Introduction to Software Defined Radio

(SDR 101)

SAARS - 3/7/2023

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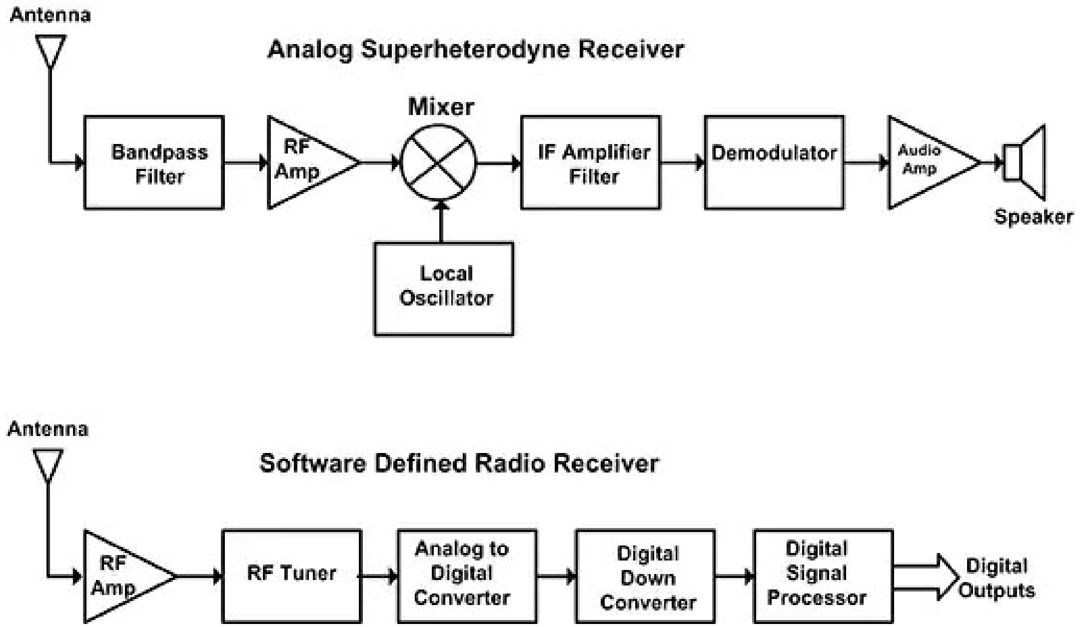
About me

- Born and raised in Italy
- Laurea degree (MSEE) and PhD in Electrical Engineering from University of Bologna
- Author of several IEEE papers and conference talks about Semiconductor Devices
- Married and living in St Johns (Jacksonville) since 1997
- Licensed in 2003
- Been playing, writing code for SDRs since 2017

What is a Software Defined Radio (SDR)

- A Software Defined Radio is a radio where all (or some) of the 'radio' work (mixers, filters, demodulators, etc) is done in software instead of hardware
- The basic idea is to convert the signal (from the antenna for RX, from the microphone for TX) to 'numbers', and then let the software/computer work on those numbers

Traditional RX (Superheterodyne) vs SDR

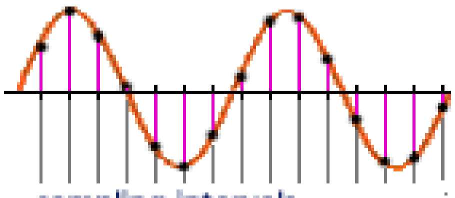


https://www.digikey.com/en/articles/learn-the-fundamentals-of-software-defined-radio

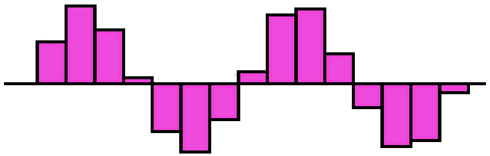
SDR Concepts

SDR Concepts – analog vs digital

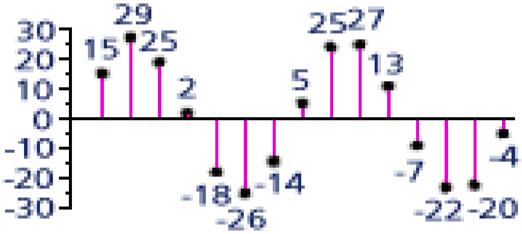
analogue signal



digital signal



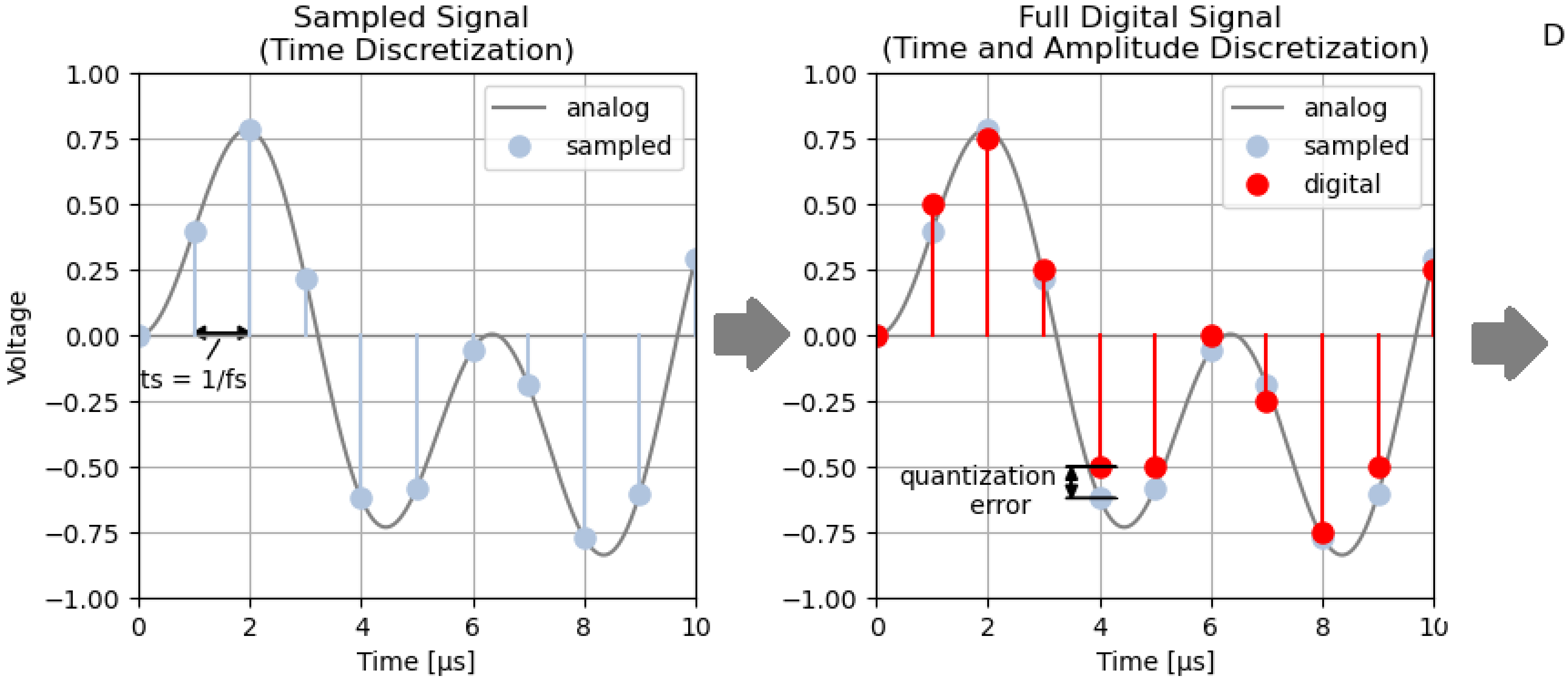
digital representation of signal



15 29 30 2 -18 -26 -14
5 25 27 13 -7 -22 -20 -4

https://www.sfu.ca/~gotfrit/ZAP_Sept.3_99/d/digital.html

SDR Concepts – Analog Digital Converter (ADC)



