Linnæus University
School of Computer Science, Physics and Mathematics

Bachelor's Thesis

Chirp Sounding and HF Application

SDR Technology Implementation

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Preface

The project was carried out in collaboration with Combitech (IK) under the supervision of Håkan Bergzén, which provided necessary equipment and guidance during the course of the project.

Abstract

From a HF propagation point of view, the ionospheric layers act as partially conducting media (plasma) in which a transmitted radio wave can reflect upon. A way of determining whether a radio wave with a given frequency will reflect from the ionosphere or completely penetrate is to utilize special radar instruments know as ionosondes or chirp sounders. The technique is widely used by amateur enthusiasts and military radio users for monitoring available radio channel links between two remote locations and can often serve as a base for HF radio prognoses.

The objective of this Bachelor's Thesis was to explore, implement and test a single channel receiver for monitoring ionospheric sounders. The implementation is based on Software Defined Radio (SDR) technology and relies on the GNU Chirp Sounder (gcs) open source script program.

Sammanfattning

Från en vågutbrednings synvinkel så beter sig jonosfären som ett delvist elektriskt ledande skikt och kan därför reflektera radiovågor. Ett sätt att avgöra om en radiovåg med en given frekenvens kommer att total reflekteras från jonosfären eller helt tränga igenom den är att tillämpa användingen av speciella radar system under benämningen jonosond. Tekniken används i stor utsträckning av amatör radio entusiaster och militära radio användare för undersökning och prognoser av tillgängliga radio länkar mellan två avlägsna platser.

Syftet med denna kandidatexamens avhandling var att undersöka jonosfärens egenskaper för radio kommunikations ändamål samt att implementera och testa ett jonosond system. Genomförandet grundar sig på tillgänglig mjukvaru radio teknik samt det öppna källkod programmet GNU Chirp Sounder.

Table of Contents

1 Communication Systems

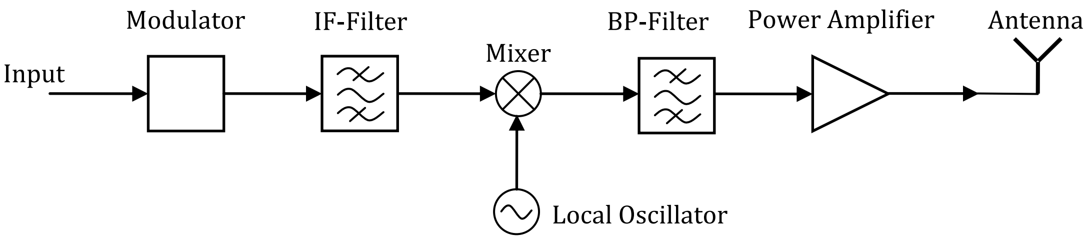
This chapter gives a brief review of a communication system, analog radio systems and the architecture behind receiver and transmitter design. The architecture is described using basic block diagrams for the Radio Frequency (RF) stages and provides an introductory discussion of the main RF components used. The operation and design of these components is not described in detail. Instead, the purpose is to illustrate the concepts and principles behind a basic radio system. Types of radio communication systems deployed depend on technology, standards, regulations and radio spectrum allocation. To avoid any confusion in categorizing a wireless system in terms of their operating frequency, the radio spectrum allocation, frequency planning and international standardization procedures are also discussed.

1.1 Communication System Principles

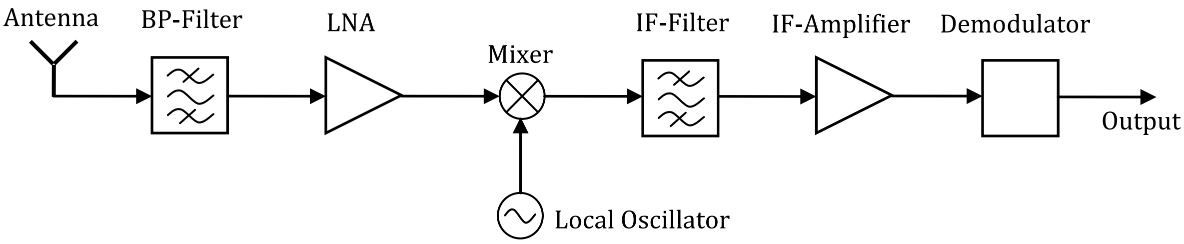
In general a communication process can be considered to consist of five basic elements, namely, information source, transmitter, channel, receiver and user of information [1a]. The source is responsible for generating the message signal containing the information that is to be transmitted across a communication channel. This information can either be analog, such as an audio signal, or digital, such as bit streams. Besides from being analog or digital, the message signals are usually baseband signals, meaning that the range of frequencies of the signal is measured from close to 0 Hz to a cut-off frequency, a maximum bandwidth or highest signal frequency. This can be seen as the signal energy being concentrated around low frequencies. Here after we will only deal with analog communication systems composed of a transmitter, channel and receiver. Before the message signal is actually sent over a specific channel, it is being processed by the transmitter. For an analog RF signal the processing mainly involves operations like modulation, filtering, mixing and amplification. In contrast to a baseband signal, the transmission signal is often a bandpass signal. That is, the signal is centered at a frequency much higher than the highest frequency component of the message signal. From a communication point of view, the channel refers either to a physical transmission medium such as a wire or to a medium such as a radio channel. The transmitted bandpass signal propagates over the channel and eventually reaches the receiver. However, due to channel imperfections, noise and interference, the received signal may arrive as a corrupted version of the originally transmitted signal. The channel imperfections contribute on damping the signal level while the noise can be seen as added undesired frequency components. The interference is likely due to multipath propagation or other nearby communication systems working in the same frequency range. The main objective of the receiver is to extract, reconstruct and deliver the original message signal as accurately as possible to the information user.

1.2 Basic Radio System

Radio Frequency (RF) is a rate of oscillation in the range of about 3 kHz to 3 GHz, which corresponds to the frequency of radio waves. However the abbreviation RF is not consistent with the standards provided by the International Telecommunication Union (ITU), even though it is a common term used in the English literature. Other common terms not following the recommendations of ITU are the Intermediate Frequency (IF) and the Audio Frequency (AF). Section 1.3 covers the different notations resolving the ambiguity. The unfamiliar reader is advised to revisit this section before proceeding. The block diagram of a typical RF stage containing a radio transmitter and receiver is shown in Fig 1.1 below.



(a)



(b)

Figure 1.1 Block diagram representing a basic radio system: (a) radio transmitter, (b) radio receiver

1.2.1 Transmitter

The input signal, also referred to as the baseband signal may be voice, video, data, or other information to be transmitted to one or more distant receivers. Signals at higher frequencies can be radiated much more efficiently, and use the RF spectrum more efficiently, than the direct radiation of a baseband signal [2a]. Therefore the basic function of the transmitter is to modulate the baseband information onto a carrier sine wave with a much higher frequency. There are common modulation techniques, both analog and digital, that function by varying either the amplitude, frequency, or phase of the carrier sine wave. The output of the modulator is referred to as the Intermediate Frequency (IF). Ideally the mixer operates as a multiplicator producing the difference and the sum of the input IF signal frequency and the frequency of a separate Local Oscillator (LO). The IF signal is then shifted up in frequency, or up-converted, to the desired RF transmit frequency. A Band Pass Filter (BPF) located after the mixer selects the sum frequency component that is to be transmitted by the antenna. If necessary, a power amplifier is used to increase the output power of the transmitter. Finally, the antenna converts the modulated carrier signal form the transmitter to a propagating electromagnetic plane wave.

1.2.2 Superheterodyne Receiver

The receiver type in Figure 1.1 (b) is known as a superheterodyne receiver and is by far the most popular type of receivers used today. It represents the accumulation of over 50 years of receiver development, and is used in majority of broadcast radios and televisions, radar systems, cellular telephone systems, and data communication systems [2b]. The receiver recovers the transmitted baseband signal by essentially reversing the process of the transmitter components. Since the antenna receives electromagnetic waves from many sources over a relatively broad frequency range, an input BP-Filter provides some selectivity by filtering out undesired frequency components. The Low Noise Amplifier (LNA) amplifies the possibly weak received signal, while at the same time minimizing the noise power that is added to the received signal. In this case the mixer is used to down-convert the received RF signal to the IF signal that was initially produced by the modulator in the transmitting stage. By setting the LO frequency close to the that of RF input, the output difference frequency from the mixer will be at relatively low frequency, allowing easy filtering by the IF bandpass filter. A high gain IF amplifier raises the power level of the signal so that the baseband information can be recovered in a process called demodulation. As already mentioned, this type of RF receiver follows the superheterodyne principle that uses frequency conversion, implemented by the mixer component, to convert the high RF carrier frequency to a lower IF frequency before the final demodulation. An important fact characterizing the superheterodyne receiver is that the IF frequency is nonzero, generally selected to be between the RF frequency and the baseband signal. Tuning is conventionally accomplished by varying the LO frequency so that the IF frequency remains fixed, independently of the receivers frequency tuning. This allows for a constant center frequency of the filters in the IF amplifier regardless of the station used and is the key to the superior selectivity of superheterodyne receivers [1b]. A main drawback of the superheterodyne receiver is the appearance of image, or mirror, frequencies. The image frequencies arises from the fact that the Fourier spectrum of any real signal is symmetric about the zero frequency, and thus contains both positive and negative frequencies. Thus for every mixer in the receiver there are always two frequency input signals, positive and negative, that give rise to the same signal in the desired band after the mixer. Because of the practical importance of the superheterodyne receiver a more general block diagram is shown in Figure 1.2. The RF Front-End is a generic term for all the circuitry between the antenna and the first IF-stage. It consists of all the components in the receiver that processes the signal at the original incoming Radio Frequency (RF), before it is converted down to a lower Intermediate Frequency (IF).

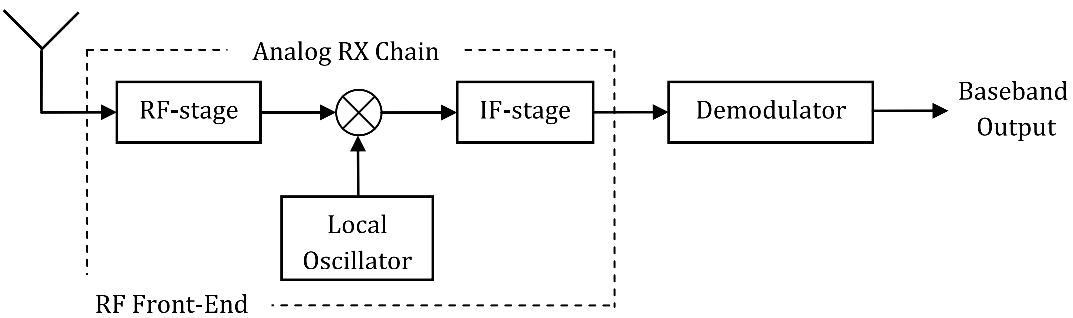


Figure 1.2 Superheterodyne receiver

1.2.3 Homodyne Receiver

In contrast to the superheterodyne receiver is the homodyne receiver, or direct conversion receiver, with the main difference being the zero IF frequency. The zero IF frequency is obtained by setting the LO frequency equal to the desired RF frequency. Some important advantage of the direct conversion receiver is that there is no image frequency produced, since the mixer difference frequency is effectively zero. The direct conversion receiver is generally simpler and less costly than the superheterodyne receiver since the IF components are replaced with baseband components, but suffers from serious precision and stability issues for higher RF frequencies.

1.3 Standardization Organizations

A property that all radio systems have in common is that the transmission of radio waves takes place in the atmosphere. Thus, all radio systems share the same communication channel and can therefore interfere with each other. The interference can be minimized by a proper separation of the systems, both geographically and in terms of the operating frequency range. The fact that the radio spectrum is common to all radio systems and that radio propagation does not recognize any geopolitical boundaries has lead to international cooperation and regulation for the worldwide use of the shared spectrum.

1.3.1 International Telecommunication Union (ITU)

The International Telecommunication Union (ITU) is the United Nations specialized agency responsible for information and communication technologies that coordinates the shared global use of the radio spectrum, promotes international cooperating in assigning satellite orbits, works to improve telecommunication infrastructure and establishes worldwide recommendations and standards [3]. Currently, ITU has a membership of 193 countries and over 700 private-sector and academic institutions. The headquartered is located in Geneva, Switzerland, and has twelve regional and area offices around the world. The main objective of the ITU is to organize telecommunication services and work for an efficient use of the telecommunication resources and radio spectrum. ITU provides three main areas of activity, described below, organized in sectors which work through conferences and meetings. Table 1.1 gives an overview of the classification of the radio spectrum and the well known notations for the different frequency bands.

- **Radiocommunication Sector (ITU-R):** The Radiocommunication Sector plays a vital role in the global management of the radio-frequency spectrum and satellite orbits. The sector covers mobile, broadcasting, amateur, space research, emergency telecommunications, meteorology, global positioning systems, environmental monitoring and communication services. The primary objective is to ensure rational, equitable, efficient and economical use of the radio-frequency spectrum by all radiocommunication services and carry out studies and approve recommendations on radiocommunication matters. The allocations of frequencies to different services in the frequency bands are established in the ITU Radio Regulations. In these regulations, the use of the frequencies for different services is described in great detail. ITU-R maintains the *Master International Frequency Register*, containing more than half a million frequency assignments with specified conditions.

- **Telecommunication Standardization Sector (ITU-T):** The ITU standards (called Recommendations) are fundamental of the operation of today's Information and Communications Technology (ICT) networks. The primary objective is to standardize techniques and operations of the international telecommunication services. For Internet access, transport protocols, voice and video compression, home networking, and other aspects of ICTs, hundreds of ITU standards allow these systems to work.

- **Telecommunication Development Sector (ITU-D)**

Table 1.1 ITU classification of the radio spectrum

Notation	Name	Frequency		Wavelength	
ELF	Extremely Low Frequency	300-3000	Hz	1000-100	km
VLF	Very Low Frequency	3-30	KHz	100-10	km
LF	Low Frequency	30-300	KHz	10-1	km
MF	Medium Frequency	300-3000	KHz	1000-100	m
HF	High Frequency	3-30	MHz	100-10	m
VHF	Very High Frequency	30-300	MHz	10-1	m
UHF	Ultra High Frequency	300-3000	MHz	100-10	cm
SHF	Super High Frequency	3-30	GHz	10-1	cm
EHF	Extremely High Frequency	30-300	GHz	10-1	mm

There are some abbreviations both in the Swedish and English literature that may have a different meaning or are not consistent with the ITU-T recommendations. The following Swedish terms collide with the ITU-T recommendations and may have a different meaning when considering the radio receivers HF, MF and LF-stage:

- **HF** (Högfrekvens): referrers to a radio signal received by the antenna regardless of the frequency band.
- **MF** (Mellanfrekvens): referrers to a radio signal after the frequency conversion in a superheterodyne receiver.
- **LF** (Lågfrekvens) alternative **AF** (Audiofrekvens): referrers to an audible signal.

In the English literature it is common to encounter abbreviations Radio Frequency (RF), Intermediate Frequency (IF) and Audio Frequency (AF), that do not collide with the ITU-T recommendations and have in principle the same meaning as the Swedish words when considering an RF-stage.

1.3.2 Swedish Post and Telecom Agency (Post-och Telestyrelsen, PTS)

PTS is a Swedish state administrative that oversees, controls and regulates postal, telephone, IT and radio services in Sweden [4]. The radio sector of PTS is responsible for dividing the radio spectrum and authorizes what frequencies are allowed to be used for different radio services. It is PTS one should consult in order to obtain permission for the use of a radio transmitter.

2 Software Defined Radio (SDR)

2.1 Background

The traditional analog hardware radio architecture is mainly based on the superheterodyne principle discussed in section 1.2. This simple design has been the key success factor for the spread of televisions, FM radios, and first generation mobile phones [5a]. The main structure of analog hardware radio transceivers consists of amplifiers, modulators, demodulators, mixers, filters and oscillators, in which all are electronic hardware components. The design of an analog hardware device is restricted by a specific type of communication, meaning that the system can only handle a certain type of waveforms operating in a given frequency range. The fast development of Digital Signal Processors (DSP) in the 80s served as the basis for the development of digital transceivers. Over the recent years DSP has been used extensively in the design of digital communication radio systems for functions like detection, demodulation, equalization, channel filtering, and frequency synthesis. DSP techniques are well established for the signal processing occurring in the baseband and is finding its way to the IF processing part of the radio receivers. A digital radio transceiver is divided into two parts: a radio Front-End (FE) and a radio Back-End (BE). The radio FE typically uses the superheterodyne/homodyne architecture to transpose a received narrowband RF signal to a low narrowband IF signal. An Analog to Digital Converter (ADC) is then used to convert the continuous quantity to a discrete time digital representation. The radio BE is responsible for the remaining digital signal processing steps, such as modulation, encryption, and channel coding. A basic block diagram indicating the conversion between an analog and digital hardware receiver is shown in Figure 2.1. "This architecture succeeded mainly because of the low cost availability of Application Specific Integrated Circuit (ASIC) chipsets but suffer from the strict limitations in terms of the flexibility", [5b]. Since the ASICs are customized for a particular task, rather than a general-purpose use, this type of digital hardware devices have limited functionality and can only be modified through a physical intervention. This leads to higher production costs and minimal flexibility in supporting the rapid evolving protocols and multiple waveform standards. The need to increase the efficiency, flexibility and functionality, allowing multimode, multiband and/or multifunctional wireless devices that can be enhanced using software upgrades led to the diffusion of Software Defined Radio (SDR).

