/s dual DAC and USB 2.0 connectivity to provide data to host processors. The modular design allows the USRP1 to operate from DC to 6 GHz. The USRP1 platform can support two complete RF daughter boards. In our case, it supports the WBX and Basic Rx daughter boards. The USRP1 provides up to 20dB gain (programmable) to both the signals. A simple block diagram of the USRP is given in Figure 5.

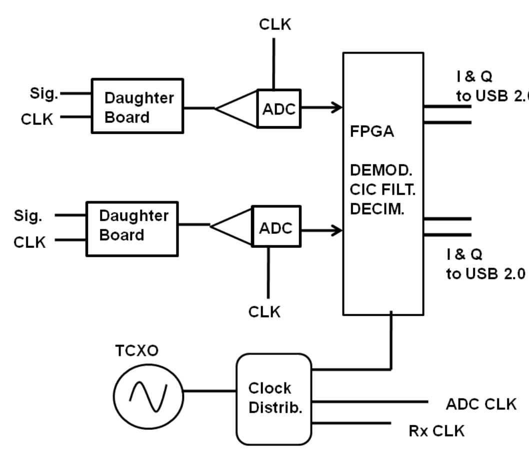

Figure 5. Simple Block diagram of USRP1, showing only the Rx path

The total gain for receiving 150 MHz becomes 49 dB [18 dB (pre amp)–10 dB (BPF) + 21 dB (LNA) + 20 dB (USRP1)] and for 400 MHz, the total gain is 79 dB [18 dB (pre amp)–10 dB (BPF) + 21 LNA +30 dB (WBX) + 20 dB (USRP1)]. In the USRP-1 we have a 12 bit ADC at +/- 1V range, and hence the smallest detectable signal variation at ADC is,∼-43 dBm. From the link budget, we can see that the signal strength at the antenna is -116 dBm for 150 MHz and -124.5dBm for 400 MHz. The necessary gain for 400 MHz is then ∼75.5 dB which is obtained through different amplifications. However, for 150 MHz, the entire circuit gives a gain of 49 dB, and hence we may require 20 dB more. However, it may be noted that after digitizing the signal, there are filtering and decimation (in USRP and in GNU radio), which further improve the signal precision. Hence, in practice, we are able to receive both 150 MHz and 400 MHz properly. By the inclusion of ZRL-700+ in the next version of GRBR, we will gain another 11 dB, which will help us to improve the reception of 150 MHz beacon signal.

3.8 GNU Radio

GNU Radio is the free software development toolkit that provides the signal processing blocks to implement software radios using readily-available external RF hardware (for example, USRP). GNU Radio applications are primarily written using the Python programming language, while the performance-critical signal processing path is implemented in C++. The software is free and open-source. We have installed GNU radio version 3.30 in Ubuntu 12.04 environment.

As mentioned earlier, after getting through the ADC and the FPGA (of USRP), the continuous signal becomes a sequence of numbers, which are processed digitally as an array in the GNU radio software. The In-phase and Quadrature (I and Q) signals which are transferred to LINUX PC through USB interface undergoes further filtering and decimation and outputs are stored in separated files.

The BPFs, LNAs, USRP and the GNU Radio (software) constitute the indoor unit of the GRBR system, which is very compact and sleek. Figure 6 shows the photo of the GRBR system installed in PRL.

Figure 6. Photograph of the GRBR system installed in PRL

4. Signal Processing Scheme

The signal from 150/400MHz antennas are amplified with pre-amplifiers, and passed through BPF (= anti-aliasing filter), and fed to USRP daughter boards, after further amplification using the LNAs. The basic Rx does not do any down conversion of the 150 MHz signal, and the signal is directly fed to the USRP main board. The USRP ADC does a 12-bit A/D conversion at 64MHz, and as we can write 150MHz = 64MHz×2 +22MHz, the signal is regarded as 22 MHz. For 400 MHz, analog down conversion is done by the WBX. PLL on the WBX daughter board is synchronized with the master clock of the USRP main board. Converted signal of about 10 MHz is sampled on the ADC of the USRP board. Further processing of the digitized signals is done by FPGA on USRP. The signals are multiplied with NCO (Numerically Controlled Oscillator) 'SIN' and 'COS' signals, and converted to base-band IQ signal. Further, CIC (cascaded integrator-comb) low-pass filtering and decimation are performed. The USRP supports decimation factors 1- 256 (programmable). We have chosen the decimation factor of 100 (64 Ms/second from ADC ÷100) hence the total effective sampling speed is reduced to 640 kHz. Then the receiver band is ±320 kHz around the tuned frequency of 150/400 MHz. Finally, the I and Q signals are transferred to LINUX PC through USB 2.0 interface. A simple block diagram summarizing the signal processing by USRP is given in Figure 7.