Digital Signal

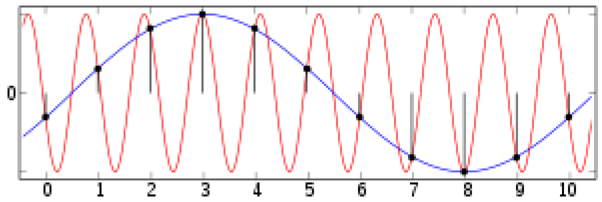
0.00
0.50
0.75
0.25
-0.50
-0.50
0.00

fs = 1 MHz

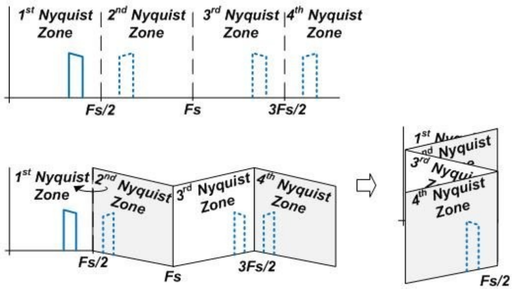
https://panoradio-sdr.de/analog-digital-conversion/

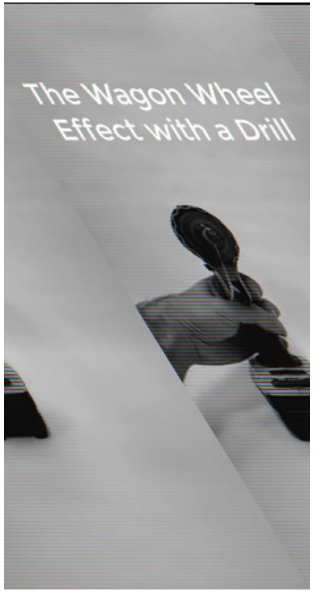
SDR Concepts – Sampling and Aliasing

- The Wagon Wheel effect
- Aliasing



- Nyquist zones

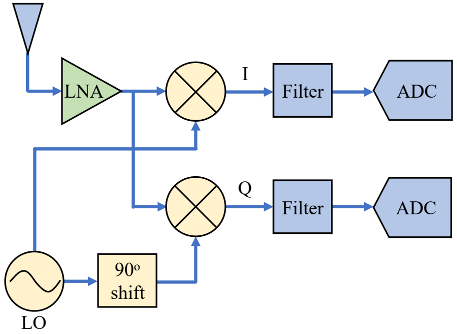




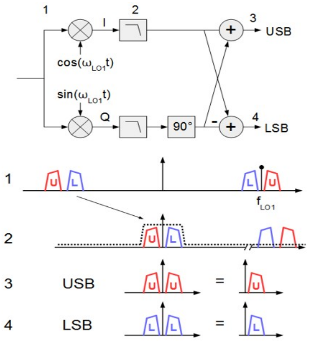
Credit: Science Buddies YouTube channel

SDR Concepts – I/Q (+ a tiny bit of complex numbers)

I/Q (in phase and quadrature)



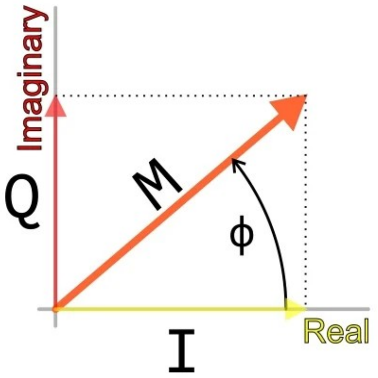
SSB demodulation



Complex numbers – magnitude and phase

$$M=\sqrt{I^2+Q^2}$$

$$\phi=\tan^{-1}\left[\frac{Q}{I}\right]$$



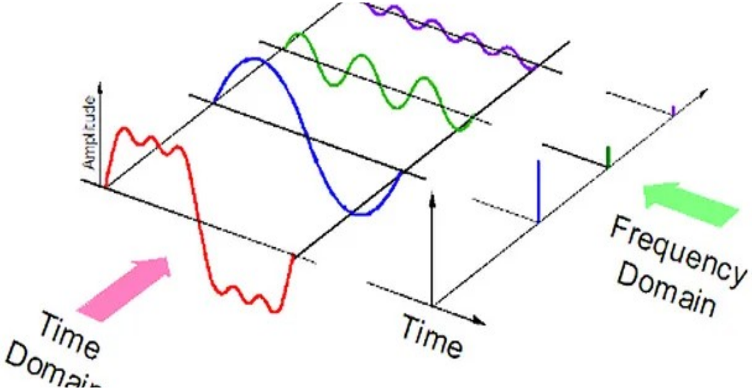
- AM demod = Magnitude (M)
- FM demod = Change in phase (φ) over time

SDR Concepts – Digital Signal Processing (DSP)

- Digital Signal Processing is the field of engineering and computer science that studies how to work with digital signals (i.e. streams of numbers)
- Using DSP we can create the digital equivalents of:
  - filters (Finite Impulse Response, Infinite Impulse Response)
  - mixers (frequency shifting)
  - demodulators
  - noise removers, noise blankers, equalizers, etc
- 99% of DSP operations is just add (+) and multiply (x)

SDR Concepts – Fourier Transform (FT & FFT)

- Fourier Transform (FT) is the mathematical equation/method of transforming a signal from the time domain to the frequency domain