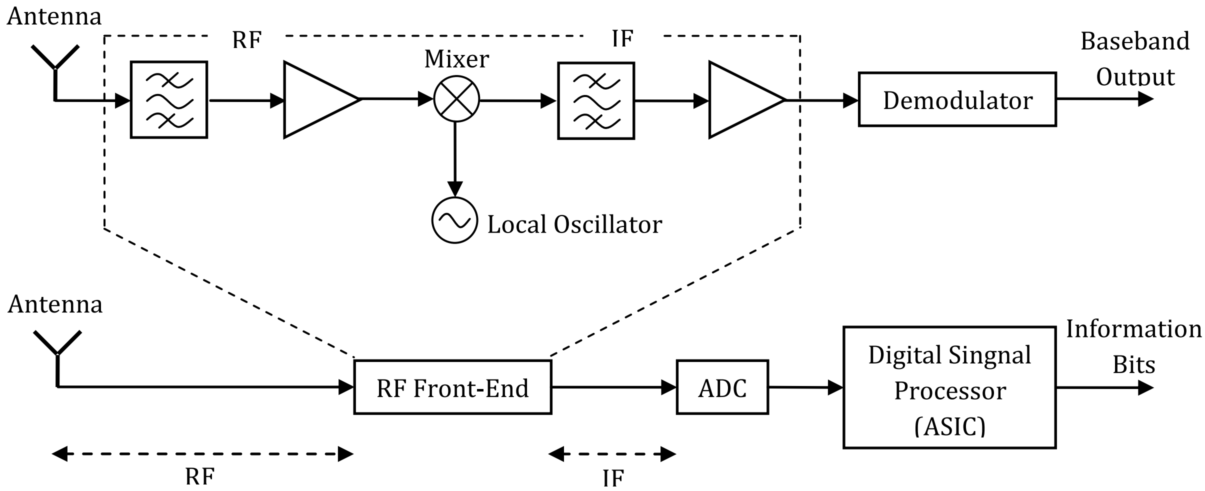


Figure 2.1 Analog and digital hardware receiver

2.2 Definition

Software Defined Radio (SDR) is a rapidly evolving technology for implementing radio communication systems. Analog radio systems are being replaced by digital radio systems for various applications in military, civilian and commercial use. Some of the functional modules in a radio system such as modulation/demodulation, signal generation, coding and link layer protocols that have been typically implemented in hardware are instead implemented by means of software running on personal computers or other embedded computing devices. One can think of SDR being a radio communication system in which some (or all) of the physical layer functions are software defined. In these systems the signal processing is managed via software by using Field-Programmable Gate Arrays (FPGA), General Purpose Processors (GPP), or any other programmable device. By using SDR, engineers try to move the software domain as close as possible to the antenna, thereby turning hardware problems into software problems. The decision of what should be implemented in software and what in hardware depends on the performance requirements of each particular implementation. “The exact definition of a SDR is controversial, and no consensus exists about the level of reconfigurability needed to qualify a radio as a software radio. A radio that includes a microprocessor or digital signal processor (DSP) does not necessarily qualify as a software radio. However a radio that defines in software its modulation, error correction, and encryption processes, exhibits some control over RF hardware, and can be reprogrammed is clearly a software radio”, [6a]. The degree of reconfigurability is mainly determined by a complex interaction between a number of common issues in radio design. This includes system engineering, antenna factors, RF electronics, baseband processing, power management, and the speed and the degree of hardware reconfigurability. The Wireless Innovation Forum (SDR-Forum) is a non-profit corporation dedicated on driving technology innovation in commercial, civil, and defense communications around the world. Working in collaboration with the Institute of Electrical and Electronic Engineers (IEEE) they have managed to establish a definition of SDR that provides consistency and clear overview of the technology and its benefits.

> Software Defined Radio (SDR) is a collection of hardware and software technologies that enable reconfigurable system architectures for wireless networks and user terminals. SDR provides an efficient and comparatively inexpensive solution to the problem of building multi-mode, multi-band, multifunctional wireless devices that can be enhanced using software upgrades. As such, SDR can really be considered an enabling technology that is applicable across a wide range of areas within the wireless industry. SDR-enabled devices can be dynamically programmed in software to reconfigure the characteristic of equipment. In other words, the same piece of hardware can be modified to perform different functions at different times, [7].

The Wireless Innovation Forum has also defined the following categories for various radio communication systems. ISR and CR represent future technologies that are likely to evolve based on studying the potential usage and benefits of SDR.

- **The Hardware Radio:** The radio is implemented using hardware components only and cannot be modified except through physical intervention.

- **Software Controlled Radio (SCR**): Only the control functions of an SCR are implemented in software, thus only limited functions are changeable using software. Typically this refers to digital radio systems that are using application specific, none programmable processors.

- **Software Defined Radio (SDR):** SDRs provide software control of a variety of modulation techniques, wide-band or narrowband, communications security functions, and waveform requirements of current and evolving standards over a broad frequency range. The frequency bands covered may still be constrained at the Front-End requiring a switch in the antenna system.

- **Ideal Software Radio (ISR):** ISRs provide dramatic improvement oven a SDR by eliminating the analog amplification or heterodyne mixing prior to digital-to-analog conversion. Programmability extends to the entire system with analog conversion only at the antenna, speaker and microphones.

- **Ultimate Software Radio (USR):** USRs are defined for comparison purpose only. It accepts fully programmable traffic and control information and supports a broad range of frequencies, air-interfaces and application software. It can switch from one air interface format to another in milliseconds, use Global Positioning System (GPS) to track the user's location, or provide video so that the user can watch a local broadcast station or receive a satellite transmission.

- **Cognitive Radio (CR)** is a form of wireless communication in which a transceiver can intelligently detect which communication channels are used and which are not, and instantly moving into non used channels while avoiding the occupied. This optimizes the use of available Radio Frequency (RF) spectrum while minimizing interference to other users.

2.3 Architecture

Implementation of an ISR would require either the digitalization at the antenna, allowing complete configurability in the digital domain, or design of a completely flexible radio frequency (RF) Front-End able to handle a broad range of frequencies and modulation formats [6b]. The ISR could consist of an antenna, an ADC, and a software defined subsystem. Realizing such a device requires that each of the following three conditions is satisfied [5c]:

- The antenna should be capable of operating over a broad frequency range, possibly maintaining the same performance in terms of antenna efficiency, radiation power density, gain and directivity.

- The Analog to Digital Converter (ADC) and Digital to Analog Converter (DAC) should have a sampling rate of at least two times the highest frequency of interest. This is a result that follows from the Nyquist Sampling Theorem.

- The software subsystem is a programmable processor that should have enough processing power to handle the signal processing of all the radio signals of interest.

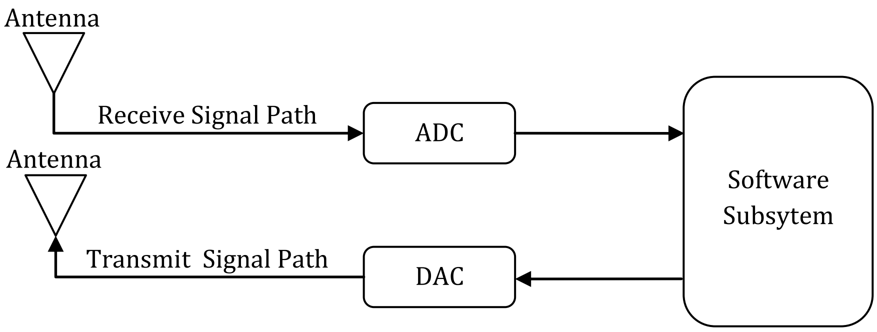


Figure 2.2 Ideal software radio (ISR)

The ISR shown in figure 2.2 is not yet fully exploited in commercial systems due to technology limitations and cost considerations. In practice the ADCs and DACs are not fast enough to process a large portion of the spectrum and the antennas are generally designed to operate in a specific frequency band (see table 1.1). A more realizable and practical approach is to include a wideband RF Front-End that transposes a part of received RF spectrum to the IF prior to the digitalization. In the receiving path the ADC is followed by a Digital Down Converter (DDC) that converts the digitalized real signal centered at an IF frequency to complex baseband signal centered at zero frequency. DDCs are capable of decimating the signal to a lower sampling rate, allowing signal processing by lower speed processors. They are often necessary to interface the digital hardware that creates the modulated waveforms to the ADC. In the transmission path, this process is essentially reversed by using a Digital Up Converter (DUC). The DDC/DUC and baseband processing require allot of computational power which are generally implemented using ASICs or other stock DSPs. Implementation of the software subsystem using non programmable processors results in a fixed-function digital radio system. Any change made to the RF section will impact the operation of DDC/DUC requiring nontrivial changes in the converters and the processor. In a SDR system both the baseband processing and DDC/DUC are programmable modules, allowing the RF Front End of the system to be modified or completely exchanged. It is important to note that the radio Front-End used in a digital transceiver is narrowband; while the one used in SDR is usually wideband. This makes SDR superior since it can be used for many different technologies operating in different frequency bands. The programmable device is supported by firmware and hardware drivers that can be loaded and updated when needed via the host PC. Universal Serial Bus (USB) controller or a Gigabyte Ethernet (GbE) interface provides connectivity of data streams between the SDR and the host processor. The standard solution for the USB port is USB 2.0 (Hi-speed) that offers a maximum transmission capacity of 480 Mbit/s (Mbps). In fact even if the ADC/DAC is capable of handling much higher speed, USB 2.0 can many times act as a bottleneck, limiting the maximum throughput between the SDR and the host processor. This problem can be avoided by using the GbE interface instead that can operate at a rate of a Gbit/s.

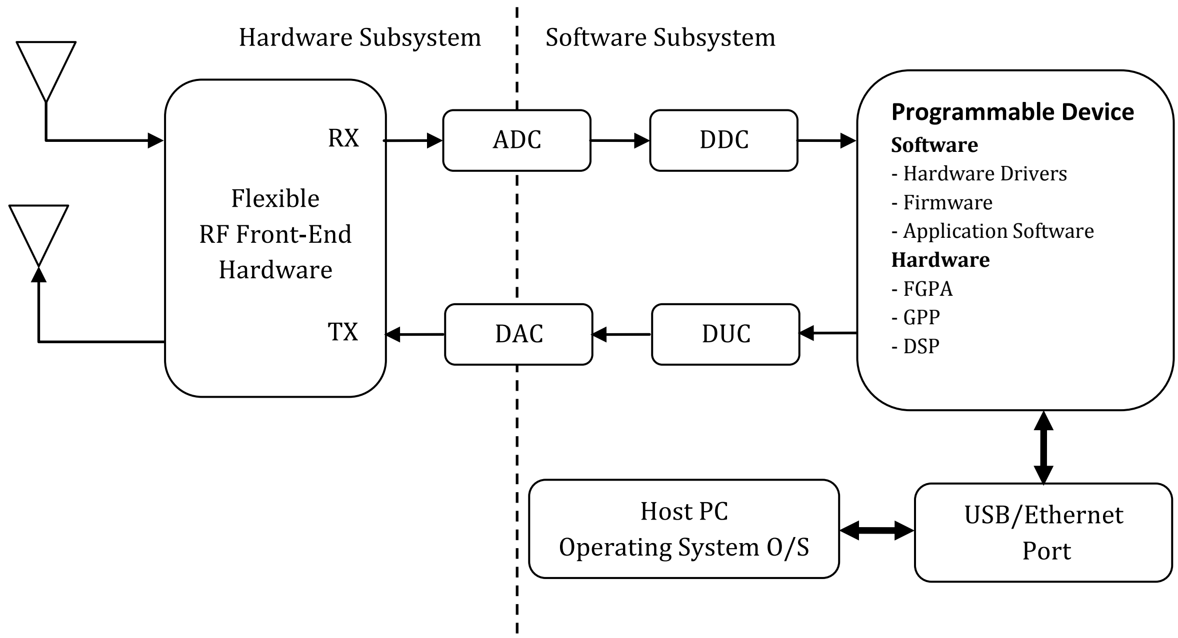


Figure 2.2 Block diagram of a SDR

There are several SDR products available on the market. In the remainder of this chapter we focus on the solution provided by *Ettus Research*, covering the Universal Software Radio Peripheral (USRP) family, the Universal Hardware Driver (UHD) and the signal processing software GNU Radio.

2.4 Open Source SDR Solution

2.4.1 Universal Software Radio Peripheral (USRP)

The Universal Software Radio Peripheral (USRP) is a flexible Software Defined Radio (SDR) unit that allows general purpose computers to function as high bandwidth software radios. They are designed and sold by Ettus Research [8], a company that has specialized in low-cost, high-quality SDR systems. The USRP product family is intended to be comparatively inexpensive hardware platform solution for software radio and is widely used by research labs, universities and hobbyists. It was developed as a part of the GNU Radio Project [9] that provides open source radio software, designed to operate on PC compatible hardware running primarily on Linux. All of the schematics for the various USRP models and RF Front-End's (FEs), called daughterboards are freely available for download. The primary driver for all Ettus Research products is Universal Hardware Driver (UHD) [10], which is considered to be stable and actively maintained. Together these three categorizes (fig 2.3) provide a complete software defined radio communication solution capable of supporting RF applications from DC to 6 GHz, GPS Disciplined Synchronization and Multiple Input Multiple Output (MIMO) configuration.

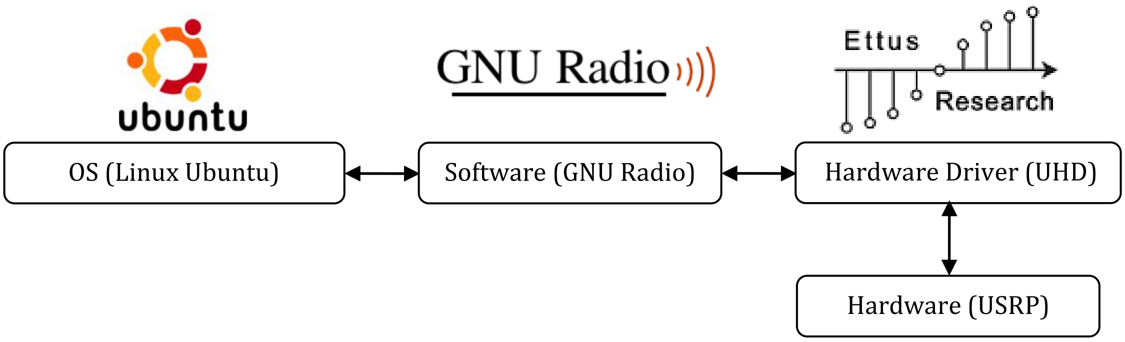


Figure 2.3 Open source SDR solution

Ettus Research is currently offering a series of different USRP models and RF daughterboards. The choice of a model (table 2.1) depends on the number of RF channels, Host Interface connection type, Host Bandwidth (BW), sampling rate of the ADC/DAC, MIMO capability and the processing power of the CPU that is needed for a certain application. The daughter boards (table 2.2) offer a choice in frequency range, BW, power output and noise figure. Besides from the technical details, the main architecture of the USRP remains the same. GNU Radio provides various installation paths supporting all of the common operating systems such as Linux, Windows and Mac Os. However the difficulty of the installation procedure strongly depends on the OS choice. For the moment it is highly recommended to use an up-to-date Linux distribution, where Ubuntu and Fedora are the most common among GNU Radio community. The fact that the build and installation procedures of GNU Radio are based on Linux scripts and tools, several third-part libraries are used where each library may have its own often system-dependent installation procedure and most GNU Radio applications must interface to hardware (soundcard or USRP) which require system dependent drivers, makes the installation procedure on other operating systems not yet a routine. As already mentioned the primary driver for all Ettus Research products – including the USRP – is UHD. Original USRP drivers still exist and are available within GNU Radio.

However they are no longer maintained and therefore not recommended for the user. The USRP firmware and FPGA image files can easily be reloaded through the host interface connection. Common reasons for updating the firmware include fixing bugs or adding new features to the device.

Table 2.1 USRP table

Series	Model	RF Channels	Host Intf	Host BW (MHz)	DAC	ADC	MIMO
	USRP2*	1TX/RX	GbE	50	16-bit, 400 Msps	14-bit, 100 Msps	Yes
Networked	N200	1TX/1RX	GbE	50	16-bit, 400 Msps	14-bit, 100 Msps	Yes
	N210	1TX/1RX	GbE	50	16-bit, 400 Msps	14-bit, 100 Msps	Yes
Embedded	E100	1TX/1RX	Embedded	4-8	14-bit, 128 Msps	12-bit, 64 Msps	No
	E110	1TX/1RX	Embedded	4-8	14-bit, 128 Msps	12-bit, 64 Msps	No
Bus	USRP1	2TX/2RX	USB 2.0	16	14-bit, 128 Msps	12-bit, 64 Msps	Yes
	B100	1TX/1RX	USB 2.0	16	14-bit, 128 Msps	12-bit, 64 Msps	No

* This model is no longer provided on the market and is replaced by the Networked-series

Table 2.2 Daughterboards table

Model	Type	Frequency	BW (MHz)**	Power Output (mW)	Noise Figure (dB)
TVRX2	RX	50 MHz - 860 MHz	10	N/A	4-10
RFX900	TX/RX, Full-Duplex	750 MHz - 1050 MHz	30	200	5-10
RFX1200	TX/RX, Full-Duplex	1.15 GHz - 1.45 GHz	30	200	5-10
RFX1800	TX/RX, Full-Duplex	1.5 GHz - 2.1 GHz	30	100	5-10
RFX2400	TX/RX, Full-Duplex	2.3 GHz - 2.9 GHz	30	50	5-10
WBX	TX/RX, Full-Duplex	50 MHz - 2.2 GHz	40	100	5-10
SBX	TX/RX, Full-Duplex	400 MHz - 4.4 GHz	40	100	5-10
XCVR2450	TX/RX, Half-Duplex	2.4 GHz - 2.5 GHz	33	100	5-10
DBSRX2	RX	800 MHz - 2.35 GHz	1-60	N/A	4-8
LFTX	2xTX	DC - 30 MHz	60*	1	N/A
LFRX	2xRX	DC - 30 MHz	60*	N/A	N/A
Basic TX	2xTX	1 MHz - 250 MHz	100*	1	N/A
Basic RX	2xRX	1 MHz - 250 MHz	100*	N/A	N/A

*Specified BW valid when two ports are used as complex pair
**Limited by USRP motherboard chosen

Even if the recommended OS is chosen for the installation of GNU Radio and UHD, the inexperienced Linux user is likely to encounter barriers involving unreported or unsolved bugs, missing dependencies and libraries. **Appendix A** contains instructions on how to make a clean installation of the latest stable GNU Radio and UHD release running on Linux Ubuntu. It is worth mentioning the USRP2 model that is no longer provided for sale on the market. This specific model uses an external Secure Digital (SD) card containing the image files which must be loaded or updated manually before using a newly purchased device. The main advantage of an external SD card is that the user can switch between several SD cards, each containing a separate version of the image files. The disadvantage lies in the fact that not every host PC has a port supporting SD cards. The solution to this problem is the USRP Network (N)-series that can be seen as an upgrade intended to replace the USRP2 model. It contains an On-board flash memory allowing the image files to be reloaded through the GbE interface. From an application point of view both N200 and N210 have the same behavior and no necessary software changes are needed to switch between them, including the USRP2 model. **Appendix B** deals with the configuration of the USRP2 and N-series model, where instructions can be found on how to setup a host interface connection, reload the image files and change the IP address of the device. Other useful commands are also provided that can be used to check if the device is being recognized and working as expected. It is important to remember that GNU Radio and UHD must be installed properly according to Appendix A, before proceeding with the configuration of the USRP device in Appendix B.