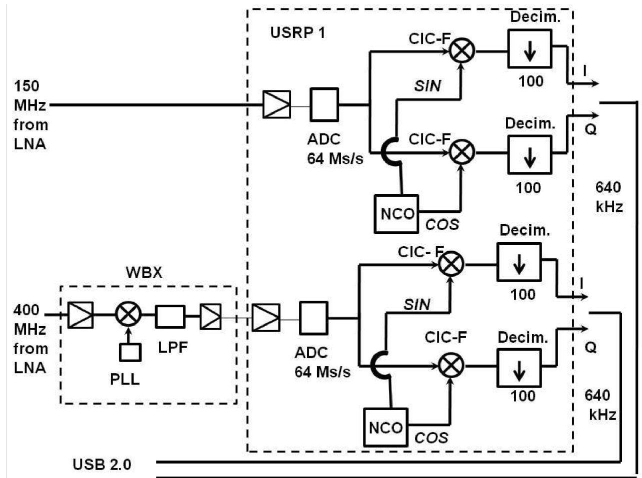

Figure 7. Simple block diagram showing the signal processing by USRP. The basic Rx block is not included, because it does not do any down conversion of the 150 MHz signal

On PC, the GNU Radio software does the further signal processing. The input signal (640 KHz) is first filtered using a FIR (finite impulse-response) filter and 20 times decimation is achieved. The expected Doppler shift at 400 MHz is about ±10 kHz, which is well within the final bandwidth. The resultant signals (@ 32kHz) of 150 and 400MHz are stored in separate files.). A simple block diagram summarizing the signal processing GNU radio is given in Figure 8.

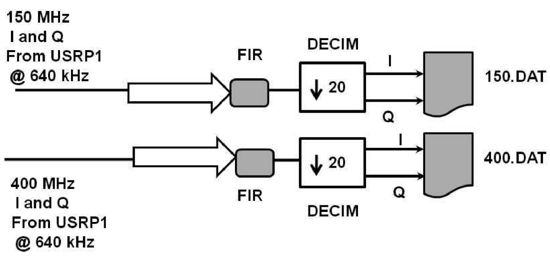

Figure 8. Simple block diagram showing the signal processing by GNU radio

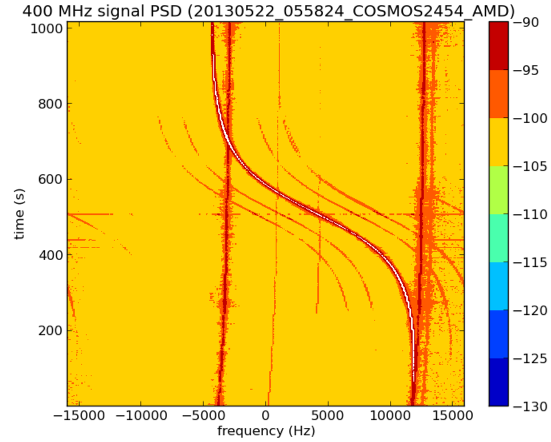

Figure 10. 400 MHz signal from Cosmos 2454 satellite pass, on 22 May 2013, at 05:58: UT

5. Method of TEC and trajectory calculation

The TEC values are estimated by off-line data processing, using the same method given by Yamamoto [2008]. As described in the previous section, the raw data (o/p from the GNU radio) are stored as time series with 32-kHz sampling rate. First, 8192-point FFT is performed to calculate the power spectrum of the data. Examples of the output spectra are shown in Figure 9 and 10. The distance between spectral points is 3.91 Hz, corresponding to 0.256-s cadence. This contains both signal and noise components, but the actual beacon signal appears as an intense peak in each spectrum with the Doppler frequency shift corresponding to the satellite motion.