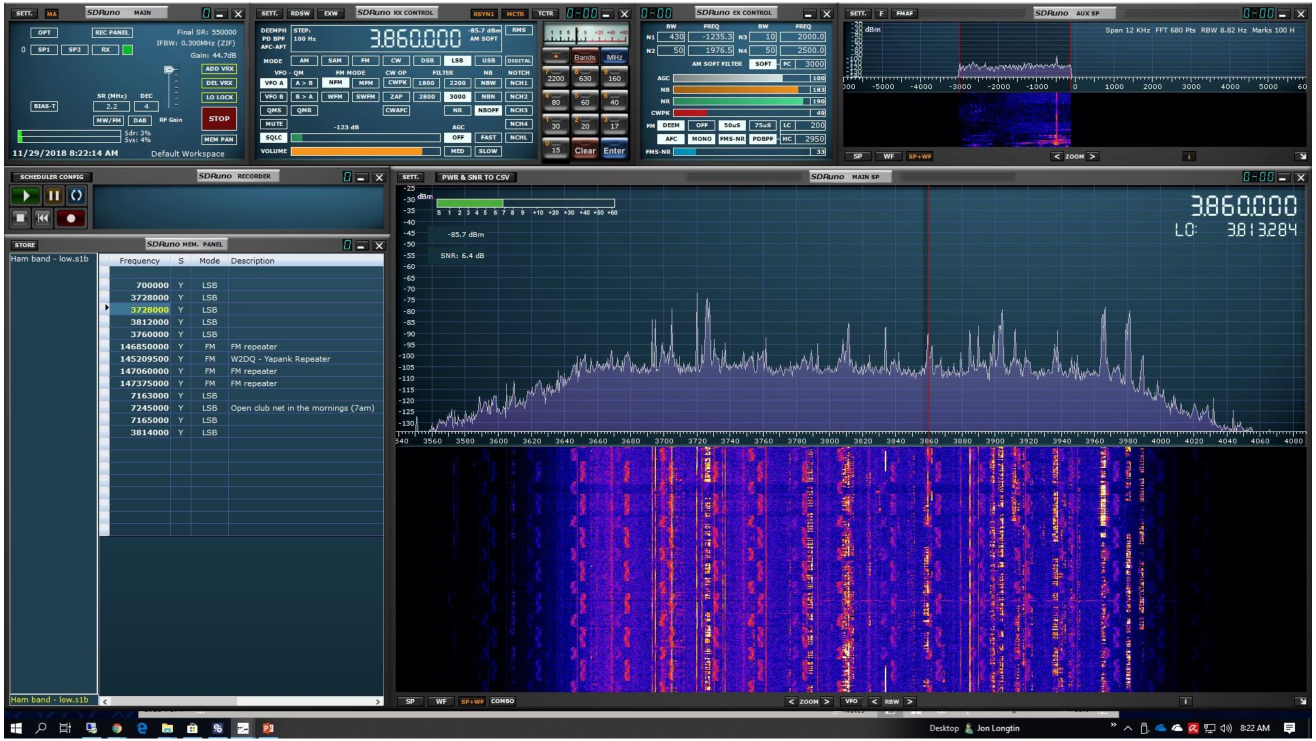


- In 1965 Cooley and Tukey (re)discovered a very efficient way to compute the FT, known as the Fast Fourier Transform (FFT)
- Without FFT we probably wouldn't have SDRs!

Why SDR?