2.4.2 Motherboard

"The basic design philosophy behind the Universal Software Radio Peripheral (USRP) has been to do all of the waveform-specific processing, like modulation and demodulation, on the host CPU. All of the high speed general purpose operations like digital up and down conversion, decimation and interpolation are done on the FPGA", [11]. The USRP is an integrated board which incorporates AD/DA converters, radio Front-Ends called daughterboards capable of receiving/transmitting , FPGA which does some of the important computational pre-processing of the input signal and a host interface supporting either the USB port or GbE. All system blocks except for the daughterboards are a part of the main board referred to as the motherboard. The USRP is completely designed under an open specification project using free and open source CAD software where schematics, cad files and all other specification details are available for download [12]. The FPGA design is also open source, allowing modification of the firmware. While most often used with GNU Radio software, the USRP is flexible enough to accommodate other options. Some users have created their own SDR environments, while others have integrated the USRP into LabView and Matlab/Simulink environments. Currently the USRP consists of one motherboard capable of handling up to four daughterboards. A simplified block diagram of the USRP is shown in figure 2.4.

Recall form section 1.3 that an Ideal Software Radio (ISR) would require completely flexible radio frequency (RF) Front-Ends able to handle a broad range of frequencies. Ettus Research has applied this principle by making exchangeable daughterboards capable of handling frequencies from DC to 6 GHz. Depending on the application and the price, the user can choose an optional daughterboard. Note that the antennas are not a part of the USRP system, limiting the overall operating range. Even if there are daughterboards capable of operating over a wide band of frequency range like the SBX (400 MHz - 4.4 GHz), one would have difficulties in finding an antenna covering the same frequency range. Instead the choice of the antenna is determined by the actual application.

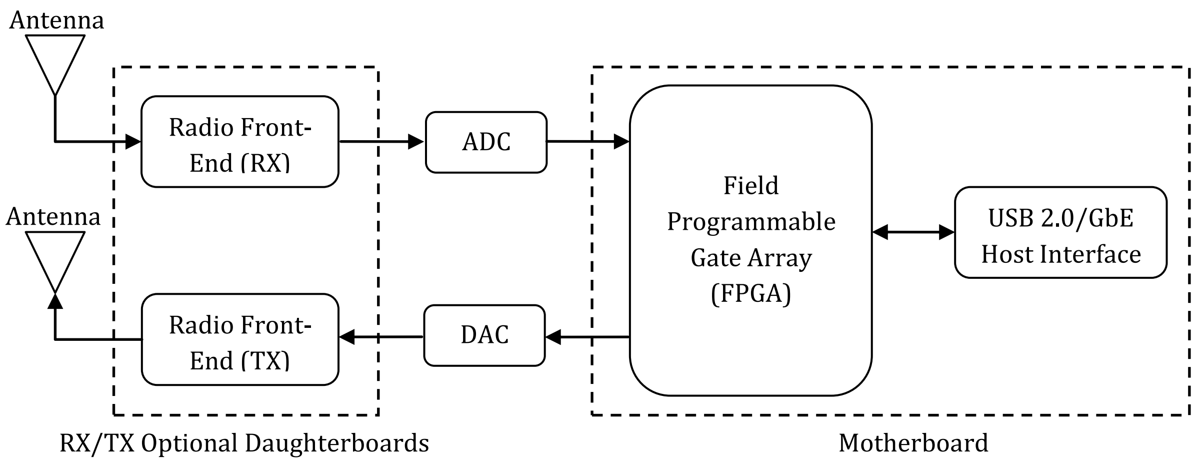


Figure 2.4 USRP simplified block diagram

The USRP1 is the original Universal Software Radio Peripheral hardware that provides RF processing capability mainly intended for cost sensitive users and applications. This architecture contains four high-speed 12 bit per sample ADCs with the sampling rate of 64 Mega samples per second (Msps or MS/s) respectively, capable of digitizing a signal with a bandwidth up to 32 MHz according to the Nyquist Theorem. If we sample a signal with the IF larger than 32 MHz, the effect of aliasing will be introduced, and the actual signal of interest is mapped to same place between -32 MHz and 32 MHz. Although aliasing is an undesired effect, it can be useful in receiving signals without any radio Front-End. There is Programmable Gain Amplifier (PGA) prior to the ADCs that can amplify the possible weak input signal to utilize the entire input range of the ADCs. The full range of the ADCs is 2 V peak to peak, and the input is 50 Ω differential. The PGA is software programmable and can be set to a maximum gain of 20 dB. In this case only 0.2 Vpp is needed to reach the full scale of the ADCs, giving higher sensitivity for weaker signals. On the transmitting side there is four high-speed 14 bit DACs with the sampling rate of 128 Msps. In this case the Nyquist frequency is 64 MHz, although oversampling is recommended for better filter performance. The DACs can supply amplitude of 1V to a 50Ω differential load. The PGA in the transmitting path is also software programmable with a maximum gain of 20dB. These 4 input and 4 output channels connect to an Altera Cyclone EP1C12 FPGA. The FPGA plays a central role in the USRP design utilizing the Verilog hardware description language. Verilog is compiled by using Quartus II web edition from Altera available for free. The advanced user can therefore customize the Verilog code uploading it to the FPGA firmware. The standard FPGA configuration is already suitable for a variety of applications, and in most cases there is no need to change it. The FPGA is responsible for the pre-processing of the digitalized signal. Here, a multiplexer route the signal to the appropriate Direct Down Converter (DDC) that converts the complex or real signal from the IF band to the baseband. The DDC is implemented with 4 Cascade Integrator-Comb (CIC) filters, a numerically controlled oscillator and a digital mixer. CIC are very high performance filters using only adders and delay elements. From here the data is passed in 16 bit (2 bytes) samples onto the Cypress FX2 USB 2.0 interface chip, were it is further transmitted to the Host CPU. The USB 2.0 has a maximum speed of 480 Mbit/s, or 480/8 = 60 Mbyte/s (MB/s). Usually one refers to the nominal bandwidth corresponding to 32 Mbyte/s or 256 Mbit/s half-duplex, i.e. the bandwidth is portioned between down and up link. Since the data is transferred in 16 bit samples, this yields a sample rate of 16 Msps. Applying the Nyquist sampling theorem yields a maximum bandwidth of 8 MHz. The actual samples sent over the USB interface are 16 bit signed integers in IQ format, 16 bit I and 16 bit Q, corresponding to 32 bit per complex sample resulting in 8 Mega complex samples per second across the USB or a total spectral bandwidth of 8 MHz. On the transmitting path this process is essentially reversed. The baseband I/Q complex signal is passed onto the Digital up Converter (DUC) that will interpolate the signal, up convert it to the IF band and finally send it through the DAC. Figure 2.5 illustrates some of the main connections on the motherboard. Two Analog Devices AD9862 Mixed Signal Front End (MxFE) processors contain the ADCs/DACs. In addition they provide gain control in the analog path and some signal processing in the digital path. In principle, the USRP1 offers 4 input and 4 output channels when using real sampling. The flexibility can be extended if complex (IQ) sampling is used instead, giving 2 complex inputs and 2 complex outputs. The signal type, PGA gain, decimation factor and the interpolation factor can in turn all be specified by the application software controlled by the user. Shown in figure 2.6 is the actual USRP1 device equipped with Basic RX/TX daughterboards.

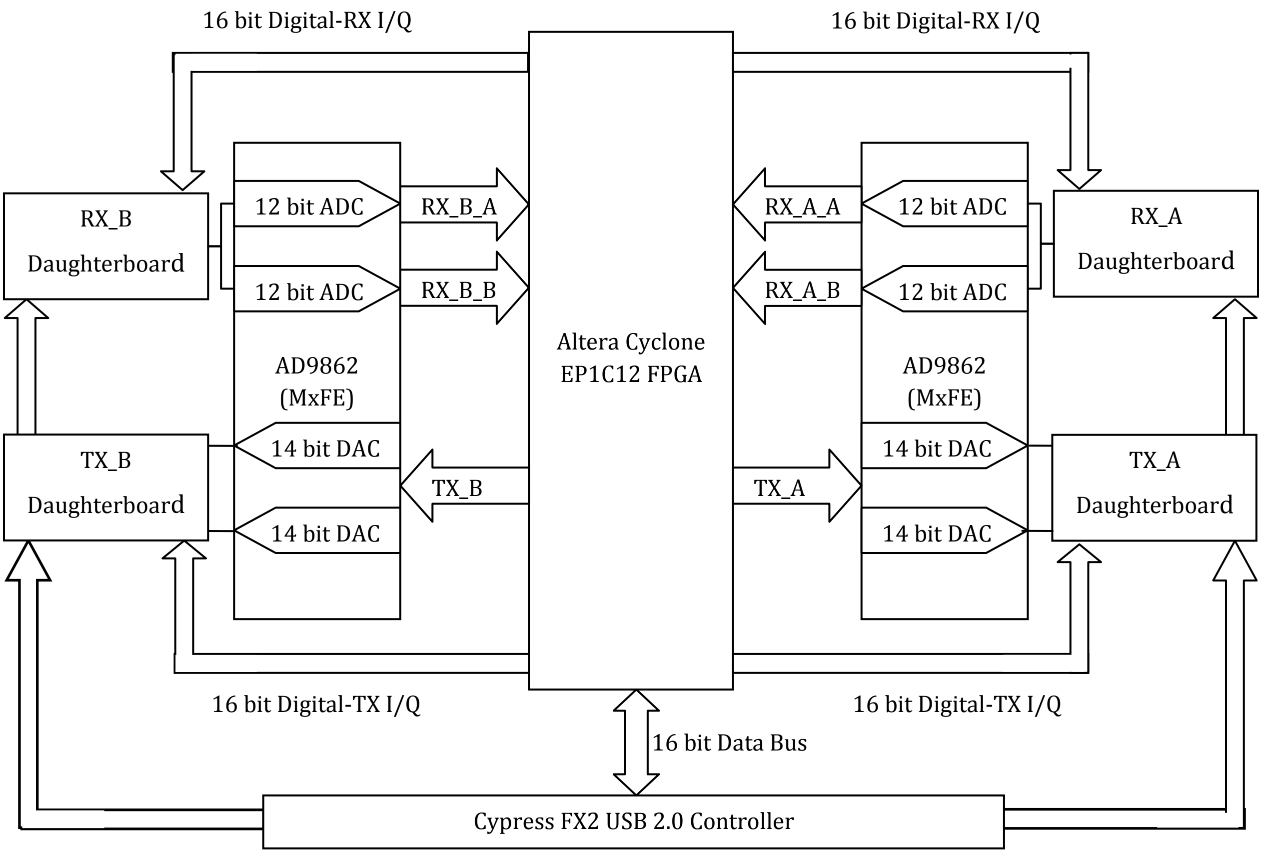


Figure 2.5 USRP1 main connections

Figure 2.6 USRP1 device equipped with Basic RX/TX daughterboards

2.4.3 Daughterboards

The daughterboards can be seen as an entry between the signals captured by the antenna and the USRP motherboard. For most applications they are intended to serve as an radio FE, converting the high RF band captured by the antenna to a much lower IF band that can be directly processed by the ADCs. For users that instead want to experiment with raw signals or use an external FE, the Basic RX/TX and LFRX/LFTX provide a simple wideband interface to the ADC/DAC of a USRP. Daughterboards that are compatible with a specific USRP model can directly be attached to the USRP motherboard, without the need of any configuration. Every daughterboard has an I2C EEPROM onboard which identifies the board to the system. This allows the host software to automatically set up the system properly based on the installed daughterboard. Also, the Universal Hardware Driver (UHD) provides commands that can be used to detect the USRP device and print out the properties about the detected daughterboards, frequency range, gain range, etc. On the other connection side of the daughterboard are two SMA connectors terminated with 50 Ω impedance that can directly be connected to the antenna or even external signal generators.

Table 2.2 shows all of the currently available daughterboards classified according to three different types: receiver (RX), transmitter (TX) and transceiver (TX/RX) boards.

2.4.4 GNU Radio

After the signal has been pre-processed by the USRPs FPGA, the streams of bits enter the host CPU and the GNU Radio software. GNU Radio is free & open source developing toolkit, licensed under the General Public License (GPL), which provides signal processing blocks to implement software radios. While not primarily a simulation tool, GNU Radio does support development of signal processing algorithms using pre-recorded or generated data. In GNU Radio, an application is represented by a graph, where the vertices are signal processing blocks and the edges represent the data flow between them. The blocks which represent the performance-critical signal processing are created in C++. Each block is characterized by attributes that indicate the number of input and output ports, and the data type that it can process [5d]. The package in itself includes by default a set of libraries with several building blocks for signal and information processing. The graph for a certain application is constructed and run in Python. This is made possible by using Simplified Wrapper and Interface Generator (SWIG) to connect the libraries written in C++ with the Python script language. In principle C++ is used as a lower level programming language, while Python is used to construct the flow graph, create higher level blocks and execute the program. By using SWIG all C++ libraries are made accessible from the Python source code. It is important to remember that GNU Radio provides classes to interface with the USRP and it is strongly recommended by the developers to use this device. Figure 2.6 depicts the GNU Radio class hierarchy.

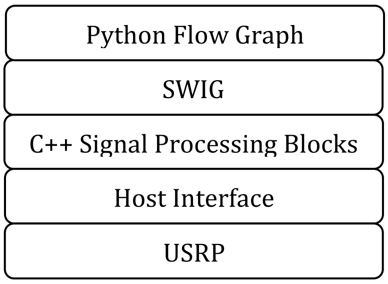


Figure 2.5 GNU Radio class hierarchy

In order to fully explore the features of GNU Radio requires extensive knowledge over a wide range of areas, including wireless communication systems, digital signal processing, basic hardware and circuit design and Object Oriented Programming (OOP). A way to temporarily bypass the programming requirement is to use GNU Radio Companion (GRC), a Graphical User Interface (GUI) that is bundled with GNU Radio. GRC is a graphical tool for creating signal flow graphs and generating flow graph source code. It comes with a set of tools and utility programs that allow the user to create signal processing applications in an environment similar to the MATLABs graphical interface Simulink. Every block is defined by the function it performs, the number of Input Output (IO) ports, signal type and a set of internal variables. In general we can categorize the blocks according the number of IO ports. Signal processing blocks perform operations on the signals passing through them, so they must at least have one input and one output port. Cleary a source block can only have outgoing ports while the sink block can only have incoming ports. In addition to these three, there is a fourth category consisting of variable blocks that have no IO ports. The variable block maps a unique id (variable name) to a particular value. GRC includes also several graphical variable blocks that allow one to create WX GUI flow graphs with graphical controls using sliders, text boxes, buttons, drop downs and radio buttons. In many cases there is a need to extend the functionality by adding a new block, or create applications where the interactions between the blocks are too complex for GRC. For higher level blocks or non performance critical applications, Python is the easiest way to go, while for performance critical signal processing blocks it is recommended to write C++ code.

2.4.5 Wide Band FM (WBFM) Receiver

The hardware used in this example to capture a part of the FM spectrum (87.5 MHz - 108 MHZ) is a USRP1 device equipped with a Basic RX (1 MHz - 250 MHz) daughterboard and a simple omni-directional vertical antenna. The Basic RX board serves as a simple entry point for the received signal and does not contain any mixers, filters or amplifiers. Since the basic RX card has no downconverter, it operates in direct sampling mode. Thus for frequencies above fs/2, 32 MHz for the ADCs of the USRP1 device, the card is used in alias mode. UHD will set-up the DDC in the FPGA appropriately to use 2nd/3rd Nyquist zone sampling. However in order to for that to work properly, one needs to filter the signals to constraint them to the proper band. Figure 2.6 shows the corresponding flow graph constructed in GRC for demodulation of Wideband FM and some additional processing of the signal. USRPs receiving side is represented by the source block UHD: USRP Source. The received signal is of complexfloat32 type sampled at a rate of 500 ksps with the center frequency set to a default value of 104.3 MHz. If there are multiple daughterboards connected to the USRP motherboard one needs to specify the subdevice, channel and the antenna that is used. For more instructions see the UHD-USRP Hardware Driver documentation notes, [17].