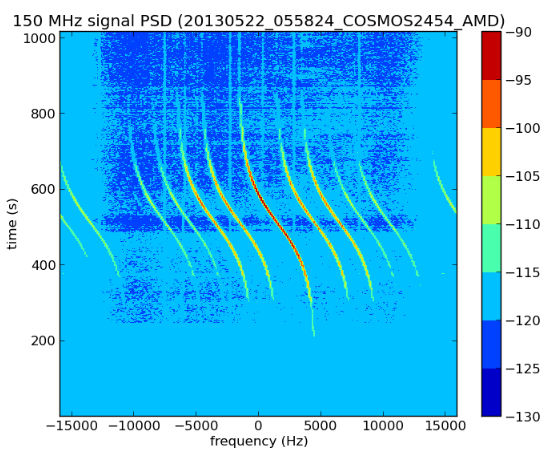

Figure 9. 150 MHz signal from Cosmos 2454 satellite pass, on 22 May 2013, at 05:58: UT

To locate the true beacon signal, the following procedure is used. First, the power spectral densities are multiplied and the multiplied spectrum (at 150 MHz) is stored. A priori information on the satellite motion is made use of along with a hyperbolic tangent model, to generate an initial guess of the Doppler variation. This initial guess and the multiplied PSD values are used in an iterative least square algorithm to locate the actual spectra. After the 'true peak' signal is located, only few points (7 points for 400 and 3 points for 150) around the peak are retained, whereas all other values are set to zero. This is a very narrow BPF with a pass-band of only 20–30 Hz. From these clean spectra, we calculate complex time series by the inverse FFT.

We then calculate the ratio,

S=(150MHz complex signal)^8 / (400MHz complex signal)^3.

The phase of S is the differential phase evaluated at the frequency of the least common multiple of two frequencies, i.e, at 1200 MHz. The resultant values are unwrapped to get the continuous phase variation. This method of estimation is different from the earlier methods [for example, see Davies, 1980] where the phase is estimated at the greatest common divisor, 50 MHz. The TEC estimation software is also written in Python. The signal powers (relative, dB) are also stored along with the TEC values in 'summary' (.txt) files. The cadence of these values is 8 Hz. These are slant relative TEC values. A sample plot is shown in Figure 11.

To estimate the trajectory of the satellite pass an open source software code written in Python is used (http://www.rish.kyoto-u.ac.jp/digitalbeacon/tle2azel.htm). This code uses the NASA two line elements (TLE), location of the receiver and time of observation as inputs and uses an SGP4/SDP4 propagator to calculate the parameters like azimuth, elevation, range and range rate and store in 'trajectory' (.txt) files.

6. GRBR software description

The GRBR software written in Python by Yamamoto [2008] is used for the observations, and the TEC estimation software. This is an updated version [Yamamoto, 2013, personal communication]

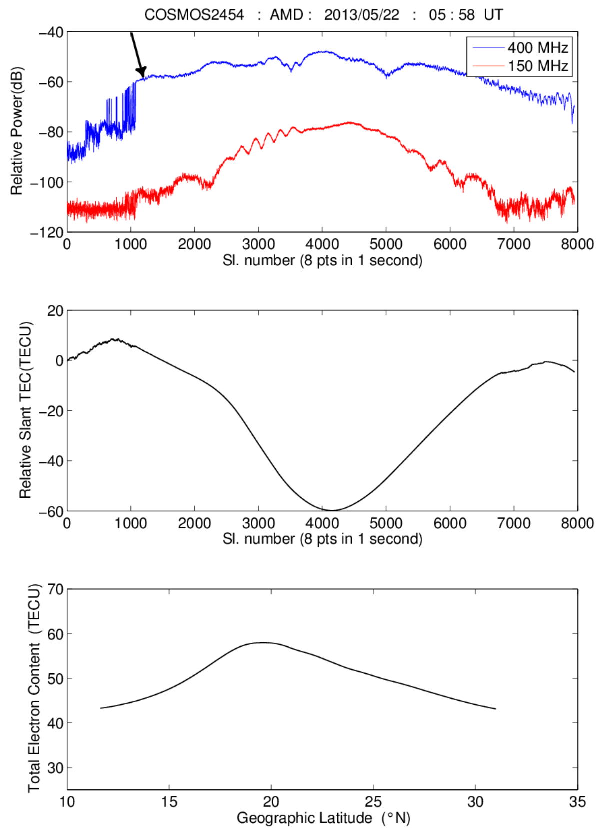

Figure 11. GRBR observations from Ahmedabad, using Cosmos 2454 satellite pass on 22 May 2013, at 05:58: UT. The signal power at two frequencies (top panel), the Relative Total Electron Content variation (middle panel), and the absolute TEC variation (bottom panel) are shown. The small arrow indicates the time when the receiver gets locked to the signal. The absolute TECs are determined using the method described in Thampi et al (2014, Manuscript under revision, Radio Science).

wherein we use Ubuntu 12.04, and GNU radio version 3.30. The main programs and their purpose are described below.