Why SDR? - See signals with your eyes

Frequency spectrum and waterfall

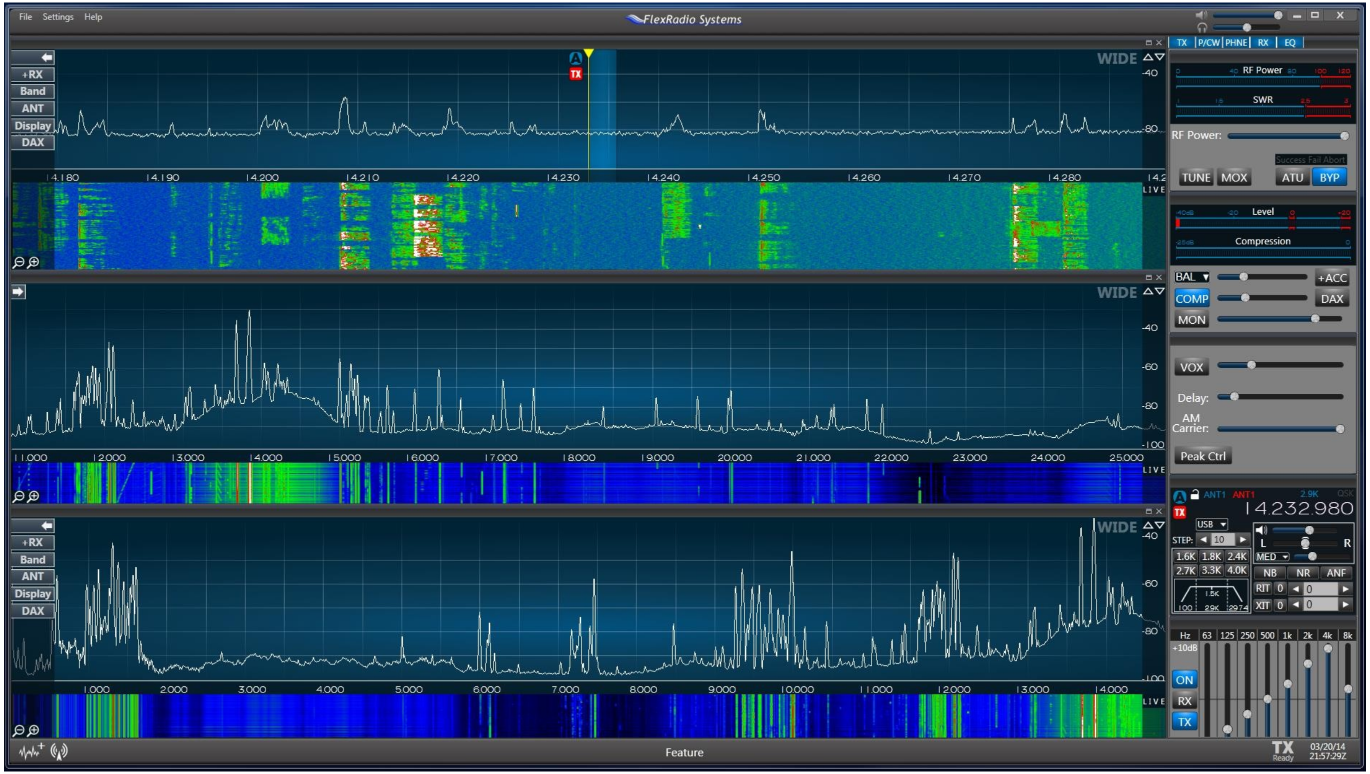


Why SDR? - Multiple receivers for free

20m

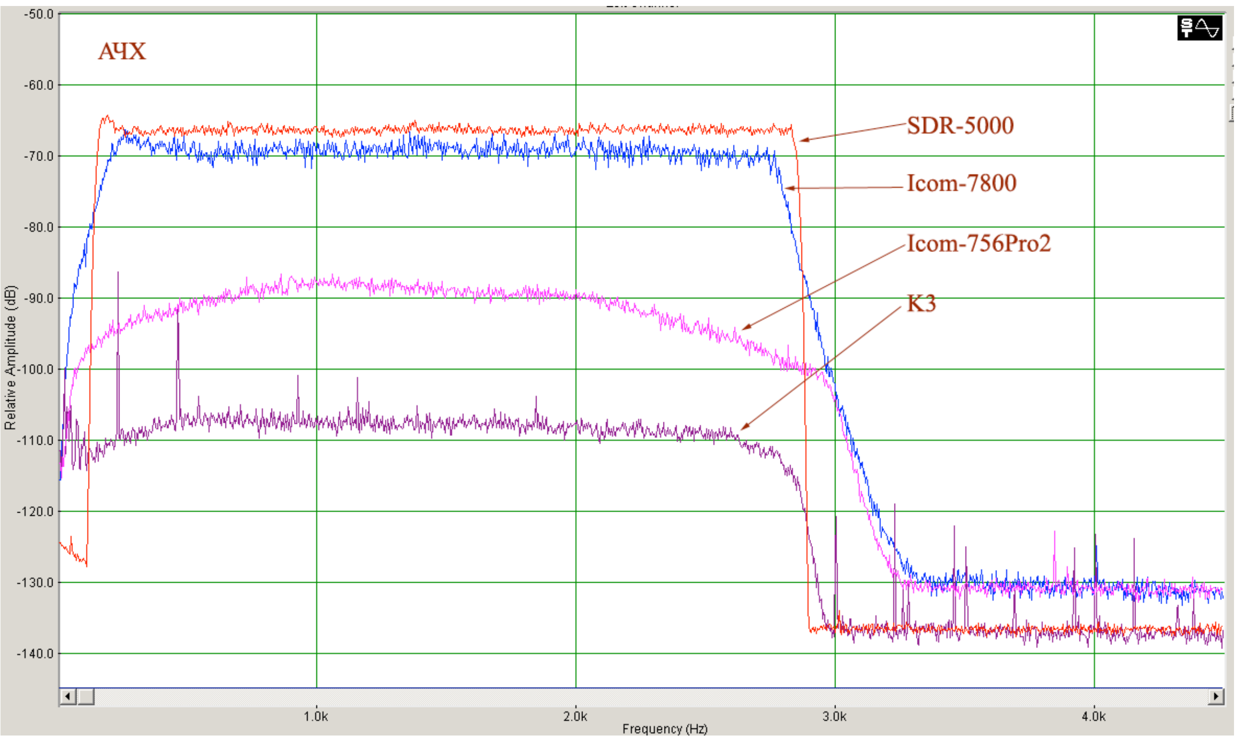
11-25MHz

0-14MHz



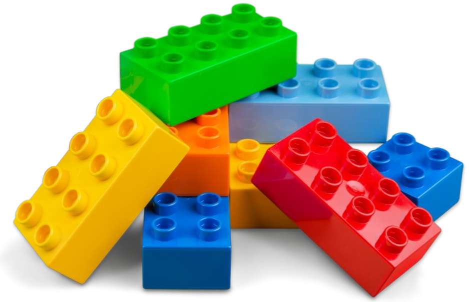
Why SDR? - ‘brick-wall’ filters

Flex SDR-5000 2.8kHz SSB filter



Why SDR? - Flexibility and versatility

- **In a SDR all the parts written in software can be easily changed and upgraded:**
  - new and better filters
  - new modulation schemes (for instance with a traditional radio it is not possible to add SSB to a FM only radio)
  - radio controls (buttons, knobs) can be changed to better fit the usage
  - less obsolescence
  - greater scope for experimentation



Why SDR? - record whole band(s) now; tune later

- With an SDR it is possible to write to a file the raw I/Q recording of a whole band (or multiple bands depending on the sample rate of the SDR)
- Days, months, years later one can ‘play’ that recording to tune and demodulate signals as if they were there at the time the recording was taken

Why SDR? - Diversity reception

- Diversity reception combines the signals from two synchronized receivers (connected to two different antennas)
- Can be used for local noise cancellation

Why SDR? - Other advantages

- No need for sound cards interfaces
- Very flexible using virtual audio cables (VACs)
- Remote operation out of the box
- Lighter and more portable than a traditional radio

Why SDR? - Caveats

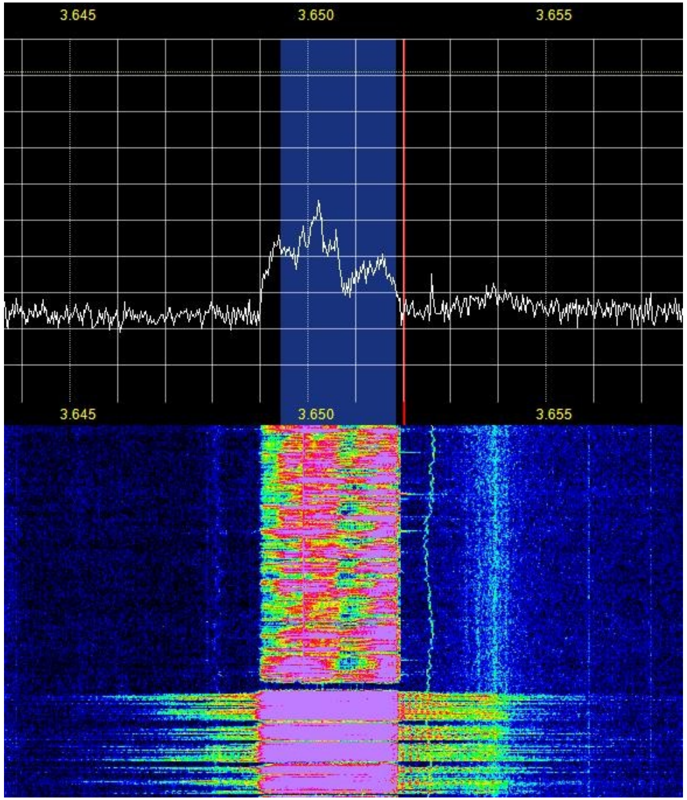
- **Real ones:**
  - Lack of physical controls (knobs, buttons, etc) – but one can add them (e.g. Tmate 2)
  - Latency (both intrinsic and due to buffers) – but see WDSP by Warren Pratt, NR0V
  - ADC overflow → heavy distortion (RF gain is important)
- **Not really (or no longer) a problem:**
  - Requires a computer (c’mon it’s 2023!)
  - Cost (true perhaps 10 years ago; not any more)
  - Learning curve (but the same can be said of many radios)

Why SDR? - They can help with TX too!

- According to Rob Sherwood NC0B: "Receivers today have vastly improved. Transmitters have gotten worse!"
- SDR "adaptive pre-distortion" systems like PureSignal can help clean up the TX signal (especially with PA)

Apache with Pure Signal

Kenwood



Why SDR? - if you want to...

- Receive TV and Radio in areas where DVB and DAB are present.
- Receive amateur television transmissions.
- Listening to unencrypted Police/Ambulance/Fire/EMS conversations.
- Listening to aircraft traffic control conversations.
- Tracking aircraft positions like a radar with ADS-B decoding.
- Decoding aircraft ACARS short messages.
- Scanning trunking radio conversations.
- Decoding unencrypted digital voice transmissions.
- Tracking ship movement with AIS decoding.
- Decoding POCSAG/FLEX pager traffic.
- Scanning for cordless phones and baby monitors.
- Tracking and receiving meteorological agency launched weather balloon data.
- Receiving HF weatherfax.
- Receiving NOAA weather satellite images.
- Monitor amateur frequencies
- APRS Rx Gateway

Credit: Grant Hopper KB7WSD - SDR Radio Dongles

Why SDR? - if you want to...

- Noise Sniffer
- Tracking your own self launched high altitude balloon for payload recovery.
- Receiving wireless temperature sensors and wireless power meter sensors.
- Listening to HF/VHF/UHF/Microwave amateur radio.
- Oh, and LF now too!
- Decoding APRS data.
- Watching Digital Amateur TV.
- Sniffing GSM signals.
- Using rtl-sdr on your Android device as a portable radio scanner.
- Receiving GPS signals and decoding them.
- Receiving Inmarsat transmissions
- Using rtl-sdr as a spectrum analyzer.
- Listening to satellites and the ISS.
- Receiving Outernet transmissions
- Radio astronomy.
- Monitoring meteor scatter.

Credit: Grant Hopper KB7WSD - SDR Radio Dongles

Why SDR? - if you want to...

- Decoding satellite message traffic
- Cross band repeater
- WSPR signal reception.
- FUNCube Satellite monitoring.
- Listening to FM radio, and decoding RDS information.
- Listening to and looking at DAB broadcast radio signals.
- Use rtl-sdr as a panadapter for your traditional hardware radio.
- Decoding taxi mobile data terminal signals.
- Use rtl-sdr as a high quality entropy source for random number generation.
- Use rtl-sdr as a noise figure indicator.
- Reverse engineering unknown protocols.
- Triangulating the source of a signal (RDF).
- Searching for RF noise sources.
- Characterizing RF filters and measuring antenna SWR.
- Decoding digital amateur radio ham communications such as CW/PSK/RTTY/SSTV.
- Receiving Digital Radio Mondial shortwave radio (DRM).

Credit: Grant Hopper KB7WSD - SDR Radio Dongles

Why SDR? - if you want to...