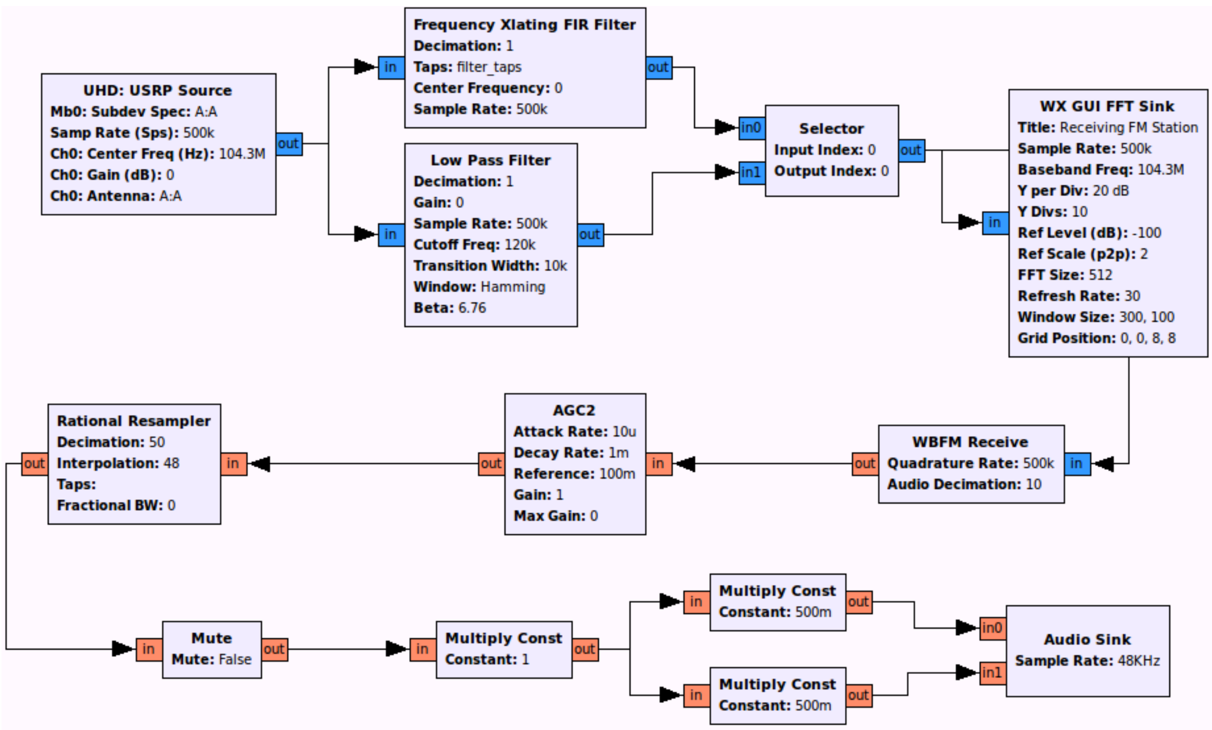


Figure 2.6 Wideband FM demodulator GRC flow graph

Frequencies above 32 MHz are actually mapped somewhere between -32 MHz and 32 MHz, therefore a Low Pass Filter (LPF) at the input is essential to extract the desired station. The selector offers the possibility to switch between the two different filter methods. A WX GUI FFT sink displays the receiving 500 kHz spectrum band. It is possible to receive simultaneously a spectrum band of 8 MHz with the USRP1 device, a value constrained by the USB 2.0 host interface connection. The WBFM Receiver block demodulates the signal, decimates it with a user set factor and outputs a float (real) type signal. We need to decimate the signal to a sampling frequency that can be supported by the host PC audio card, in this case 48 KHz. To achieve the desired sampling rate, the audio decimation factor is combined with a Rational Resampler. An automatic gain control AGC2 block adjusts the gain to an appropriate level for a range of input frequencies, effectively reducing the volume if the signal is strong and raising it when the signal is weak. In addition to the AGC, the receiver is supplemented with mute, volume and balance control. Every block accepts a set of arguments corresponding to the adjustable function parameters for a specific block type. For example, in the LPF signal processing block one can define the cutoff frequency, transition width, low frequency gain, decimation factor, sample rate and the Window function. Instead of assigning a fixed value for every argument, we can make use of the graphical variable blocks to control the parameters in real time. Figure 2.7 shows the final control display of the WBFM receiver, tuned at 105.8 MHz. The basic RX board is primarily intended as a way of interfacing to other hardware at IF levels, which makes it highly insensitive for "off-air" experiments. Fortunately, the USRP1 has an onboard RF gain that together with the software LPF gain allowed me to tune in three different stations with good sound quality. The stations can be saved manually for fast switching using the radio control buttons. A function that is harder to implement using GRC is the automatic scan, where the program scans the entire FM spectrum and saves the stations that exceed a defined minimum gain. In this case one would have to program the desired signal processing block in C++.

Figure 2.7 WBFM receiver control display

3 Ionospheric Sounding and HF Application

3.1 History

Guglielmo Marconi was one of the foremost pioneers of long distance radio communication. Marconi performed a series of experiments transmitting radio signals across the North Atlantic Ocean. On December 12, 1901, he managed to receive the first trans-Atlantic radio signal in Newfoundland (Canada) that was transmitted from a station located in Poldhu Cornwall (UK), about 3500 km apart [13a]. According to the accepted groundwave propagation model at that time, communication over such distances was not possible. In order to explain this extremely long range, the British scientists Oliver Heaviside and Arthur Edwin Kennelly suggested that the atmosphere contained an electrically conducting layer in which the radio wave is reflected back to earth. During the years 1924-29, Edward Appleton and Robert Watson-Watt were able to confirm this theory by experiments. They discovered such a conducting region in the upper layers of the atmosphere, known as the "Ionosphere". In reality, it turned out to be a much more complicated phenomenon than expected. Appleton was able to show that it was not only one conducting layer, but several distinct ones. By comparing the relative delays of ground wave and the sky wave reflected in the ionosphere, an estimation of the layers altitude could be calculated. Appleton was awarded a Nobel Prize in 1947 for his confirmation in 1927 of the existence of the ionosphere. In fact, during 1912 the U.S. Congress imposed the Radio Act on amateur radio operators, limiting their operations to frequencies above 1.5 MHz. This eventually led to the discovery of HF (3 - 30 MHz) radio propagation via the ionosphere.

3.2 Ionosphere Formation

3.2.1 Ionization

The ionosphere is composed of a number of ionized regions located in the upper part of the atmosphere, from 85 km to 600 km altitude. The principal source of ionization in the ionosphere is electromagnetic and particle energy radiated mainly from the sun. The process of ionization works slightly different depending on whether an ion with positive or a negative net electric charge is produced. A positively charged ion is produced when an electron bounded to an atom (or molecule) absorbs the proper amount of energy to escape from the electrically potential barrier. The energy required to detach an electron is called ionization potential, or ionization energy. A negatively charged ion is produced when a free electron collides with an atom and is caught inside the electric potential barrier, releasing any excess energy. The degree of ionization in the atmosphere varies with altitude in a non-uniform way. In the lower part of the Earth's atmosphere, the troposphere extends from the surface to about 12 km. Above 12 km is the stratosphere followed by the mesosphere. At these altitudes there are plenty of molecules available, but most of the energy has already been absorbed by the time the ionizing radiation from the sun reaches these altitudes. In addition, at high molecular densities, electrically charged particles have only a short life expectancy since they will quickly recombine with a particle of opposite charge. In contrast, at higher altitudes there is an abundance of energy available, but the number of molecules available that may be ionized is small. This is a consequence of the fact that the atmosphere for higher altitudes is thinner. The particles that do get ionized stay electrically charged for a long time since they fail to find particles of opposite charge to recombine. At certain altitudes between the exosphere and the mesosphere, conditions are particularly favorable with respect to the radiation density and relatively low recombination rates. Thus, the Earth's neutral atmosphere is sufficiently thin that collisions between particles happen far less frequently then in the lower altitudes, allowing free electrons to persist much longer. As a result, characteristic layers emerge of higher ionization than the surrounding atmosphere. This highly ionized portion of the atmosphere is a plasma state of matter, referred to as the ionosphere. Figure 3.1 illustrates the relationship between the atmosphere and the formation of the ionosphere. The electron density represents the amount of free electrons per unit cubic meter (m^{-3}) and is an important parameter when considering the ionization.

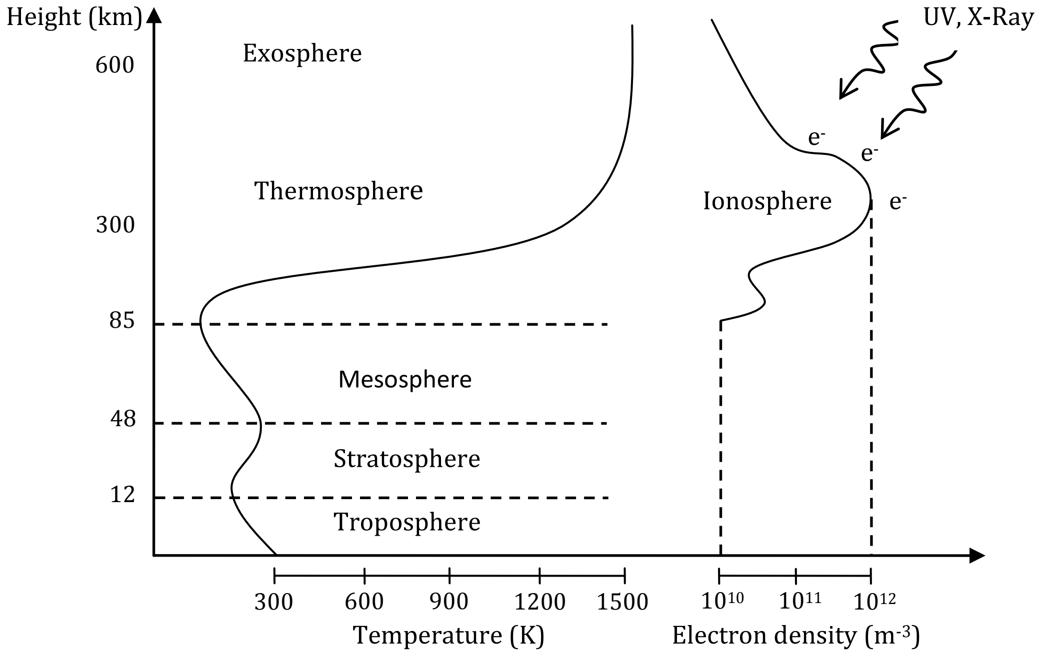


Figure 3.1 Formation of the ionosphere

The density of the electrons in the ionosphere varies with altitude in counter balance between varying wavelengths or energies from electromagnetic and particle radiation originating from the Sun and its activities, and the neutral atmospheric recombination chemistry [14a]. The Ionospheric structure varies widely over the Earth's surface, since the strength of the sun's radiation varies considerably with geographical location (polar, aurora zones, mid-latitudes and equatorial regions). In addition, there are also diurnal and seasonal effects. The activity of the sun is associated with the sunspot cycle, where more active sunspots usually indicate higher radiation density. There are also mechanisms such as solar flares that disrupt and decrease the ionization. Solar flares are associated with release of charged particles into the solar wind that reaches the Earth and interacts with the geomagnetic field. Other factors that complicate the environment are the motion of the neutral atmosphere, but also the magnetic and electric currents interacting with the ionized particles.

3.2.2 Structure

The ionosphere plays an important role in HF radio wave propagation. The different ionization layers or regions are believed to influence radio waves mainly because of the presence of free electrons. For historical reasons of Appleton's research, the ionosphere is divided into three layers designated D, E and F, respectively, in order of increasing altitude [1c]. At night time the F layer is the only layer of significant ionization present, while the ionization in the D and E regions is extremely low. During the day, the D- and E-layers become much more pronounced. The F layer actually splits into two different layers denoted F1 and F2, where the F1 region is usually weaker. Figure 3.2 illustrates a typical layer distribution at day- and night-time for the electron density as a function of the height. From the viewpoint of HF propagation, the E- and F-regions act mainly as radio wave reflectors, while the D-region acts primarily as an absorber, causing signal attenuation in the HF range.

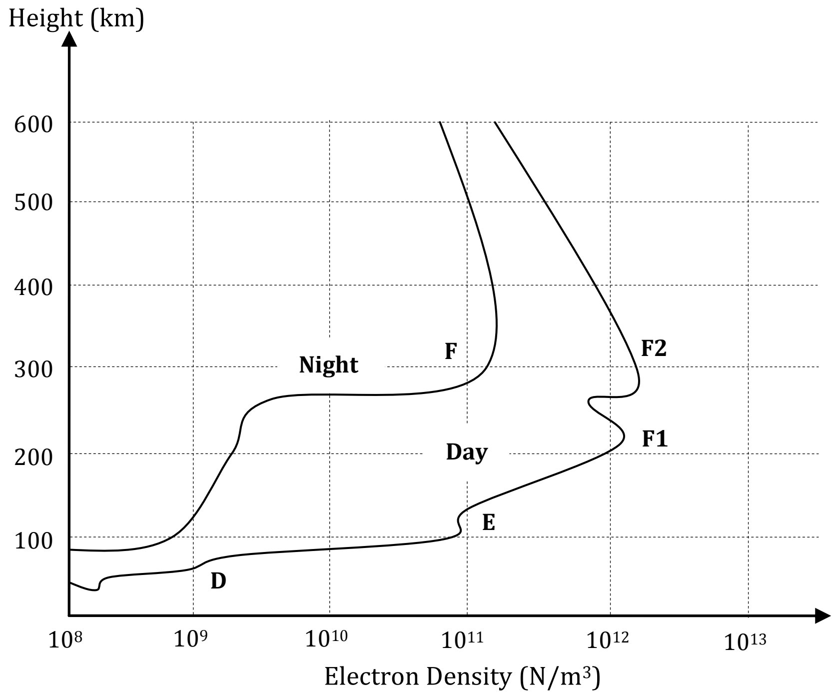


Figure 3.2 Day-Night layer distribution effect

The ***D-layer*** spans the approximate altitude range of 50-90 km exhibiting a rather low concentration of free electrons, in the order of $10^9/m^3$. The electron density must be compared to the molecular density of the natural atmosphere, which at these heights is approximately $10^{20}/m^3$. Thus, the recombination is high, giving a low net ionization effect. In addition, the loss of wave energy is great due to frequent collision of the electrons. It is therefore in this region that the main absorption of low frequency (< 5MHz) propagating radio waves takes place. For frequencies above 10 MHz, this layer does not cause any serious refraction. The D-layer indicates large diurnal variations, where a maximum electron density can be seen after local solar noon and a minimum during night time.

The ***E-layer*** occurs mainly during the daylight hours, but weak remnants may persist into the night. This layer can be found at altitudes between 90-130 km exhibiting an electron density of $10^{11}/m^3$. In fact, the E-region encompasses the so-called normal and sporadic layers. Normally, at oblique incidence, the layer can only reflect radio waves with frequencies less than 10 MHz. However, during intense sporadic events, the sporadic E-layer can reflect frequencies up to 50 MHz. Sporadic layers can be seen as small thin clouds of considerably higher electron density, causing much greater critical frequencies. Its occurrence is strongly latitude, seasonal and diurnal dependent. The normal E-layer is important for daytime HF propagation at distances less than 2000 km. Relations between electron density, critical frequency and maximum communication distance are discussed in section 3.3.

The ***F-layer*** extends upwards from about 150km to 400 km, with the electron density exceeding $10^{12}/m^3$. It is the densest point of the ionosphere, indicating that signals penetrating this layer will escape into space. The F-region is probably the part in the ionosphere that is of greatest practical importance, serving as a principal reflecting region for long distance HF communication. During night time the F-region consists of a single layer, but when subjected to high radiation levels at daytime the layer often splits into two less distinct layers denoted F1 and F2. Occasionally the F1-layer is the reflecting region for HF transmission, but more usually oblique incident waves that penetrate the E-layer also penetrate the F1-layer and are reflected by the F2-layer. Height and ionization density vary diurnally, seasonally and over the sunspot cycle.

3.2.3 Ionospheric Model

An ionospheric model is a mathematical description of the ionosphere which is generally a function of geographical location, altitude, time of the day, season, phase of the sunspot cycle and geomagnetic activity. The state of the ionospheric plasma may be described by four parameters: electron density, electron/ion temperature and ionic composition. Further, the model may be based on basic physics of the interactions between the electrons/ions with the neutral atmosphere and sun activity, or it may be a statistical description based on a large number of observations. One of the most widely used models is the International Reference Ionosphere (IRI), which is based on the four parameters mentioned, [15]. These complicated models are mostly used for scientific analysis, where much of the calculations are solved by computer programs. It is a common procedure to study an idealized, normal ionosphere with a smooth and homogeneous charge distribution. In fact, from a propagation point of view the ionospheric layers act as partially conducting media (plasma), *uniquely determined by the density of free electrons*. This principle is applied in section 3.3, together with some physical laws, to derive basic properties about radio wave propagation in the ionosphere.

3.3 Wave Propagation in the Ionosphere

3.3.1 Refraction and Reflection

When a radio wave travels through the ionosphere its electric field imparts an oscillatory motion to the free electrons, which in turn re-radiate with a local resonant frequency, or plasma frequency [13b]. Depending upon the density of the electrons, the frequency and amplitude of the incident radio wave, the effects may range from total absorption to selective refraction. The plasma frequency determines many aspects of how the radio wave continues to propagate in the ionosphere and what fraction of energy is refracted, reflected or absorbed [14b]. The refraction occurs as a direct consequence of Snell's law (see figure 3.3). The incident electromagnetic wave enters a medium in which the electron density changes, affecting the velocity of the propagating wave.