- GRBRhousekeeping.py: This is the basic Housekeeper of GRBR software system. This program runs every 10-min to monitor the observation control program (GRBRautorun.py) and data-analysis control program (GRBRautoanalysis.py)" and keep running them. Every day at 23:00 UT, it invokes the scheduler program (GRBRschedule.py) to generate the schedule of observation for the next day.

- GRBRschedule.py: This program generates the schedule of observations for each day. The inputs required are:

- GRBR-config.txt: Site name, location (longitude, latitude, height), list of satellites (name and beacon channel). The presently available satellites and their channel offsets are given in Table 3.

Table 3. List of satellites being tracked, their orbital information and frequency offsets

	Orbital Info(Altitude, Inclination, Period)	**Channel offset (ppm)**
COSMOS2407	951/1007 km, 83°, 104 min	-200
COSMOS2414	910/967 km,83°, 103 min	-200
COSMOS2429	956/1010 km,83°, 104 min	+200
COSMOS2454	922/952 km, 83°, 103 min	-400
COSMOS2463	975/1029 km, 83°, 105 min	-400
RADCAL	791/900 km, 89.5°, 101 min	+80
DMSPF15	837/851 km, 98.1°, 101 min	+80

- Cosmic.tle: TLE satellite parameter file. The latest file can be downloaded from (http://www.rish.kyoto-u.ac.jp/digitalbeacon/sub2.html) or directly from NORAD webpage (http://celestrak.com/). To obtain the TLE data from web, another python script, GRBRtlecollector.py is used. This program uses GRBR-satinfo.txt, which contains Satellite TLE source (URL) and list of aliases of the satellites (satellite name used in GRBR, without white spaces, only alpha numeric characters are allowed).

- GRBRautorun.py: This program runs at the background, reads schedule file, and starts observation program (GRBRobs.py) according to the schedule.

- GRBRobs.py: This is the GRBR observation program started by GRBRautorun.py. Output files are raw data of 150/400MHz.

- GRBRautoanalysis.py: This is the GRBR data analysis controller. At every 10 minutes this program searches the data directory of the day, start the TEC calculation program (GRBR_TECanalysis.py) if raw data exist. After TEC computation it deletes the raw data, if the user prefers that option.

- GRBR_TECanalysis.py: This program is used to read raw data and estimate TEC. This program is normally started by GRBRautoanalysis.py. This program also needs information of the satellite pass from the trajectory file, which is the output of tle2azel.py:

- GRBRmon.py: This is a script which can be used to manually monitor GRBR, and show if the housekeeping and other programs are running or not, show satellite info, current and next schedule, etc. This is useful to know current status of the system.

7. Summary and concluding remarks

The GRBR is a digital radio frequency receiver, based on open source software and hardware components. The system is very compact, and sleek. Some of the advantages of GRBR systems over conventional analog systems are:

- Hardware based on off-the shelf units and parts
- "Open source" software–easy to augment and make changes
- Simultaneous multi-channel reception enables to track up to 3 satellites simultaneously
- Easy-to-tune for new frequency offsets
- Low cost (1/10th of the commercial analog receiver)

Currently, the GRBR systems are operational over Japan, Southeast Asia, Pacific and African regions. The receivers are installed mainly by ionospheric research groups from Kyoto University and SRI International, USA. The GRBR has provided interesting results about the mid-latitude [Thampi et al., 2009a] and equatorial ionosphere [Thampi et al., 2009b; Thampi and Yamamoto, 2010; Tsunoda et al., 2011, Tulasiram et al., 2012].
The present GRBR system is the first one, being operational over Equatorial Anomaly crest location, over Indian longitudes. A GPS receiver and a DPS-4D Digisonde system [see Reinisch, 1996 for the system details] over the same location provide complementary ionospheric measurements over this region. All these measurements would be used in conjunction to understand the variability of the low-latitude ionosphere. Further, we plan to network the receivers to image the ionosphere using tomography technique [Austen et al., 1988] to study the spatio-temporal variability of the ionosphere over this longitude sector.

8. Acknowledgments

The design information of the system is open, and is available at the http://www.rish.kyotou.ac.jp/digitalbeacon/. We have made use of the information from this webpage, and had many personal communications with Prof. Mamoru Yamamoto. We thank him for providing all the information and the Python codes for the GRBR installation. Thanks are due to Mr. Mitesh Bhavsar for his participation in the testing and evaluation of the system. We also acknowledge Mr. Fazlul Islam Laskar and Mr. Shashi Prabhakar for their help in the installation of the software in Ubuntu environment. Thanks to Mr. Vishnu Patel for his participation in fabricating the antenna system. ST thanks Profs. R. Sekar and R. Sridharan for the discussions during the course of this project. The authors acknowledge the support of the Director, PRL for this activity. The work is supported by Department of Space, Government of IndiaST also thanks Science and Engineering Research Board, India for the Woman Excellence Award grant for the project entitled 'Radio-investigations of planetary ionospheres- Development of Digital Receiver Systems'.