- Listening to international shortwave radio.
- Looking at RADAR signals
- Decoding telemetry
- Over the horizon (OTH) radar, HAARP
- Detecting Meteor ‘echos’
- Monitoring the local RF environment
- Detecting and deciphering digital RF transmissions
- Decoding keyfob transmissions
- Examining DECT transmissions
- Glider tracking as part of the Open Glider Network
- Examining Rail Road data transmissions
- Listening to smart meter transmissions
- Detecting wireless doorbell transmissions
- Monitoring 2.4GHz wireless video transmissions
- ...just to start the list

Credit: Grant Hopper KB7WSD - SDR Radio Dongles

SDR Architectures

SDR Architectures – Direct Sampling

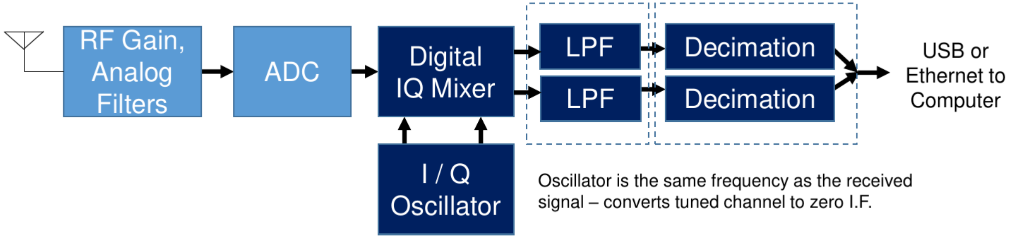
A Simple Digital SDR

- Why Not ?
  - Let's say … DC ~ 6 meters.
  - Spurious Free Dynamic Range ~ 100 dB. LTC2208 ADC 16 bits.
  - Nyquist criteria: Fsample > 2 * maximum frequency.
    - Fsample > 54 MHz * 2 = 108 Ms/s.
    - Common sample rate: 122.88 Ms/s (harmonically related to 48K).
  - 16 bits * 122.88 MHz = 1.966 Gigabits / second to the computer.
  - Add in IP & Ethernet overhead: 3 x Gigabit Ethernet, or 1 x 10GE.
  - It's a FIREHOSE !!
    - Whoa ! Gulp. Help. Open the pod bay doors, HAL.

Credit: Tom McDermott N5EG – SDR from DC to (almost) Daylight

SDR Architecture – Direct conversion

2. Homodyne Digital SDR Receiver

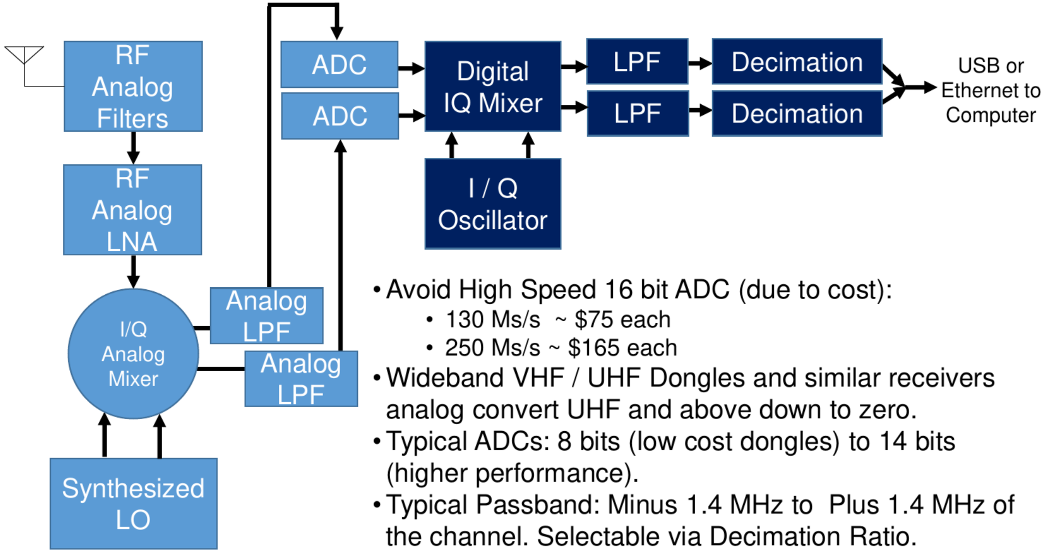


- Essentially a Direct-Conversion receiver.
- Down convert R.F. to Zero I.F. (Open HPSDR, Flex 6000, many others).
  - SSB & CW don't require demodulation – filter, decimate, and send to speaker.
    - Need a way to reject opposite sideband (negative frequencies):
      - Weaver method, Complex Filter method, Phasing method (Hilbert).
  - FM requires demodulation, AM usually best when demodulated.
- Typical Passband: Minus 192 KHz to Plus 192 KHz. of the channel. Selectable via Decimation Ratio.
- Typical ADC: 14 or 16 bits. Baseband is ~24 bits (achieved via decimation).
- Very high opposite sideband rejection without adjustment.
- I/O to Computer: 384 Ksps → about 19 Megabits/sec

Credit: Tom McDermott N5EG – SDR from DC to (almost) Daylight

SDR Architectures: Hybrid conversion

3. Hybrid Conversion SDR Receiver



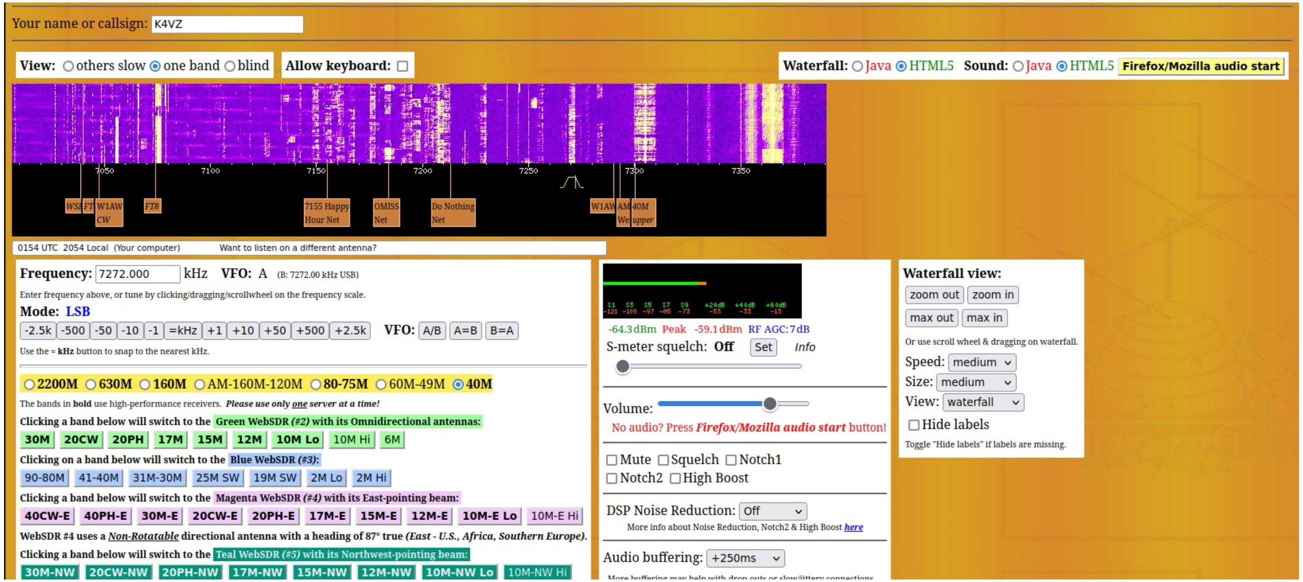
- Avoid High Speed 16 bit ADC (due to cost):
  - 130 Ms/s ~ $75 each
  - 250 Ms/s ~ $165 each
- Wideband VHF / UHF Dongles and similar receivers analog convert UHF and above down to zero.
- Typical ADCs: 8 bits (low cost dongles) to 14 bits (higher performance).
- Typical Passband: Minus 1.4 MHz to Plus 1.4 MHz of the channel. Selectable via Decimation Ratio.
- Used for coherent high-data-rate optical fiber (optical mixing and DSP) [Almost Daylight]

Credit: Tom McDermott N5EG – SDR from DC to (almost) Daylight

Let’s do SDR!