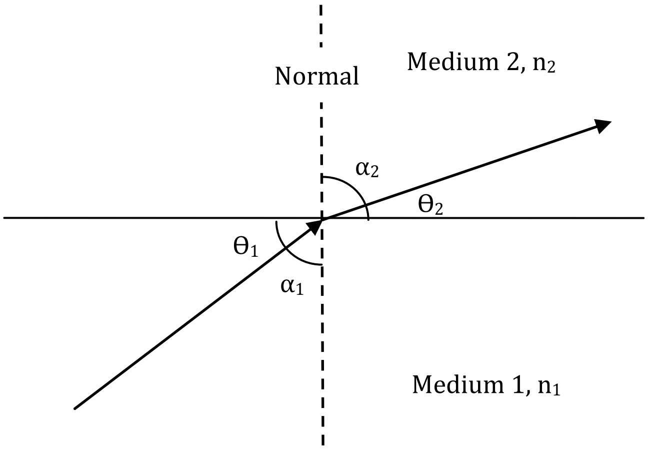


Figure 3.3 Angles of refraction

The angles of incidence satisfy Snell's equation:

$$n_1 \sin \alpha_1 = n_2 \sin \alpha_2 \tag{3.1}$$

where n_1 and n_2 represents the refractive index of respective media. The corresponding relation for the grazing angles is given by:

$$n_1 \cos \theta_1 = n_2 \cos \theta_2 \tag{3.2}$$

The index of refraction is defined as n = c/v, where c is the speed of light in vacuum and v is the speed in the actual medium. Inserting this relation in equation 3.1 yields an alternative representation of Snell's law:

$$v_2 \sin \alpha_1 = v_1 \sin \alpha_2 \ \leftrightarrow \ \frac{\sin \alpha_1}{\sin \alpha_2} = \frac{v_1}{v_2} = \frac{n_2}{n_1} \tag{3.3}$$

Due to varying ionization of different layers, the refractive index of each layer is different. If the effect of the Earth's magnetic fields are ignored then the refractive index n of the ionosphere is given by, [18]:

$$n^2 = 1 - \left(\frac{f_p}{f}\right)^2, f_p \propto \sqrt{N} \tag{3.4}$$

where f is the frequency of the transmitted wave and f_p is the plasma frequency which is proportional to the square root of the electron density N. As the ascending wave encounters the first region of the ionosphere, the refractive index falls since the electron density increases with height. If the ionized layer is sufficiently thick, refraction will continue until the angel of incidence reaches 90°. If the electron density is further increased, the angle will exceed 90° and the wave will be reflected down to Earth. In reality, the variation of electron density is continuous and the actual path of the traveling wave (ray) will also be a continuous curve [16]. Figure 3.4 illustrates how the actual ray is refracted as it travels through an ionospheric layer with increasing electron density. Here we assume that layer can be divided into a number of thin strips each having a uniform electron distribution and a higher electron density then the preceding one. Another assumption is that the distance between transmitter and receiver is small enough such that the curvature of the Earth and the layers can be neglected.

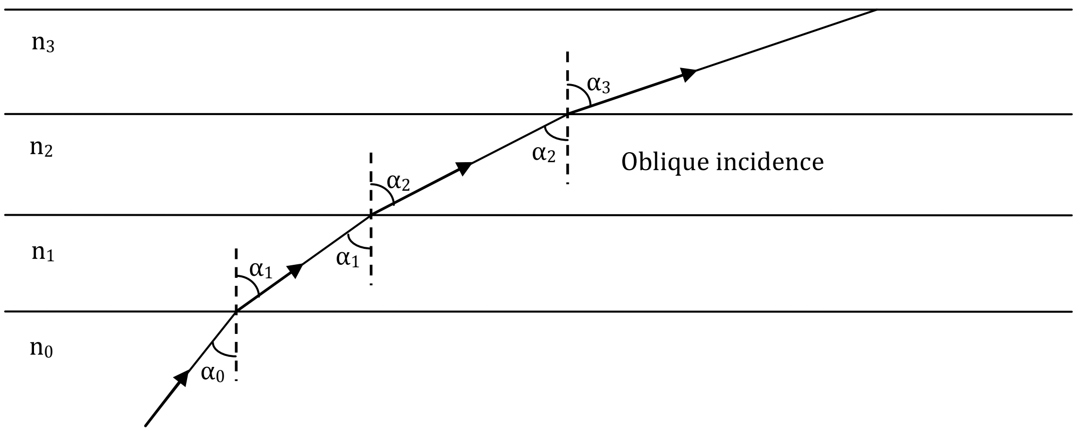


Figure 3.4 Refraction in a layered medium

In this way we can apply Snell's law derived in equation 3.1 at the boundary of each strip:

$$n_0 \sin \alpha_0 = n_1 \sin \alpha_1 = \cdots = n_n \sin \alpha_n \tag{3.5}$$

Assuming that $n_0 = 1$, the ray entering the ionosphere at an angle of incidence α_0 will be reflected at a height where the ionization is such that n = sin (α_0), indicating that $\alpha_n = 90°$ ($\pi/2$). At vertical incidence the reflection occurs when n = 0. Referring back to equation 3.4 yields that this happens when $f = f_p$. If $f = f_v$ represents the vertically incident frequency reflected at the level where the plasma frequency if f_p, then we can express the following relation (**Martyns theorem**) between oblique and vertical incidence.

$$sin^2 \alpha_0 = 1 - \left(\frac{f_p}{f}\right)^2 = 1 - \left(\frac{f_v}{f}\right)^2 \rightarrow f_v = f \cos \alpha_0 \tag{3.6}$$

The equivalent relation in terms of the grazing angel Θ_0 is given by

$$f_v = f \sin \theta_0 \,, where\ \theta_0 = 90° - \alpha_0 \tag{3.7}$$

Thus a frequency f incident on the ionosphere at an angle α_0 will be reflected at the same electron density, or *real height*, as the equivalent vertical incidence frequency f_v. From equation 3.6 we can see that a given ionospheric layer will always reflect higher frequencies at oblique incidence than at vertical incidence. We have already mentioned that the plasma frequency is proportional to the square root of the electron density. The relation between electron density and the plasma frequency in its simplest case is shown to be

$$\omega_p = 2\pi f_p = \sqrt{\frac{Ne^2}{\varepsilon_0 m_e}} \qquad \rightarrow f_p \approx \sqrt{81N} = 9\sqrt{N} \tag{3.8}$$

where

N = electrons per cubic meter

e = electron charge = $1.6*10^{-19}$ (C)

m_e = electron mass = $9.1*10^{-31}$ (kg)

ε_0 = vacuum permittivity = $8.854*10^{-12}$ (F/m)

Substituting f_p from equation 3.7 into equation 3.4 yields a more practical expression for the refraction index of the ionosphere as a function of the electron density, or ionization level.

$$n^2 = 1 - \left(\frac{f_p}{f}\right)^2 = 1 - \frac{Ne^2}{\varepsilon_0 m_e \omega^2} = 1 - \left(\frac{81N}{f^2}\right) \qquad \rightarrow n = \sqrt{1 - \frac{81N}{f^2}} \tag{3.9}$$

Since the electron density varies with height N (h), then the plasma frequency must also vary with height f_p (h). This means that the profile in figure 3.2 can either be represented as a function of the electron density or plasma frequency. If we let N_m be the maximum electron density in a given ionized layer, then all waves with a frequency less than the plasma frequency entering the ionosphere at vertical incidence will be reflected back to Earth. We define the highest frequency for which the wave will return as the *critical frequency* f_c given by

$$f_c = 9\sqrt{N_m} \tag{3.10}$$

It follows from Martyns theorem that

$$f \cos \alpha_0 = f \sin \theta_0 = f_v \leq f_c \tag{3.11}$$

This is an important result that can be used to predict the performance of HF sky wave link based on the measurement of the electron density or the plasma frequency. For oblique incidence, it depends upon the angle of incidence whether a wave will reflect back or not for a given critical frequency. Conventionally one defines the *Maximal Usable Frequency (MUF)* as the highest frequency for which the wave will return to Earth for a given angle of incidence, referred to as the critical angle.

3.3.2 Virtual Height

Ionospheric characteristics are determined from measurements of the critical frequency that may be converted to electron density at the various ionospheric layers. Usually a transmitter radiates vertically through a set of frequencies, and a nearby receiver picks up both the direct signal and the reflected signal. The time difference between the signals is used to calculate the height at which the reflection occurs. The height actually determined by this measurement is the virtual height h', see Figure 3.3. This is the height that from which the wave would appear to be reflected from if the ionosphere were a perfectly conducting surface. From physics we know that the propagation group velocity of the wave will be proportional to the index of refraction. Since the index of refraction decreases with increased electron density, the group velocity of the wave will get slower. The actual path delay for the real trajectory ADC will be exactly the same as the delay on the virtual path ABC for a wave propagating in vacuum being subject to ideal reflection a the virtual height h'. This result is formally known as the *Breit-Tuve Theorem*. For radio communication purposes it is particularly useful to find the virtual height since it can be used to estimate the communication distance for given frequency. The practical frequency range usually lies in the HF band. For higher frequencies the ionization level or electron density is rarely sufficient to reflect the waves. In the case of lower frequencies < 1 MHz, main part of the wave energy will be absorbed.

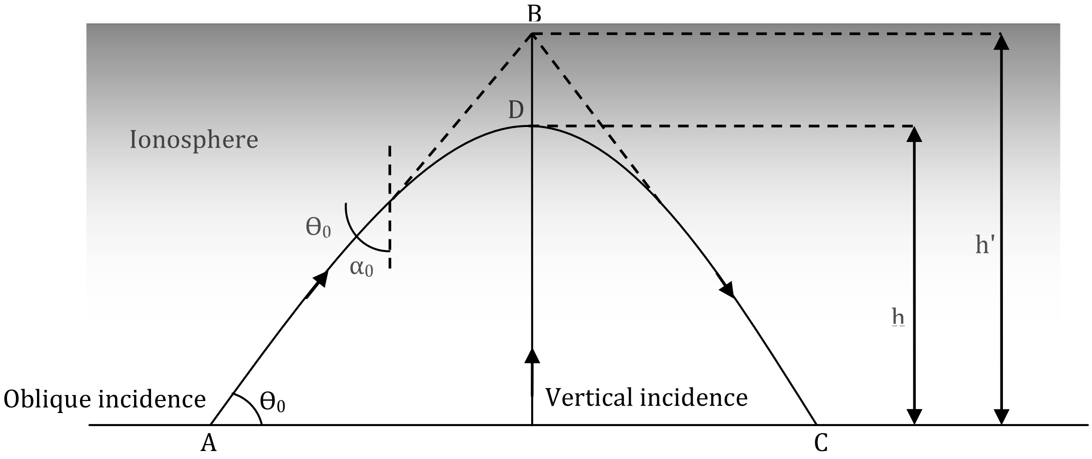


Figure 3.5 Real height h versus virtual height h'

3.3.3 Skip Distance

In section 3.3.1 we defined the critical frequency f_c as the maximum frequency for which the wave, transmitted vertically towards the ionosphere, will reflect back to Earth. If the frequency of the incident wave is higher than the critical frequency f_c, it depends upon the grazing angle whether the wave will return or not. Figure 3.6 illustrates the possible scenarios for a wave with a fixed frequency entering the ionosphere at different angles. When the grazing angle is small, the communication distance is large, as indicated by ray (1). As the angle is further increased (2) the range will continue to decrease until a minimum communication distance is reached. The ray that gives rise to the minimum distance is called a *skip ray* (3). For transmitting waves with a frequency above f_c, there will always be a minimum communication distance, referred to as the *skip distance*. This can be realized by studying the relation in equation 3.11. Assume that the transmitting frequency is $f = 2f_c$, then the maximum grazing angle for which the wave will reflect back is $\Theta = 30°$. This angle geometrically yields a minimum communication distance. To reach shorter distances would require a too steep angle, resulting in a deeper penetration of the ionospheric layer. The ray may either reflect at a higher point in the layer (4), or completely penetrate the layer. A ray that completely penetrates the ionosphere is called an escape ray (5). For waves with a frequency less or equal to the critical frequency f_c, there is no skip distance present.

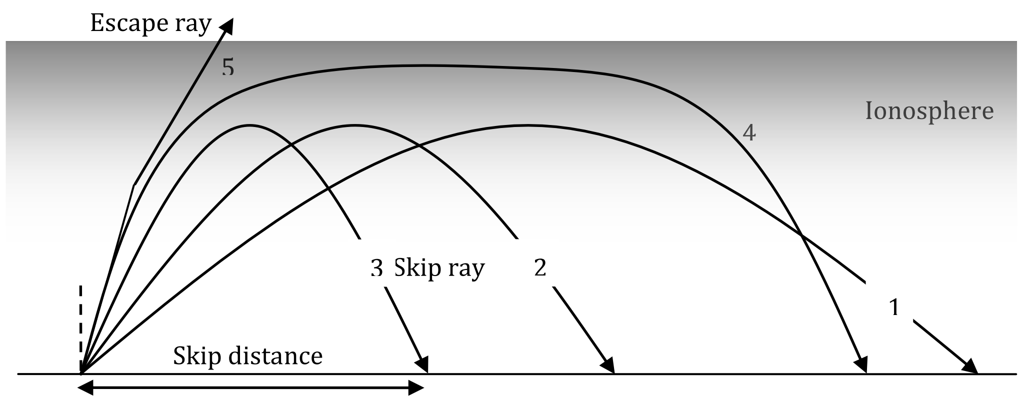


Figure 3.6 Ray paths as a function of the grazing angle for a fixed frequency

3.4 Ionospheric Sounding

So far we have discussed the formation of the ionosphere in terms of the ionization process, layer structure and the main variation factors. For radio communication purpose we could state that the ionospheric layers act as a partially conducting media, uniquely determined by the density of free electrons. In the simplest case the curvature of the Earth and the impact of the Earth's magnetic field can be neglected. Applying basic physical laws, under the assumption that the free electrons are uniformly distributed, a useful relation between the refraction index, electron density/plasma frequency and the frequency of the transmitting wave was presented. This relation can be used to predict whether a propagating wave, transmitted vertically or obliquely, will reflect from an ionospheric layer with a known electron density or completely penetrate it. The way the electron density profile is determined experimentally is either by incoherent scatter radar techniques, which are large and expensive facilitates, or with a more common instrument called an *Ionosonde* [14c]. Two main types of ionosondes can be distinguished, namely the system for *Vertical sounding* and the system for O*blique sounding*.

3.4.1 Vertical Sounding

Both vertical and oblique sounding work on the same principles and the main difference between these two techniques is the location of the transmitter with respect to the receiver. Vertical ionosondes are special radars that transmit HF (X - 30 MHz) radio waves vertically up to the ionosphere. The transmitted radio waves will reflect at a height where the ionospheres refraction index is equal to zero, or equivalently where the plasma frequency of the ionosphere is equal to the transmitted wave frequency (see equation 3.4). Given sufficiently accurate clocks, or the same clock reference used at both the transmitter and receiver, a receiver system placed nearby the transmitting station can detect and measure the time-of-flight for the returned echo signal. The time-of-flight can be converted to virtual reflection height that generally lies between 85 and 600 km. Figure 3.7 illustrates the geometrical principle behind vertical sounding.

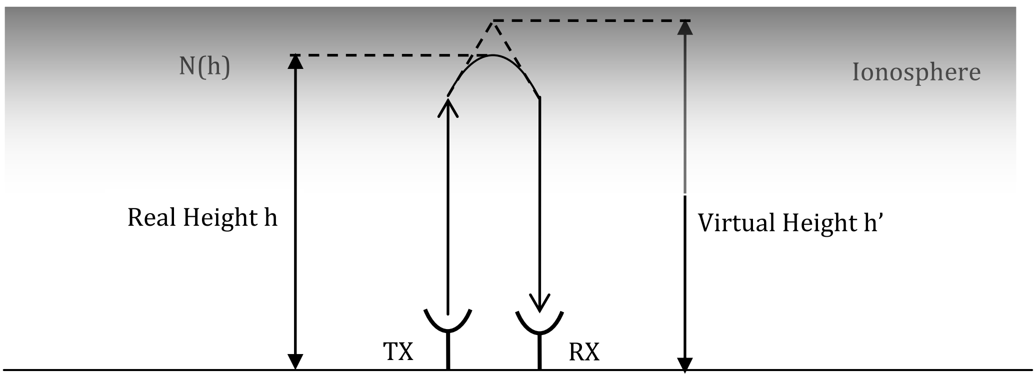


Figure 3.7 Vertical sounding

By sweeping through a set of frequencies in the HF band and listening to the return echoes, the receiver system can determine a characteristic graph called an *Ionogram* representing the virtual reflection height as a function of the plasma frequency. Using the simple relation given by equation 3.8, the plasma frequency profile can easily be converted to the corresponding electron density profile. In older ionosonde equipment (Digitally pulsed ionosonde), the transmitter sweeps through a part of the HF band, usually transmitting high powered short pulses. In this report we focus only on the ionosonde known as the *Chirp Sounder* that transmits a low powered Frequency Modulated Continuous Wave (FMCW) or “chirp”. A chirp is a continuous signal in which the instantaneous frequency varies linearly with time.

Figure 3.8 shows a typical ionogram obtained from vertical sounding. The virtual height of the ionosphere is plotted against the receiver frequency swept from 1 to 10 MHz. For every transmitted frequency, the wave will travel through the ionosphere until the electron density is sufficient to reflect the signal. A more analytic approach is that the reflection occurs when the ionospheres refraction index equals zero, which occurs when the plasma frequency is equal to the transmitted frequency. In the figure we can clearly see the formation of the E, F1 and F2 layer. The critical frequency of each layer is identified by the vertical asymptote denoted foE, foF1 and foF2. The horizontal asymptotes represent minimum virtual height for respective layer. At the asymptotes or critical frequencies the incident radio wave from the ionosonde has reached maximum resonant frequency of the layer and at this point the radio wave does not propagate. Once the critical frequency of the layer is exceeded, the transmitted radio wave will not be reflected. Instead the wave propagates until it encounters a layer of higher electron density. Eventually the transmitter frequency exceeds the critical frequency of the highest layer present and continues to propagate beyond the ionosphere. Additional complication of the ionosphere is the interaction with the Earth’s magnetic field that separates the transmitted wave into two polarizations as soon as the transmitted radio signal begins to penetrate the ionosphere. This effect can be spotted in the ionogram as an extraordinary wave (X-wave) that represents the E-field component of the incident radio wave perpendicular to the magnetic field direction. For the ordinary wave (O-wave), the E-field of the incident wave is parallel to the magnetic field. This means that filed has no influence, because a magnetic field only imposes a force on charged particles moving perpendicular to the field.