9. References

1. Austen, J. R., S. J. Franke, and C. H. Liu (1988), Ionospheric imaging using computerized tomography, Radio Sci., 23, 299– 307.
2. Davies, K.(1980) , Recent progress in satellite radiobeacon studies with particular emphasis on the ATS-6 radio beacon experiment, *Space Sci. Rev.*, **25**, 357–430.
3. Deshpande M. R. et al (1982 a), Total Electron content studies during 16 February 1980 solar eclipse by differential Doppler method, Proc. Indian Natn. Sci. Acad., 48, A , 420-426.
4. Deshpande M. R. , H. Chandra, G. Sethia, H. O. Vats, G. D. Vyas, K. N. Iyer, and A. V. Janve (1982 b), Effects of the total solar eclipse of 16 February 1980 on TEC at low latitudes, Proc. Indian Natn. Sci. Acad., 48, A, 427-433.
5. Garriott, Owen K (1960), The determination of ionospheric electron content and distribution from satellite observations: 2. Results of the analysis, J. Geophys. Res., 65, 4.
6. Rastogi, R. G. and Sharma, R. P, (1971) Ionospheric electron content at Ahmedabad (near the crest of equatorial anomaly) by using beacon satellite transmission during half a solar cycle, Planet, Space Sci., 19, 1505–1517.
7. Rastogi, R. G., Iyer K. N., and Bhattacharya, J. C.(1975), Total Electron content of the ionosphere over the magnetic equator, Current Science, 44, 531–533.
8. Rastogi, R. G., Sharma, R. P., and Shodan, V.(1973), Total electron content of the equatorial ionosphere, Planet Space Sci., 21, 713–720.
9. Reinisch, B. W.(1996), Modern Ionosondes, in Modern Ionospheric Science, (Eds. Kohl, H., Rüster, R., and Schlegel, K., European Geophysical Society, 37191 Katlenburg-Lindau, Germany, 440–458.
10. Rishbeth H., O. K. Garriott (1969) Introduction to ionospheric physics, Academic Press.
11. Thampi, S. V., and M. Yamamoto (2010), First results from the ionospheric tomography experiment using

beacon TEC data obtained by means of a network along a longitude of 136°E over Japan, Earth Planets Space, 62, 359–364.

12. Thampi, S. V., C. Lin, H. Liu, and M. Yamamoto (2009a), First tomographic observations of the Mid-latitude Summer Nighttime Anomaly over Japan, J. Geophys. Res., 114, A10318.

13. Thampi, S. V., M. Yamamoto, R. T. Tsunoda, Y. Otsuka, T. Tsugawa, J. Uemoto, and M. Ishii (2009b), First observations of large-scale wave structure and equatorial spread F using CERTO radio beacon on the C/NOFS satellite, Geophys. Res. Lett., 36, L18111.

14. Tsunoda, R. T., M. Yamamoto, T. Tsugawa, T. L. Hoang, S. Tulasi Ram, S. V. Thampi, H. D. Chau, and T. Nagatsuma (2011), On seeding, large-scale wave structure, equatorial spread F, and scintillations over Vietnam, Geophys. Res. Lett., 38, L20102.

15. Tulasi Ram, S., M. Yamamoto, R. T. Tsunoda, S. V. Thampi, and S. Gurubaran (2012), On the application of differential phase measurements to study the zonal large scale wave structure (LSWS) in the ionospheric electron content, Radio Sci., 47, RS2001.

16. Yamamoto, M (2008), Digital beacon receiver for ionospheric TEC measurement developed with GNU Radio, *Earth Planets Space*, **60**, e21–e24.

PRL research	पीआरएल के
encompasses	अनुसंधान क्षेत्र में
the earth	समविष्ट हैं
the sun	पृथ्वी एवं
immersed in the fields	सूर्य
and radiations	जो निमीलित हैं
reaching from and to	चुंबकीय क्षेत्र एवं विकिरण में
infinity,	अनंत से अनंत तक
all that man's curiosity	जिन्हे प्रकट कर सकती है
and intellect can reveal	मानव की जिज्ञासा एवं विचारशक्ति