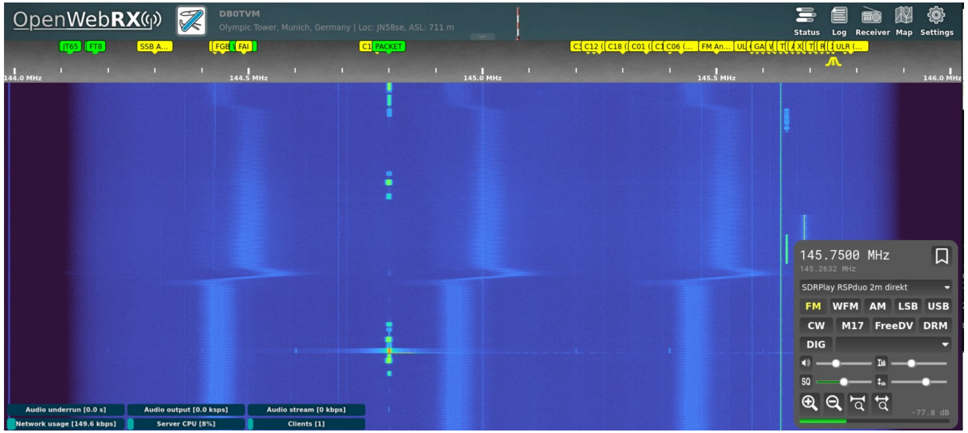
Let’s do SDR! - $0 - Web SDRs

- Web SDRs are a very easy way to get started with SDRs at no cost; just open your browser, click on the station and listen
- The mother of all Web SDRs: http://websdr.ewi.utwente.nl:8901/
- Northern Utah WebSDR: http://www.sdrutah.org/

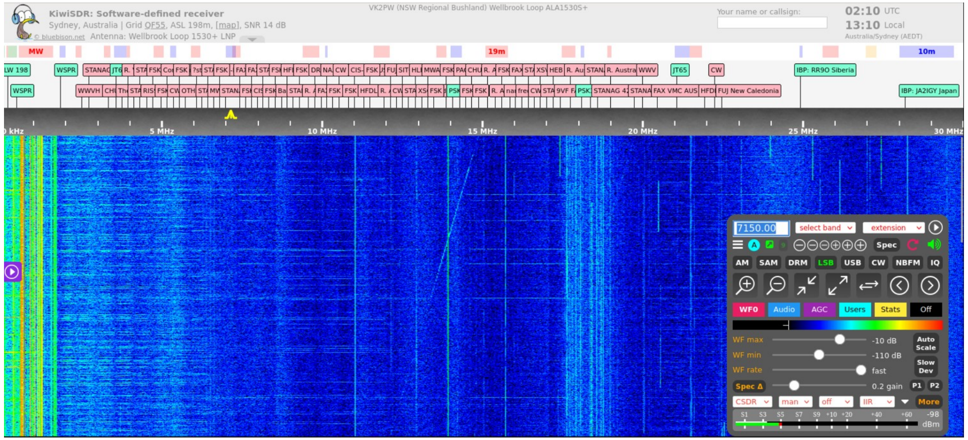


Let’s do SDR! - $0 – more WebSDRs

OpenWebRX
https://www.receiverbook.de/



KiwiSDR
http://kiwisdr.com/public/



Let’s do SDR! - $30-100 – RTL-SDR (USB dongle)

- very inexpensive (starts from about $30)
- based on DVB-T/DAB receiver on a USB dongle
- 24MHz - 1766MHz (HF with upconverter)
- 8bit resolution
- very popular
- lots of clones
- KrakenSDR uses 5 RTL-SDR ‘phase coherent’

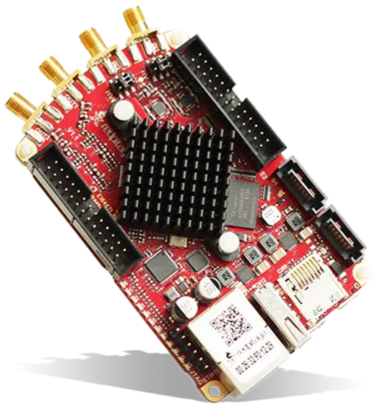
Let’s do SDR! - $100-300 – SDRplay, Airspy, etc

- **SDRplay RSPs:**
  - 1kHz – 2GHz
  - sample rate up to 10MHz
  - resolution up to 14bit
  - good RF filters (per band)
  - AM notch, FM notch
  - multiple antenna ports
  - good as a panadapter
  - RSPduo is dual tuner

- **Also consider:**
  - Airspy HF+ Discovery
  - Analog Devices Adalm Pluto
  - HackRF One
  - RX888 MkII

Let's do SDR! - $500-5000+ – bladeRF, Red Pitaya, Perseus, USRP, etc

- Direct sampling
- 16bit 125Msps ADC
- FPGA for Digital Down Conversion
- Multiple channels
- Can be very specialized
- Used in industry and academia
- Used by radio amateurs too!



Let’s do SDR! - SDR Transceivers - FlexRadio

FLEX-6400M ($3450)

FLEX-6400 ($2300)

FLEX-6700 ($7500)

Let’s do SDR! - Transceivers – Apache Labs

ANAN-8000DLE ($3800)

ANDROMEDA ($4400)

Let’s do SDR! - Icom

IC-7300 ($1100)

IC-705 ($1350)

IC-7610 ($3250)

Let’s do SDR! - Yaesu

FTDX101D ($3700)

FT710 AESS ($1050)

Let’s do SDR! - Elecraft

K4 ($4500)

Let's do SDR! - Hermes Lite 2

- Fully open source
- Reasonably priced ($300)
- Direct up/down conversion
- AD9866 + FPGA
- 0-38MHz
- 5W out
- 4 slice receivers