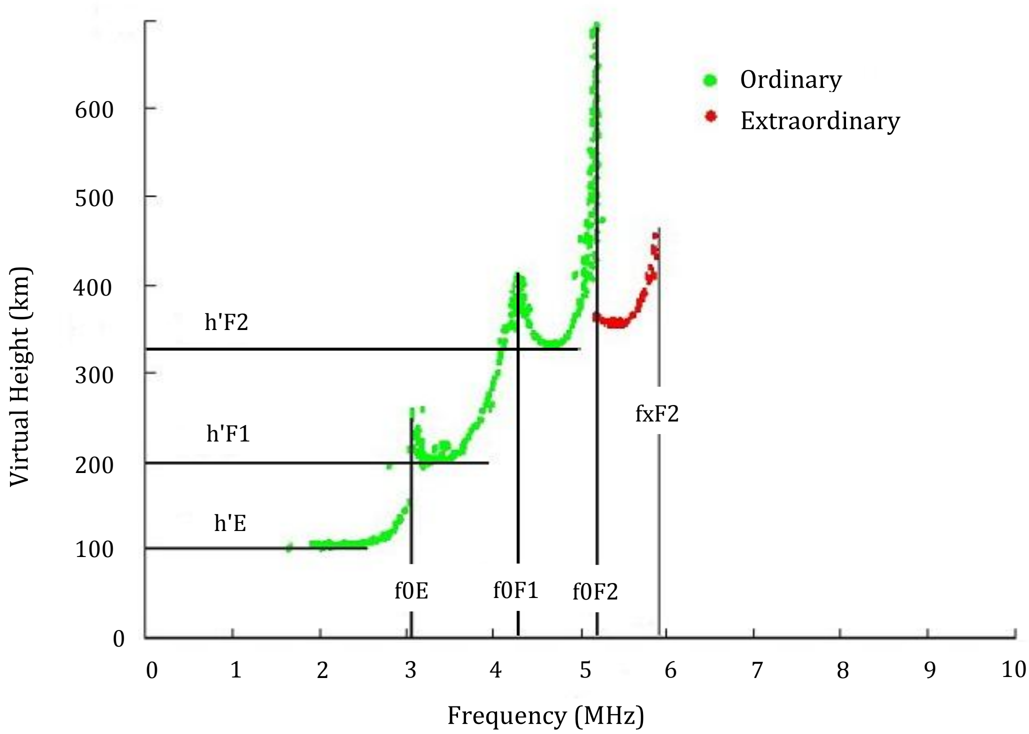


Figure 3.8 Vertical ionogram

3.4.2 Oblique Sounding

Oblique sounding is primarily used by commercial, radio amateur and military users for monitoring radio channel links between two remote locations. An ionogram obtained from oblique sounding can often serve as a base for HF radio prognoses. Vertical sounding principles also apply for oblique sounding. However, the geometry of oblique sounding makes the analysis and interpretation of the corresponding ionogram more complicated. Obliquely propagating waves are gradually refracted as they travel trough an ionospheric layer with increasing electron density, making them more receptive for variations in the ionosphere. Since the receiver is separated by thousands of kilometers from the transmitter, higher demands are placed on the receiver stability and the clock reference used [17]. The situation is further complicated by the fact that radio signals can take a variety of paths before reaching the receiver, introducing the problem of multipath propagation. Figure 3.9 illustrates the geometry for oblique sounding along with two alternative propagation paths for the transmitted radio signal.

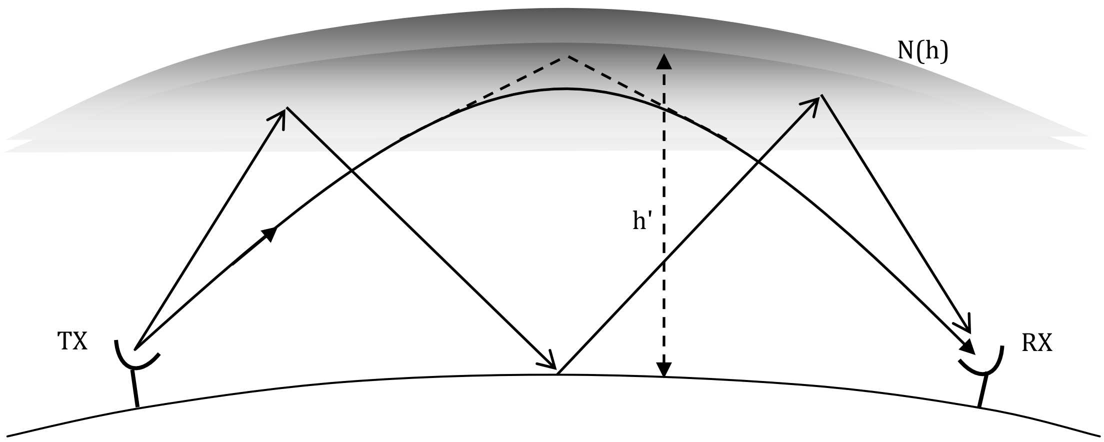


Figure 3.9 Oblique sounding

The oblique ionospheric sounder offers several important advantages over vertical sounding for understanding radio wave propagation between two locations [18]. The technique enables the possibility to monitor the ionosphere across otherwise inaccessible areas such as oceans. In addition, the same receiving station can be used to monitor several transmitting stations spread around the world. Oblique sounding permit communication users to quickly perform real time channel evaluation and identify what frequencies are most likely to propagate between selected transmitter and receiver station. Figure 3.10 shows a typical oblique ionogram measured between a transmitter station located in Svalbard (Norway) and the receiver located in Chilton (UK), about 3030 km apart. The specific example has deliberately been chosen since all background noise and HF disturbances are filtered away from the figure. This ionogram is also known as a *waterfall plot* or *spectrogram*, which shows the absolute path delay as a function of the received frequency and the received signal strength. The effect of propagation paths that involve multiple reflections from the ionosphere is clearly apparent from the separate curves. Following the frequency axis the user can determine available communication bands and the expectation of experiencing interference due to multipath propagation. For example a HF communication link that reflects once from the ionosphere between Svalbard and Chilton could be established for the frequencies between 19-24 MHz. In this band there is more than one route within the single hop, a high altitude propagation path (high-ray) and a low altitude route (low-ray), meaning that the received signal might experience interference. For the frequency band of 13-15 MHz the route involves two reflections from the ionosphere. A third band that involves two, three or four hops is located between 7-11 MHz. The received signals from this band are likely to suffer from distortion caused by multipath interference and fading, which makes the communication channel link highly unreliable. Clearly the gaps represent parts of the HF band where no communication link could be established.

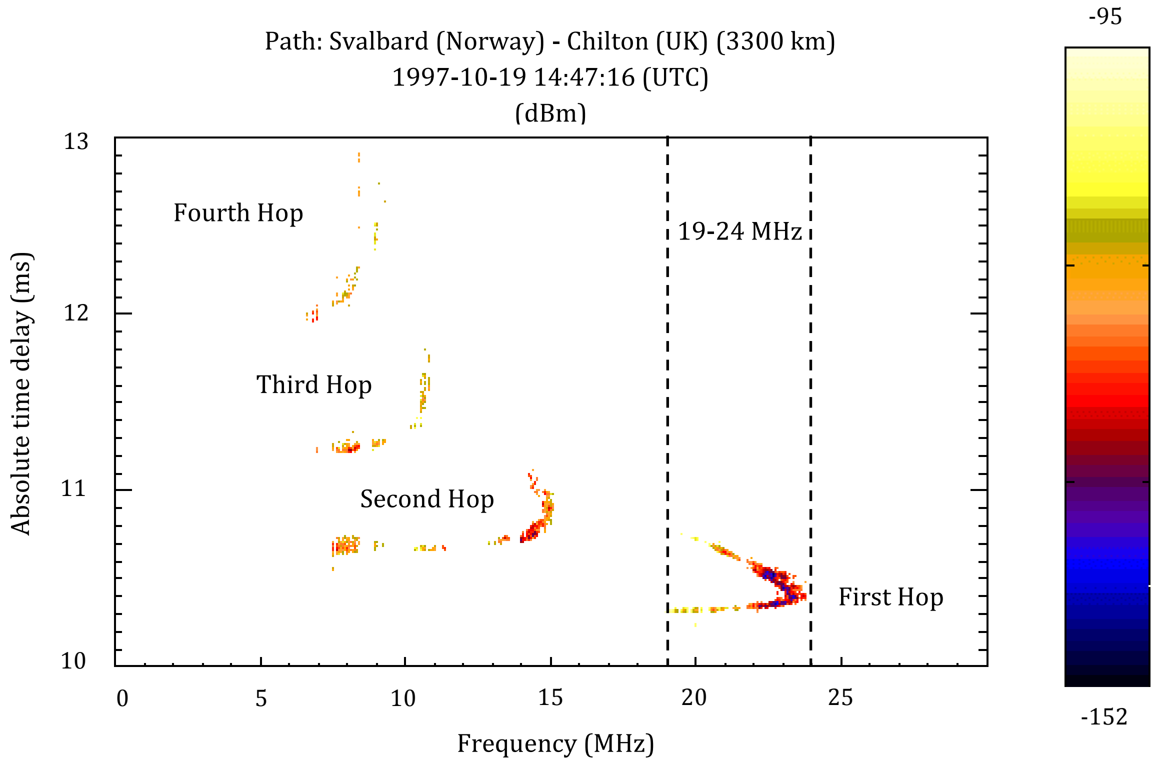


Figure 3.10 Oblique ionogram for propagation between Svalbard (Norway) and Chilton (UK)

Figure 3.11 shows the corresponding spectrogram obtained for a real time oblique measurement with the transmitting station located near Akrotiri (Cyprus) and the receiver located 2800 km apart in Vaxjo (Sweden). The transmitter station named Cyprus1 sweeps through the frequencies between 8-30 MHz at rate of 0.1 MHz/s with a repetition cycle of 300s (5min) and a offset time of 235s (3min and 55s). The receiver equipment used to detect this station relies on the open source SDR solution discussed in section 2.4 and the GNU Chirp Sounder software covered in the next section. The measured spectrogram plots the absolute time delay converted to virtual range as a function of the received frequency, with the color map indicating received signal strength given in dB. The red, cyan and yellow vertical lines are undesired signals picked up by the antenna that likely originate from transmitting amateur or military HF radio stations. From the spectrogram we can identify five separate curves between the frequencies 8-20 MHz in which probably all result from reflections with the F-layer. The available channel bands can be determined in the same way as explained with the spectrogram in figure 3.10. In reality the ionosphere changes on a time scale that can be less than one minute. A communication link that completely relies on ionospheric reflection would need constant updating on the available bands.

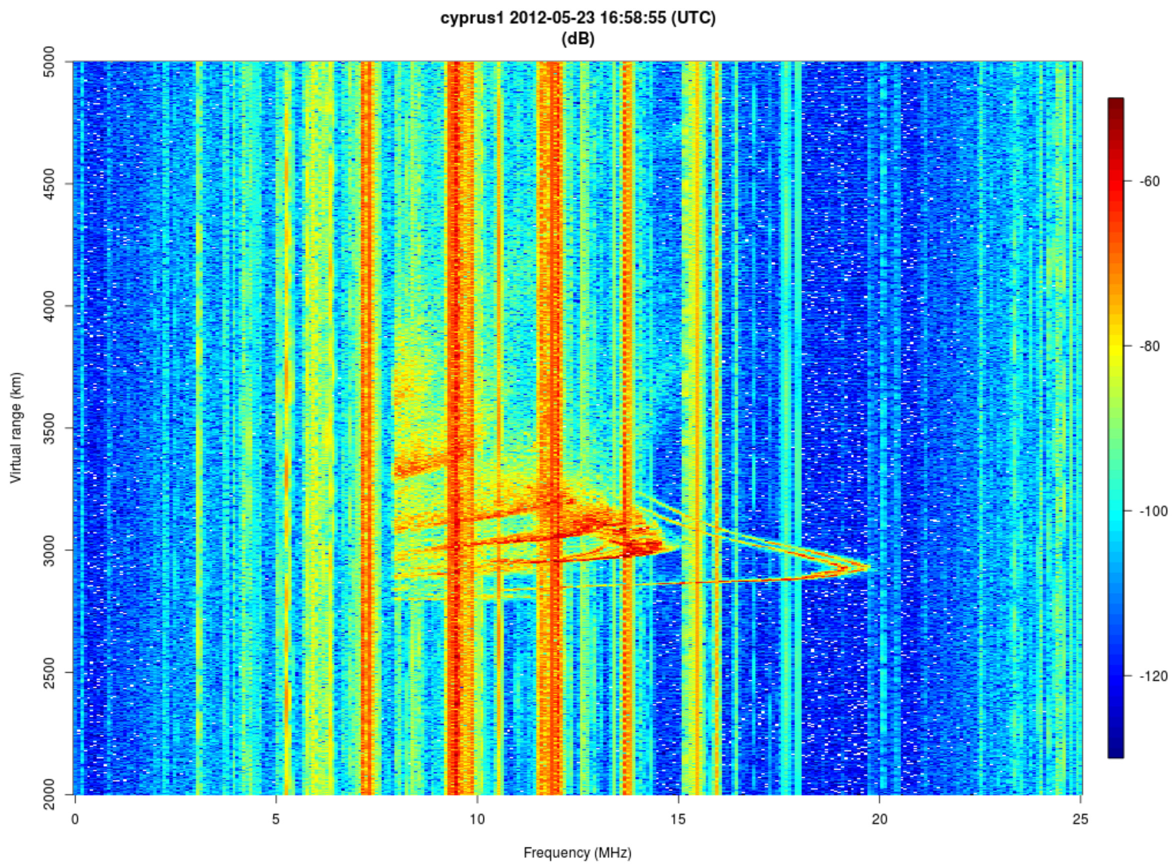


Figure 3.11 Oblique spectrogram for propagation from Akrotiri (Cyprus) to Vaxjo (Sweden), 2800 km apart

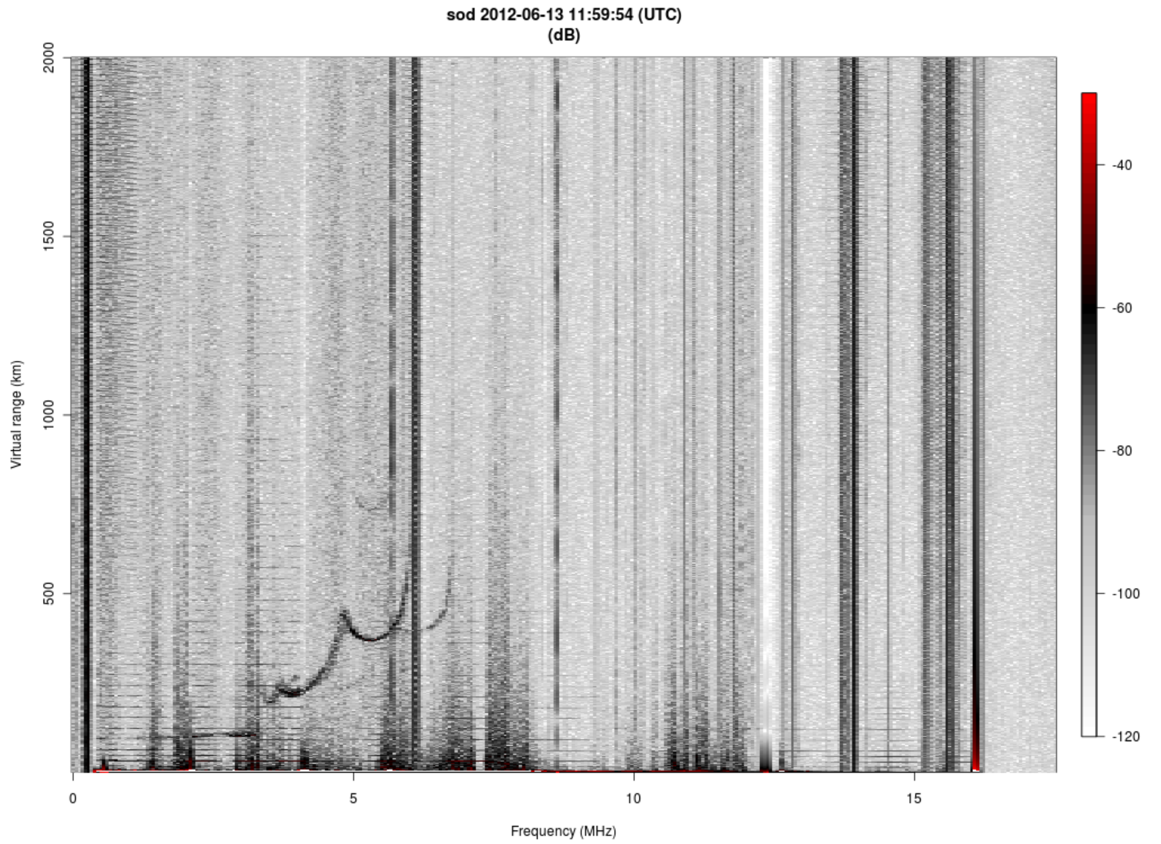


Figure 3.12 Example vertical sounding of the Sodankylä ionosonde located 1km from the receiver

The same receiver equipment can be used to detect vertical sounders as well. Figure 3.12 shows an example vertical recording of an ionosonde located at the Sodankylä Geophysical Observatory in Finland with the receiver separated 1km apart. The station is sweeping through the frequency range between 0.5-16 MHz with a rate of 0.5 MHz/s. The transmission is repeating every 60s (1min) with the offset time of 54s. From the spectrogram we can identify the E, F1 and F2 layer formation between the frequencies 1.5-6 MHz, which result from ordinary wave reflection. The fourth layer located between 6-7 MHz is probably an extraordinary trace. Corresponding critical frequencies can be determined by drawing vertical asymptotes between the transitions of each layer, as illustrated with the vertical ionogram in figure 3.8.

3.5 GNU Chirp Sounder (gcs)

3.4.1 Description

The GNU Chirp Sounder is a Software Defined Radio (SDR) based receiver for monitoring ionospheric sounders and over-the-horizon (OTH) radars that use Frequency Modulated Continuous Wave (FMCW) transmissions. The software is based on GNU Radio scripts and libraries and relies on the Ettus Research USRP2 and USRP N210 digital hardware device. It was developed and released as open source code by Juha Vierinen [19], researcher at the Sodankylä Geophysical Observatory. The gsc software is capable of handling multiple sounders simultaneously, covering transmissions trough the whole HF band. In addition the receiver can be used to perform single or dual polarization channel soundings. Dual channel recording can be used to determine the polarization from vertical soundings or for angle of arrival measurements. The current version 0.23 has only been tested on Linux Ubuntu runing GNU Radio 3.6.0. Appendix C provides instructions on how to install the gsc software.