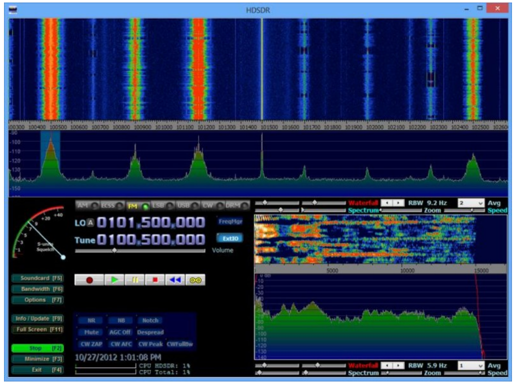
Let’s do SDR!
Software

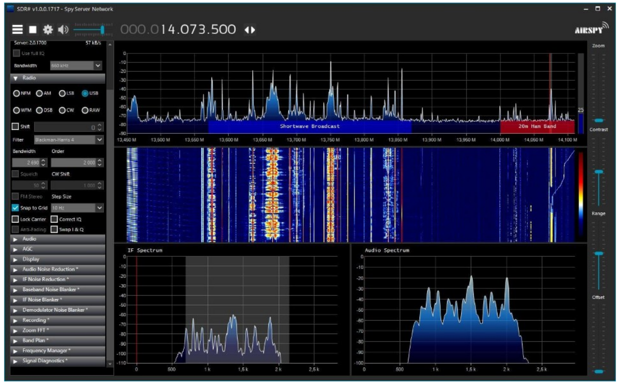
SDR Software - Windows

SDRuno

SDR Console

HDSDR

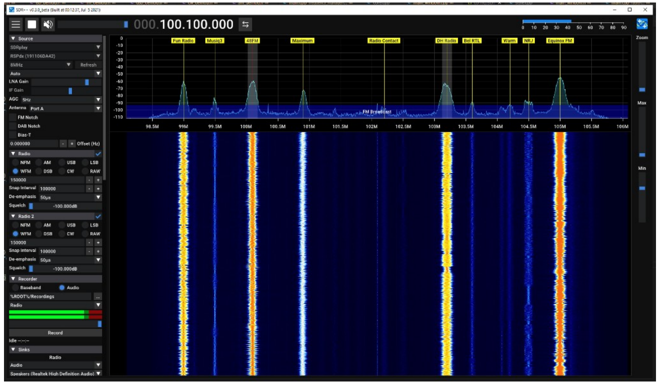


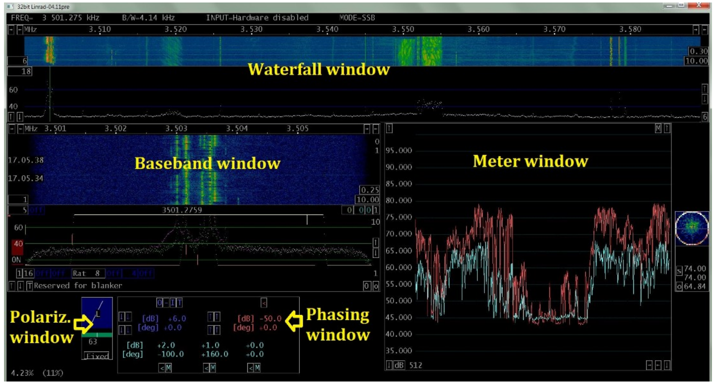


SDRSharp

SDR Software – Multiplatform (Windows, Mac, Linux)

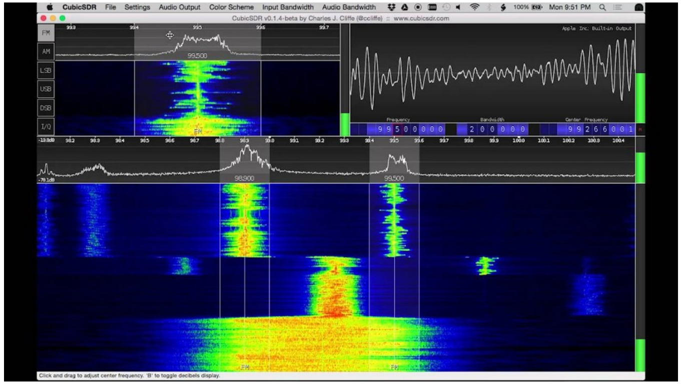
SDR++

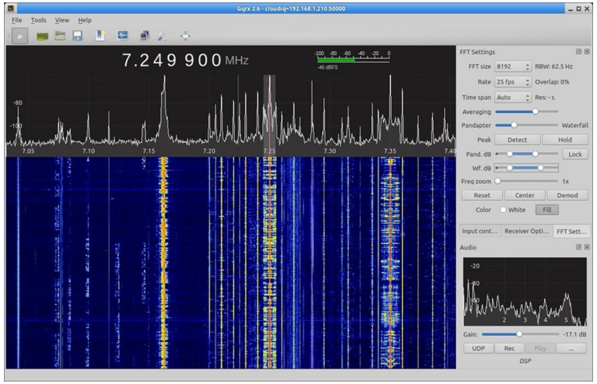




Linrad

CubicSDR

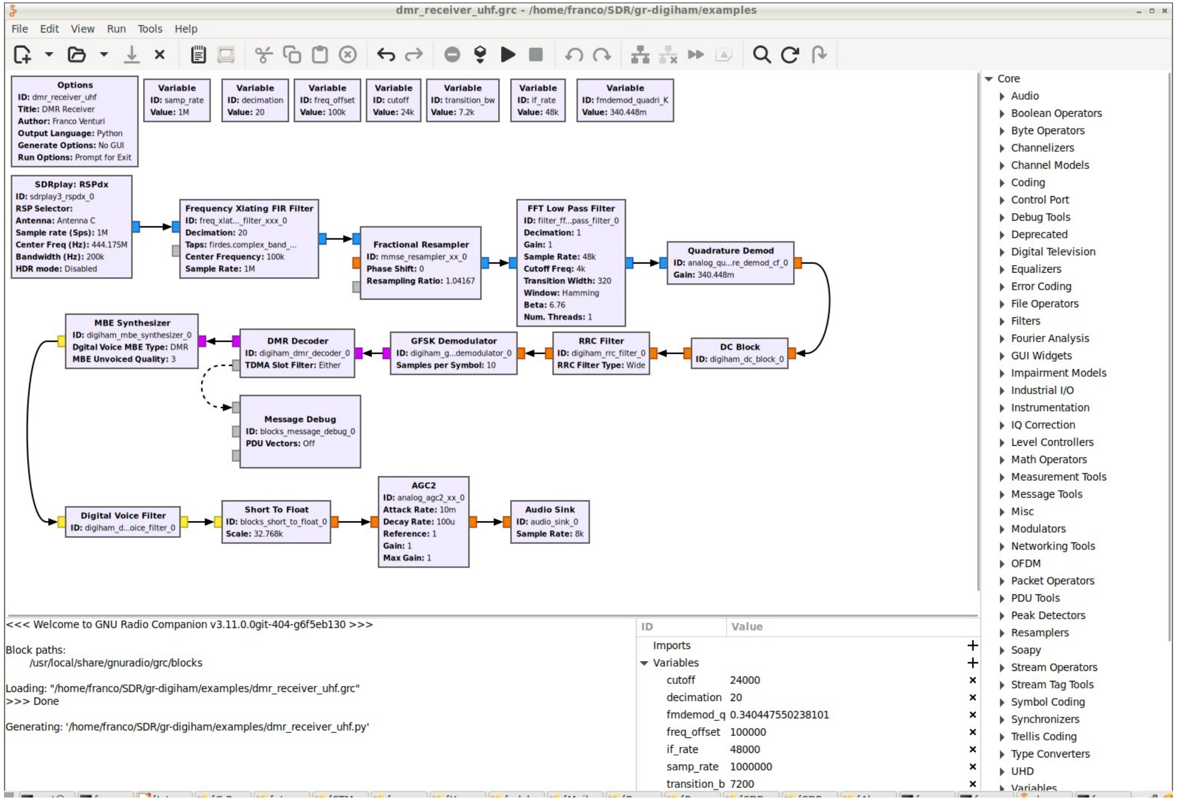




Gqrx

SDR Software – Build your own SDR!

GNU Radio



Live demo with SDRuno and RSPdx

Q&A

References

References – To learn more on SDR

- **SDR**
  - Marc Lichtman - PySDR: A Guide to SDR and DSP using Python - https://pysdr.org/index.html
  - Michael Ossman - Software Defined Radio with HackRF (videos) - https://greatscottgadgets.com/sdr/
  - Art Pini - Learn the Fundamentals of Software-Defined Radio - https://www.digikey.com/en/articles/learn-the-fundamentals-of-software-defined-radio
  - Panoradio SDR - SDR Basics - https://panoradio-sdr.de/category/sdr-basics/
  - Analog Devices - Software-Defined Radio for Engineers (2018) - https://www.analog.com/en/education/education-library/software-defined-radio-for-engineers.html
- **DSP**
  - Richard Lyons - Quadrature Signals: Complex, But Not Complicated - https://dspguru.com/files/QuadSignals.pdf
  - W2AEW - Basics of IQ Signals and IQ modulation & demodulation - A tutorial (video) - https://youtu.be/h_7d-m1ehoY
  - All About Circuits - Understanding Quadrature Demodulation - https://www.allaboutcircuits.com/textbook/radio-frequency-analysis-design/radio-frequency-demodulation/understanding-quadrature-demodulation/
  - Steven W. Smith - The Scientist and Engineer's Guide to Digital Signal Processing - http://www.dspguide.com/
- **Mentioned in tonight presentation**
  - RJ Hopper - RF sampling: aliasing can be your friend - https://e2e.ti.com/blogs_/b/analogwire/posts/rf-sampling-aliasing-can-be-your-friend
  - Rob Sherwood NC0B - Transceiver Performance for the HF DX & Contest Operator - https://www.slaarc.com/wp-content/uploads/2021/04/NC0B-SLAARC-1m.pdf
  - Warren C. Pratt NR0V - WDSP 2018 - What's new (video) - https://youtu.be/THPjQV3I81g

References – Presentations on SDR

- John Ackermann N8UR - TAPR: Tomorrow's Ham Radio Technology Today - https://www.febo.com/hamdocs/TAPR-MVUS-Presentation.ppt
- Loren Anderson KEØHZ - Software Defined Radios; Getting Started With SDR - https://w0tlm.com/sites/default/files/2022-12/SDR221121Final.pdf
- Jeffrey Bail NT1K - SDR & Flex Radio; Is It The Future Of Amateur Radio? - http://www.hcra.org/wp-content/uploads/2022/02/SDR-and-Flex.pdf
- Alan Betts G0HIQ - Syllabus 2019: Model Tutorial for Digital and SDR extracts (for Foundation, Intermediate and Full licences) - https://rsgb.services/public/exams/presentations/190329%20SDR%20Model%20Presentation%20Slides%20-%20Website.pptx
- Steven Bible N7HPR - Introduction to Software Defined Radios - https://www.qsl.net/n9zia/sdr.pdf
- Bill Craft KD2HIQ - Software Defined Radios - https://w5sc.org/wp-content/uploads/2023/01/SDR-RX-only.pdf
- Steve Dick K1RF - Software Defined Radio (SDR) for Amateur Radio - An Overview - http://gnarc.org/wp-content/uploads/2015/02/Software-Defined-Radio-SDR-for-Amateur-Radio-2015-02-11.pdf
- Lior Elazary KK6BWA - Introduction to Software Defined Radio (SDR) - http://www.cvarc.org/resources/Tech_Articles/IntroToSDR.pdf
- Andrew Gawthrope G0RVM - SDR - https://www.tsgarc.uk/wp-content/uploads/2016/08/sdr1.pdf
- Don Gibson KJ6FO- Software Defined Radio - SDR - http://squirrelengineering.com/wp-content/uploads/2020/02/Software-Defined-Radio.pptx
- Brandon Graham W0GPR - Software Defined Radio (SDR) and its Implementation - https://fb3d1a95b6.clvaw-cdnwnd.com/03aea700bf1764bea2c547f0b88a7406/200000440-2f90b308e9/SDR%20Presentation%20Brandon%20Graham%20W0GPR%20Feb%202015.pptx

References – Presentations on SDR

- Grant Hopper KB7WSD - SDR Radio Dongles - https://microhams.blob.core.windows.net/content/2017/03/RTL-SDR-dongle.pdf
- Ria Jairam N2RJ - SDR 101 - https://www.dropbox.com/sh/u8a9q5ifmz00oxx/AAC9n5gxzkr82grvJmkCgpXIa/SDR-101%20Presentation.pdf
- Gerry Jurrens N2GJ - Getting Started With SDR - https://www.nm5hd.com/documents/PRESENTATIONS/20190420_SDR_Presentation.pdf
- Jon Longtin KB8LFP - SDR Radios: One Ham's Perspective - http://www.rcarc.org/presentations/W2RC%20SDR%20Jan%202019%20presentation.pdf
- Lyle K0LR - Software Defined Radio - http://www.radioham.org/radioham_files/wp-content/uploads/2015/04/SARA-SDR.pdf
- Ben Matthews - Practical SDR With OpenWebRx - https://www.rmham.org/wp-content/uploads/2022/04/PracticalSDR.pdf
- Tom McDermott N5EG - SDR from DC to (almost) Daylight - https://web.tapr.org/~n5eg/index_files/SDR%20from%20DC%20to%20Daylight.pdf
- John Melton G0ORX/N6LYT - High Performance Software Defined Radio (HPSDR) - http://oshug.org/presentations/OSHUG5_HPSDR.pdf
- Owen Morgan KF5CZO - Software Defined Radio - https://www.katyars.com/wp-content/uploads/2018/08/Software-Defined-Radio-Presentation.pdf
- Gordie Neff N9FF - Software Defined Radio Primer + Project - https://w4cae.com/wp-content/uploads/2016/03/SDR_Presentation_Final_Neff_CARC_Mar_2016-1.pdf

References – Presentations on SDR

- Niko AA2NI - SDR, HDSDR & CW Skimmer SoftRock Ensemble II Receiver - https://www.bara.org/wp-content/uploads/2014/10/AA2NI_SDR_Presentation.pdf
- Jon Pawlik AE2JP - Software Defined Radio: State-of-the-Art & State-of-the-Future - https://nparc.org/2014/Presentations2014/SDR_SOTAandSOTF.pdf
- Cliff Pulis KE0CP - Software Defined Receiver (SDR) - https://kc5our.com/wordpress/wp-content/uploads/2013/03/Software-Defined-Receiver.pdf
- Rob Sherwood NC0B - Disruptive Technologies; How they change our hobby - https://www.contestuniversity.com/wp-content/uploads/2017/06/NC0B_CTU_2017_Disruptive_Technologies_How_they_Change_our_Hobby.pptx
- Bill Trippett W7VP, Adam Farson VA7OJ/AB4OJ, Rob Sherwood NC0B - How important are receiver performance criteria in an era of software defined radios? - https://www.ab4oj.com/sdr/seapac17/sdrpres14.pdf
- Ryan Tucker W2XH - Exploring RF with Software Defined Radio - https://www.rochesterham.org/meetings/2015-12_SDR_Program.pdf
- Ethan Waldo KF5UFH - An Amateur's amateur guide to Software Defined Radio (SDR) - https://doc.lagout.org/electronics/AustinHams%20SDR.pdf
- Howard White KY6LA - Modern Radio's SDR-101 - https://wparc.us/presentations/Modern%20Radio%20SDR-101%20V1-2.pdf
- Tye Winkel KC8YEJ, John Oynoian KE8CTQ - Software Defined Radio (SDR) - http://www.k8utt.org/Presentations/Software_Defined_Radio%20_Overview_.pptx
- Steve Yothment W4OGM - Software-Defined Radio (SDR) - https://kk4gq.org/pdf/Software-Defined-Radio-W4OGM-March-2021.pdf