3.4.2 Released Code (sgo-chirp-rec-0.23)

The GNU Chirp Sounder software allows the USRP2 or USRP N210 to be used as a wideband ionosonde receiver; more specific it allows recording of FMCW ionospheric chirp sounder transmissions. The software is divided into two parts implemented as separate programs. The first part consists of data recording implemented as a combination of custom made signal processing block written in C++ and a higher layer application written in Python. The digital downconverter (USRP2, USRP N210) is instructed to start sampling at some center frequency and record a continuous raw voltage data stream at a specified bandwidth. This stream is then fed into a software defined downconverter on the CPU that follows the center frequency of the chirped waveform, band passing it and decimating the signal to a much lower bandwidth. Thus, a chirped local oscillator (LO) is used to down convert the received chirp to DC, where after the signal is integrated and decimated before stored to a file. This is made possible by a custom made GNU Radio signal processing block written in C++. The analysis part programmed in C++ also provides the capability to track multiple ionospheric chirp sounders simultaneously. The actual flow graph is constructed and executed in Python. Here the user can define the sounders that are to be received, samplings rate, decimation factor and the center frequency. The recorded data files are marked with a Unix timestamp and saved in a predefined date-directory. The second part of the program is GNU R script that analyzes the recorded files using a dynamic spectrum estimator, more commonly known as a spectrogram. This allows you to visualize the recorded data files and save the result as png image files.

3.4.3 Hardware: Single Channel Receiver

The receiver system requires a USRP2 or a USRP N210 device, equipped with the LFRX (0-30MHz) daughterboard, a GPS stabilized 10 MHz reference signal and a 1 PPS synchronization signal. The receiver antenna must provide the same performance over the entire frequency range of interest, usually 1-30 MHz. Certain types of broadband antennas may also require a RF preamplifier. If the receiver antenna is located in a noisy and disturbing environment, better results from the recorded ionograms can be obtained without any preamp. Figure 3.13 illustrates a basic block diagram of the hardware configuration for a single channel receiver used to track oblique and vertical ionospheric transmissions.

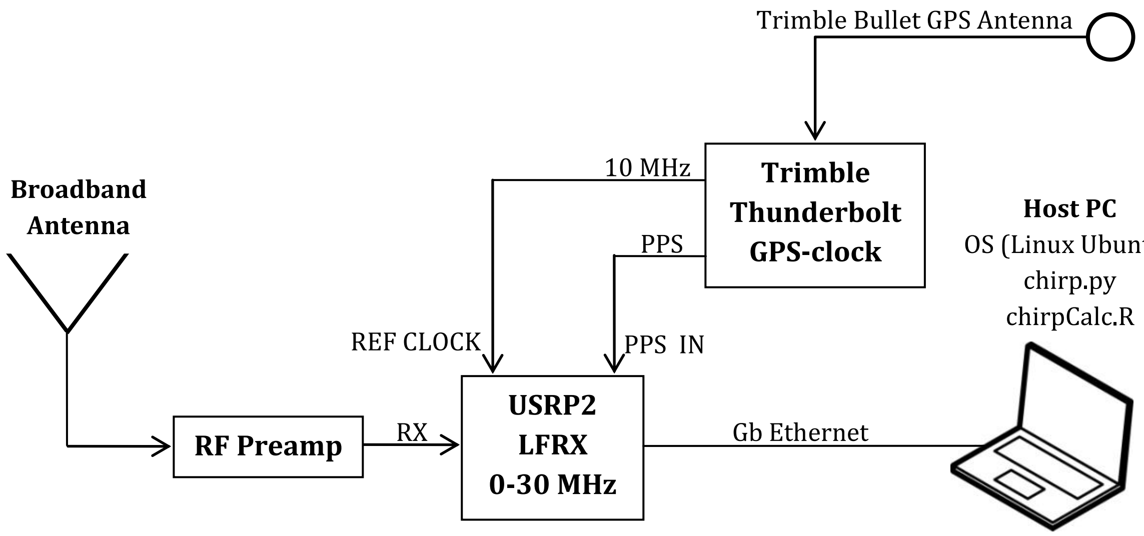


Figure 3.13 Single channel receiver

The single channel receiver system consists of one USRP2 device equipped with an LFRX daughterboard. The 100 MS/s 14-bit analog to digital converter allows applications on the host PC to receive 50 MHz of RF bandwidth from the USRP2 via the Gb Ethernet interface. Internal oscillators can be locked to an external reference, and there is a 1 pulse-per-second (1 PPS) input for precise timing applications. The LFRX daughterboard allows reception from 0-30 MHz. The board does not serve as an RF Front End and has no tunable elements or programmable gains; it simple provides an entry point between the signals captured by the antenna and the USRP motherboard. This makes the daughterboard appropriate for direct signal measurement below 30 MHz. External clocking is obtained from the Trimble Thunderbolt E GPS Disciplined Clock [20], that provides an accurate one pulse-per-second (1 PPS) signal and a stable 10 MHz frequency reference signal with an over determined solution synchronized to GPS or UTC time. For most applications, the Thunder Bolt E is ready to use out of the box. However, Trimble recommends that you install the Trimble GPS monitor software before setting up the Thunderbolt E GPS disciplined clock. This enables you to monitor the GPS performance once you start up the GPS antenna and to change its settings. Together this receiver configuration is used to track and record one transmitting chirp station at a time over the entire HF band.

3.4.4 Field Tests and Results

The single channel receiver equipment shown in figure 3.13 was tested during several occasions. The receiver antenna used during primary testing is a passive flare-dipole broadband antenna (1.5-30 MHz), where the use of an RF preamp was not required. An actual photograph of the receiver antenna and the equipment setup is shown in figure 3.14 and 3.15. The gcs 0.23 software is compiled on Linux Ubuntu 11.10 running GNU Radio 3.6.0 and UHD 3.4.1. The analysis part of the gsc software requires R≥14 to plot the corresponding spectrograms and in this case R 2.15 was used. Finding out the necessary parameters of a transmitting station turned out to be a more difficult task than expected. Unfortunately, many of the chirp sounders are not locked to GPS and their time drifts randomly. With some manual searching it is possible to determine the chirp time of these transmitters, but detecting them in an automatic fashion can be fairly difficult. The list of available chirp sounders is also narrowed down by the fact that this receiver system is designed to receive stations that are transmitting a FMCW or a linear chirp, in contrast to the older digitally pulsed ionosondes. Table 3.1 lists 4 different ionosondes that were recorded during primary testing, in which all are GPS synchronized. The most reliable sounder was the Cyprus1 located somewhere near Akrotiri (Cyprus), approximately 2800 km apart from the receiver in Vaxjo (Sweden). This sounder is sweeping between 8-30 MHz at a frequency rate of 0.1 MHz/s. The transmission is repeating every 300s with a chirp time of 235s, i.e. when the chirp starts at 0 MHz. Using the midnight time as a reference point the first transmission would start at 00:03:55 and the second at 00:08:55. Thus, during every hour the sequence would repeat itself 12 times. Figure 3.17 shows an example oblique sounding of Cyprus1 obtained on the 23 of May, 17:53:33 (UTC) or 19:53:55 local time. This station was actually recorded continually during a period of 18 hours from which one could clearly see the variations of the ionosphere during day and night time. The recordings of Cyprus2, Cyprus3 and Svalbard are shown in figure 3.18-20 respectively. At the time, these stations were only tested to confirm the respective chirp times.

Table 3.1 List of the chirp sounders received during primary testing

Name	Repetition (s)	Chirp Time (s)	Chirp Rate (MHz)	Frequency Range (MHz)
Cyprus1	300	235	0.1	8-30 MHz
Cyprus2	300	240	0.1	-
Cyprus3	900	20	0.1	-
Svalbard	300	22	0.1	-

Figure 3.14 Photograph 1: Passive Flare dipole broadband receiver antenna (1.5-30 MHz)

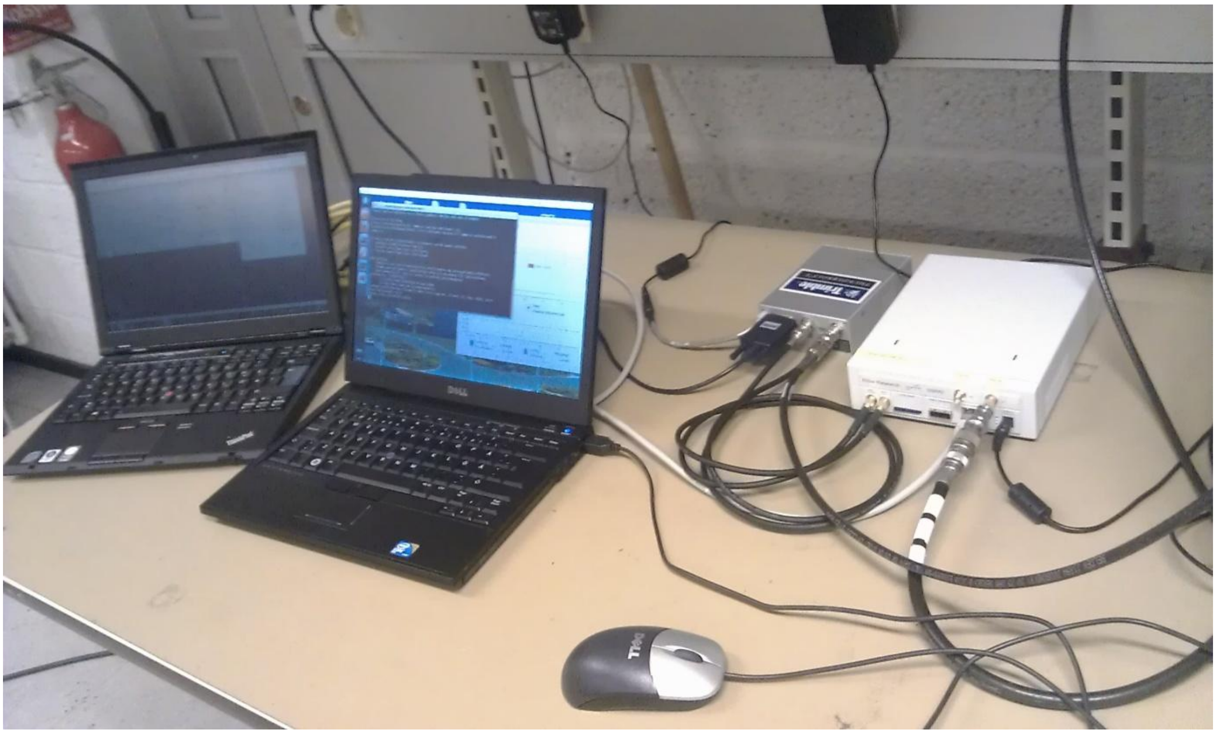


Figure 3.15 Photograph 2: Equipment setup for the single channel recorder

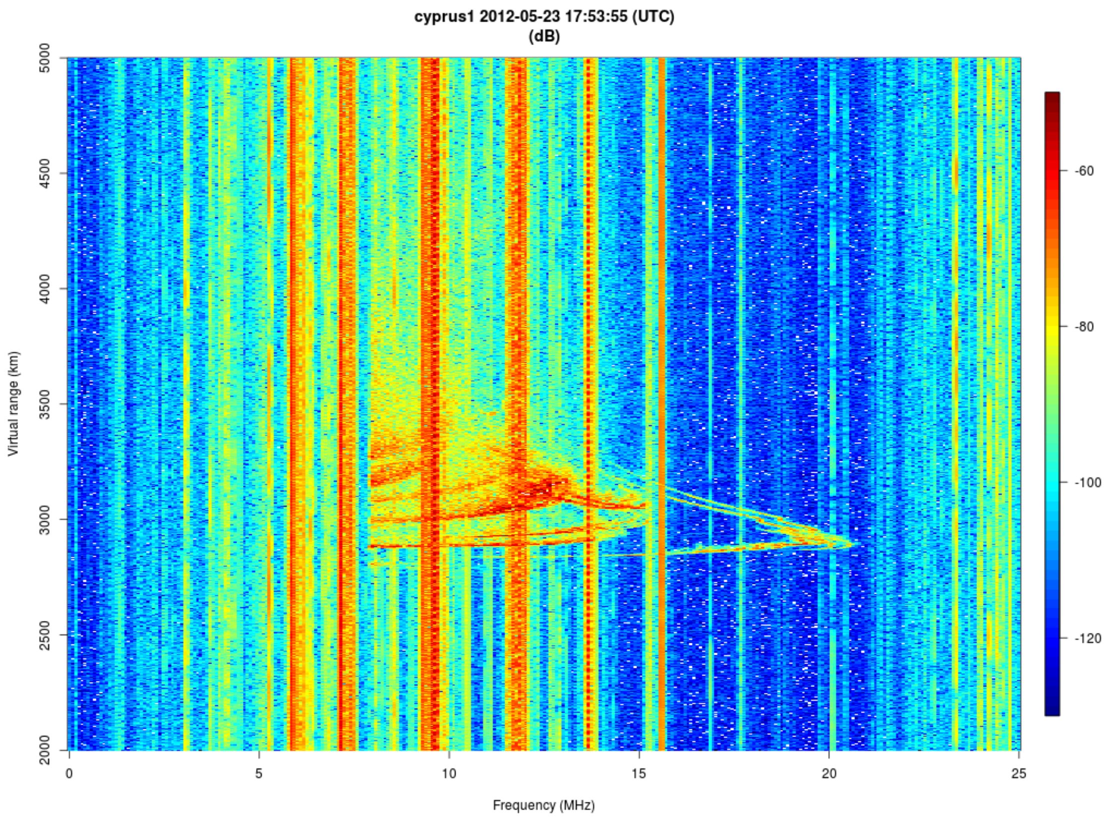


Figure 3.17 Oblique sounding of Cyprus1, 300:240 0.1 MHz/s

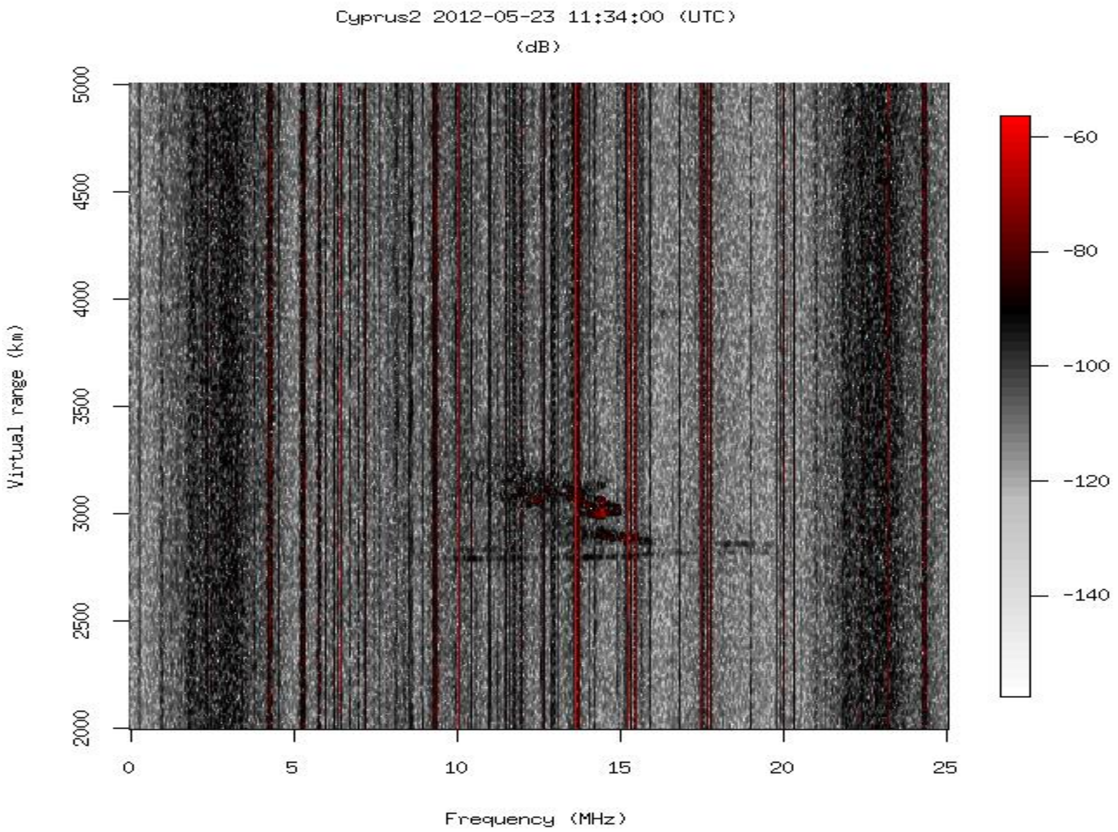


Figure 3.18 Oblique sounding of Cyprus2, 300:235 0.1 MHz/s

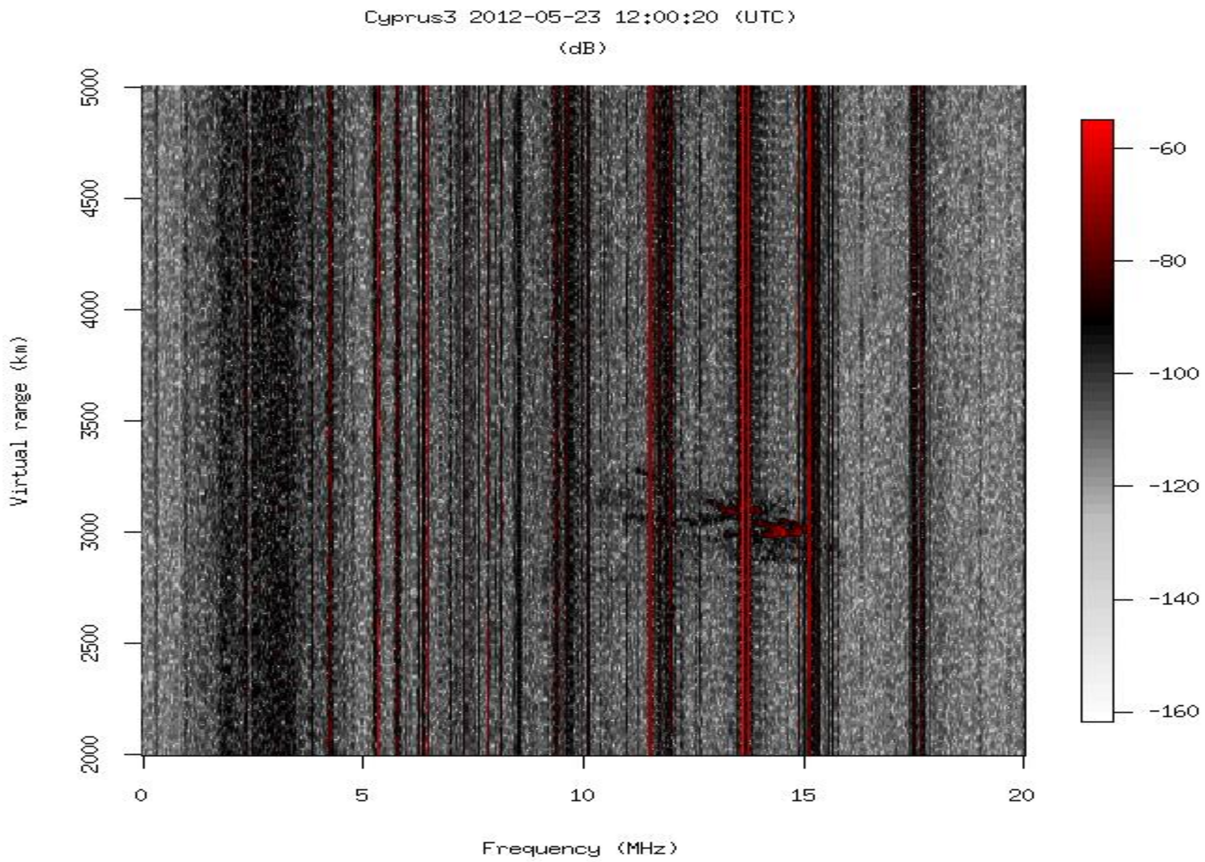


Figure 3.19 Oblique sounding of Cyprus3, 900:20 0.1MHz/s

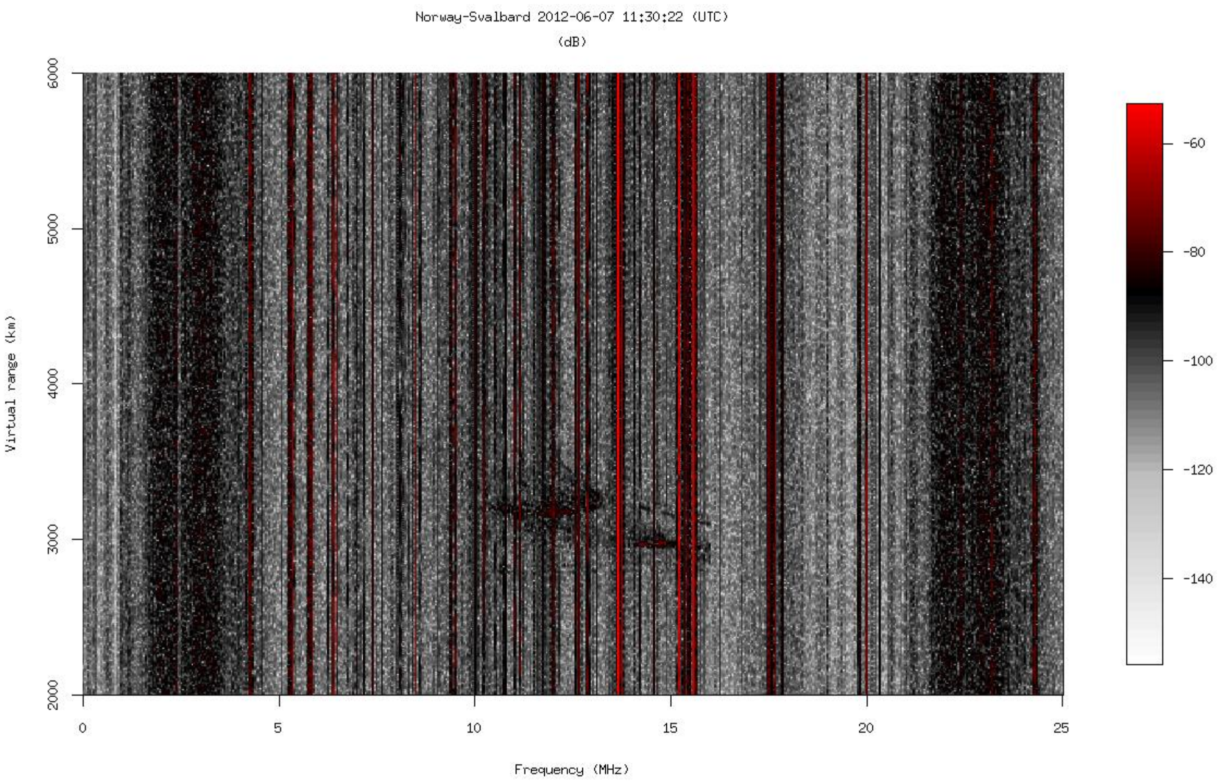


Figure 3.19 Oblique sounding of Svalbard (Norway), 300:22 0.1 MHz/s

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Appendix A: Installing UHD and GNU Radio on Linux Ubuntu

This manual will guide you through the installation of UHD and GNU Radio on Linux Ubuntu 11.10-12.04. The current version (0.23) of the GNU Chirp Sounder (gcs) software is designed and tested to compile only with **GNU Radio 3.6.0** and will not work with an older release. As a compatibility guarantee, use this version along with UHD 3.4.1 or the currently latest stable release 3.4.2. There are several installation methods available and this guide covers one of them. Since it might be undesired to receive automatic package updates, UHD is installed as a standalone package and GNU Radio is built from tarball using the Cmake build system.

1. Linux Ubuntu 11.10-12.04

Following link [1] leads to the Ubuntu download page that provides instructions on how to burn a CD or create a bootable USB stick on Windows. The users that want to run Ubuntu along with Windows can use the Windows Installer for Ubuntu Desktop (WUBI).

[1] Ubuntu Download: http://www.ubuntu.com/download
[2] Index of Releases: http://ftp.lysator.liu.se/ubuntu-releases/

2. Update the system

Open a terminal (Ctrl+Alt+T) and type the below commands to install all of the currently available updates

```
$ sudo apt-get update
$ sudo apt-get upgrade
```

3. Pre-Requisites

The below command lines will install all of the dependencies *required* for compiling various parts of GNU Radio and UHD on Ubuntu. To execute the script copy & paste the command line into a terminal

```
sudo apt-get -y install git-core autoconf automake  libtool g++ python-dev swig \
pkg-config libboost-all-dev libfftw3-dev libcppunit-dev libgsl0-dev \
libusb-dev sdcc libsdl1.2-dev python-wxgtk2.8 python-numpy \
python-cheetah python-lxml doxygen python-qt4 python-qwt5-qt4 libxi-dev \
libqt4-opengl-dev libqwt5-qt4-dev libfontconfig1-dev libxrender-dev python-opengl
```

The dependencies can also be installed manually via the graphical package management program “Synaptic”. To install Synaptic enter the following command line

```
$ sudo apt-get install synaptic
```

[3] Dependencies Ubuntu: http://gnuradio.org/redmine/projects/gnuradio/wiki/UbuntuInstall

4. Universal Hardware Driver (UHD) - Standalone Package from Maint Branch

Download and install the corresponding deb-file (.deb) that is supported by the used machine and operating system. For the chosen UHD version, download also the UHD Images containing the USRP firmware and the FPGA image files which need to be loaded on the USRP2 SD card or the USRP-N series On-board flash (see Appendix B). If some of the download links are missing, refer to the Linux binary installation instructions in link [5].

Click to download

```
uhd_003.004.001-release_Ubuntu-11.10-i686.deb   22-May-2012 16:56
uhd_003.004.001-release_Ubuntu-11.10-x86_64.deb 22-May-2012 16:56
uhd-images_003.004.001-release.tar.gz           22-May-2012 16:56

uhd_003.004.002-release_Ubuntu-11.10-i686.deb   24-May-2012 17:12
uhd_003.004.002-release_Ubuntu-11.10-x86_64.deb 24-May-2012 17:12
uhd_003.004.002-release_Ubuntu-12.04-i686.deb   24-May-2012 17:12
uhd_003.004.002-release_Ubuntu-12.04-x86_64.deb 24-May-2012 17:12
uhd-images_003.004.002-release.tar.gz           24-May-2012 17:13
```

[4] UHD Official Page: http://code.ettus.com/redmine/ettus/projects/uhd/wiki
[5] UHD Download: http://code.ettus.com/redmine/ettus/projects/uhd/wiki/UHD_Linux

5. GNU Radio

The latest stable release of GNU Radio along with an archive of older releases can be found in the GNU Radio Download Page [8]. The GNU Chirp Sounder Software is currently designed and tested to compile with *GNU Radio 3.6.0* in which Cmake is now the only build system available.

Cmake build system:

Click to download

```
gnuradio-3.6.0.tar.gz22-Apr-2012 16:51 (Tested with gcs)
gnuradio-3.6.1.tar.gz11-Jun-2012 15:58 (Currently latest release)
```

Open a terminal and proceed with the commands below

$ sudo apt-get install cmake (Skip if cmake is already installed)
$ mkdir $ (builddir) (Create a custom build directory for GNU Radio)
$ cd $ (builddir) (Navigate to the previously created folder)
$ cmake $ (srcdir) (Enter the pathway for the downloaded source folder)
$ make
$ make test
$ sudo make install

After the installation is completed you might have to run "**sudo ldconfig**" in order to update the Python paths and necessary links to shared libraries.

You can test if UHD and GNU Radio have been installed properly by executing the graphical user interface GNU Radio Companion (GRC) using the commands

```
$ gnuradio-companion
$ gnuradio-config-info        (Optional: Installation prefix, build date, version etc)
```

or by running an GNU Radio Python example audio file

```
$ cd /usr/local/share/gnuradio/examples/audio
$ python dial_tone.py         (Alternative: $ ./dial_tone.py)
```

Optional Method:

As of version 3.5, Cmake is now the default and preferred build system. If for some reasons Cmake fails, GNU Radio still includes the old autotool build process as a parallel build method.

```
$ cd $ (srcdir)
$ ./bootstrap                 (Only if not building from tarball, skip this line else)
$ ./configure
$ make
$ make check
$ sudo make install
```

Uninstall:

```
$ cd $ (builddir)
$ sudo make uninstall
$ make clean
```

[6] GNU Radio Download: http://gnuradio.org/redmine/projects/gnuradio/wiki/Download
[7] Index of Releases: http://gnuradio.org/releases/gnuradio/
[8] C++ API Documentation: http://gnuradio.org/doc/doxygen/index.html
[9] Python Manual: http://gnuradio.org/doc/sphinx/index.html

Appendix B: USRP2 and USRP-N series Configuration

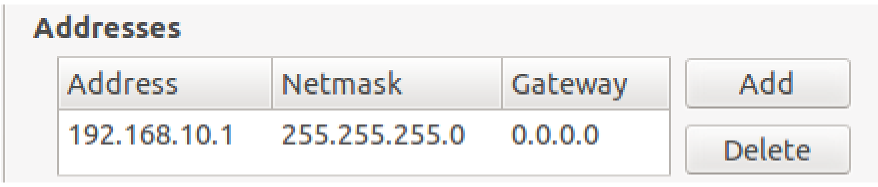
This guide provides instructions on how to setup a host interface connection on Linux Ubuntu, change the USRP2 IP address and (re)load the UHD image files. Some useful commands are also provided that can be used to check if the device is being recognized and working as expected. The official UHD documentation can be found in link [10].

[10] UHD-USRP Documentation: http://files.ettus.com/uhd_docs/manual/html/

1. Setup the Host Interface

The USRP2 communicates at the IP/UDP layer over the Gigabit Ethernet. The default IP address of the USRP2 is **192.168.10.2**. You will need to configure the host's Ethernet interface with a static IP address to enable communication. To set up a host interface connection with the USRP2 device on Linux Ubuntu, follow the instructions below.

- Open Network Connections
- Add a new connection
- Navigate to the IPv4 Settings and select Method: Manual
- Add a new address with the below recommended settings
- Check the box: Require IPv4 addressing for this connection to complete



2. Device Discovery & Properties

This command scans your system for supported devices and prints out an enumerated list of discovered devices and their addresses.

```
$ uhd_find_devices
```

The USRP will reply to ICMP echo requests. A successful ping response means that the device has booted properly and that it is using the expected IP address.

```
$ ping <device_address>
```

This command constructs an instance of the device and prints out its properties, such as detected daughterboards, frequency range, gain ranges, etc...

```
$ uhd_usrp_probe
```

3. Change the USRP2's IP Address (Optional)

Method 1: To change the USRP2's IP address the network must be setup properly as described above, for which you must know the current IP address. Connect to the USRP2 device and run the following commands (assuming the new IP address is 192.168.10.3)

$ uhd_find_devices (Check that the device is connected)
$ cd /usr/share/uhd/utils
$ ./usrp_burn_mb_eeprom --key=ip-addr --val=192.168.10.3

- Reboot the USRP2 device

Method 2 (Linux only): This method assumes that you don't know the current IP address of the USRP2. It uses raw Ethernet packages to bypass the IP/UDP layer to communicate with the USRP2. Connect the USRP2 device and run the following commands

$ cd /usr/share/uhd/utils
$ sudo ./usrp2_recovery.py --ifc=eth0 --new-ip=192.168.10.3

- Reboot the USRP2 device

4.1 (Re)Load the UHD images on the SD-card (USRP2)

$ sudo apt-get install python-tk (Run only if you receive an Import Error below)
$ cd /usr/share/uhd/utils
$ sudo ./usrp2_card_burner_gui.py

Select either the separately downloaded image files (Appendix A, step 4) corresponding to the installed version of UHD or the image files contained within /usr/share/uhd/images.

- Insert the SD card that was supplied with the USRP2
- Select Firmware Image: /usr/share/uhd/images/usrp2_fw.bin
- Select FPGA Image: /usr/share/uhd/images/usrp2_fpga.bin
- Select Device: "If you specify the wrong device, you could overwrite the hard drive"
- Burn SD Card

4.2 (Re)Load the Images onto the On-board Flash (USRP N-series)

$ cd /usr/share/uhd/utils
$ sudo ./usrp_n2xx_net burner_gui.py

- Connect the USRP N-series device trough the Gigabit Ethernet interface
- Select Firmware Image: /usr/share/uhd/images/usrp_nxxx_fw.bin
- Select FPGA Image: /usr/share/uhd/images/usrp_nxxx_rx_fpga.bin
- Select Device
- Burn Images

Front Panel LEDs

The LEDs on the front panel can be useful in debugging hardware and software issues. The LEDs reveal the following about the state of the device:

LED A: Transmitting
LED B: Mimo cable link
LED C: Receiving
LED D: Firmware loaded
LED E: Reference lock
LED F: CPLD loaded

Reference Clock (10MHz) and Pulse Per Second (PPS)

Using an external 10MHz reference clock, a square wave will offer the best phase noise performance, but a sinusoid is acceptable. The reference clock requires the following power level:

USRP2 5 to 15dBm
N2XX 0 to 15dBm

Using a PPS signal for timestamp synchronization requires a square wave signal with the following amplitude:

USRP2 5Vpp
N2XX 3.3 to 5Vpp

You can test the PPS input with the following app

```
$ cd /usr/share/uhd/examples
$ ./test_pps_input
```

Changing the Buffer Size

Raise the TCP/IP buffer size in Ubuntu to prevent your computer from acting as a bottleneck for large transfer files across your network. To change the maximum values, run the below commands. Set the values permanently by editing /etc/sysctl.conf.

```
$ sudo sysctl -w net.core.rmem_max=<new value>
$ sudo sysctl -w net.core.wmem_max=<new value>
```

Appendix C: Installing R and the GNU Chirp Sounder Software

1. R Script

R (≥ 2.14) is required for the analysis and plotting part of the GNU Chirp Sounder. Download and install the corresponding (r-base-core_2.15) deb file that is supported by the used machine and operating system.

Click to download

```
r-base-core_2.15.0-1oneiric0_amd64.deb   31-Mar-2012 15:23
r-base-core_2.15.0-1oneiric0_i386.deb    31-Mar-2012 15:08
r-base-core_2.15.0-1precise0_amd64.deb   31-Mar-2012 15:23
r-base-core_2.15.0-1precise0_i386.deb    31-Mar-2012 15:38
```

Open a terminal and type

```
$ sudo R
> install.packages("fields")
> install.packages("lattice")
```

[11] R-Project Official Page: www.r-project.org
[12] Download R for Linux: http://ftp.sunet.se/pub/lang/CRAN/

2. GNU Chirp Sounder (gcs)

The GNU Chirp Sounder (gcs) is developed and maintained by Juha Vierinen. To download the released code, click either on the file below or follow the official webpage [13].

Click to download

sgo-chirp-rec-0.23.tar.gz.

Open a terminal and type

```
$ cd $(srcdir)                          (File: sgo-chirp-rec-)
$ ./configure
$ make
$ sudo make install
$ sudo R CMD INSTALL physconstr         (Custom R package)
$ sudo R CMD INSTALL stuffr             (Custom R package)
```

After the installation is completed you might have to run "**sudo ldconfig**".

[13] GNU Chirp Sounder: http://www.sgo.fi/~j/gnu_chirp_sounder/

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