Mini-Workshop on Software Defined Radio using the RTL-SDR

IEEE Philadelphia Section

IEEE USA

IEEE Student Branch

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Mini-Workshop on Software Defined Radio using the RTL-SDR

- Signals and Systems
- I/Q Signals, SDR and the RLT-SDR
- Direct Conversion to Baseband
- RTL-SDR Hands-On and Applications
- Additional Topics

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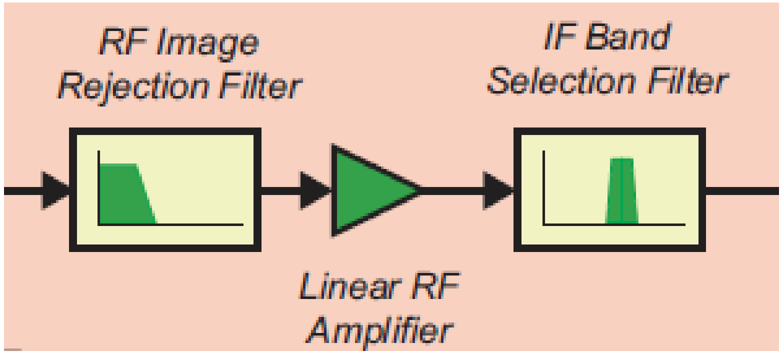
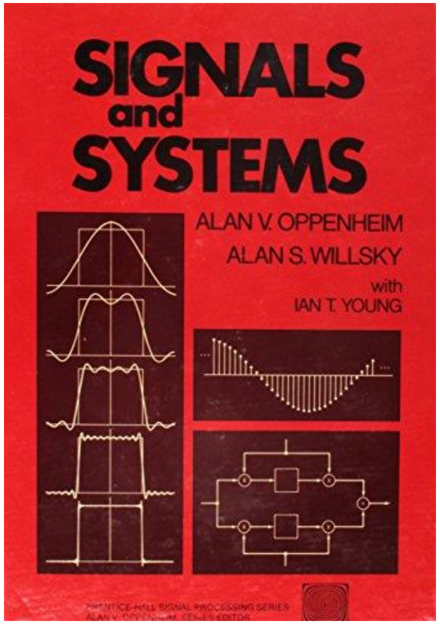
Mini-Workshop on SDR using RTL-SDR

The fundamentals of signals and systems are key to understanding communications and the Software Defined Radio (SDR). Basic operations include *linear* and *non-linear* signal processing using sinusoids.

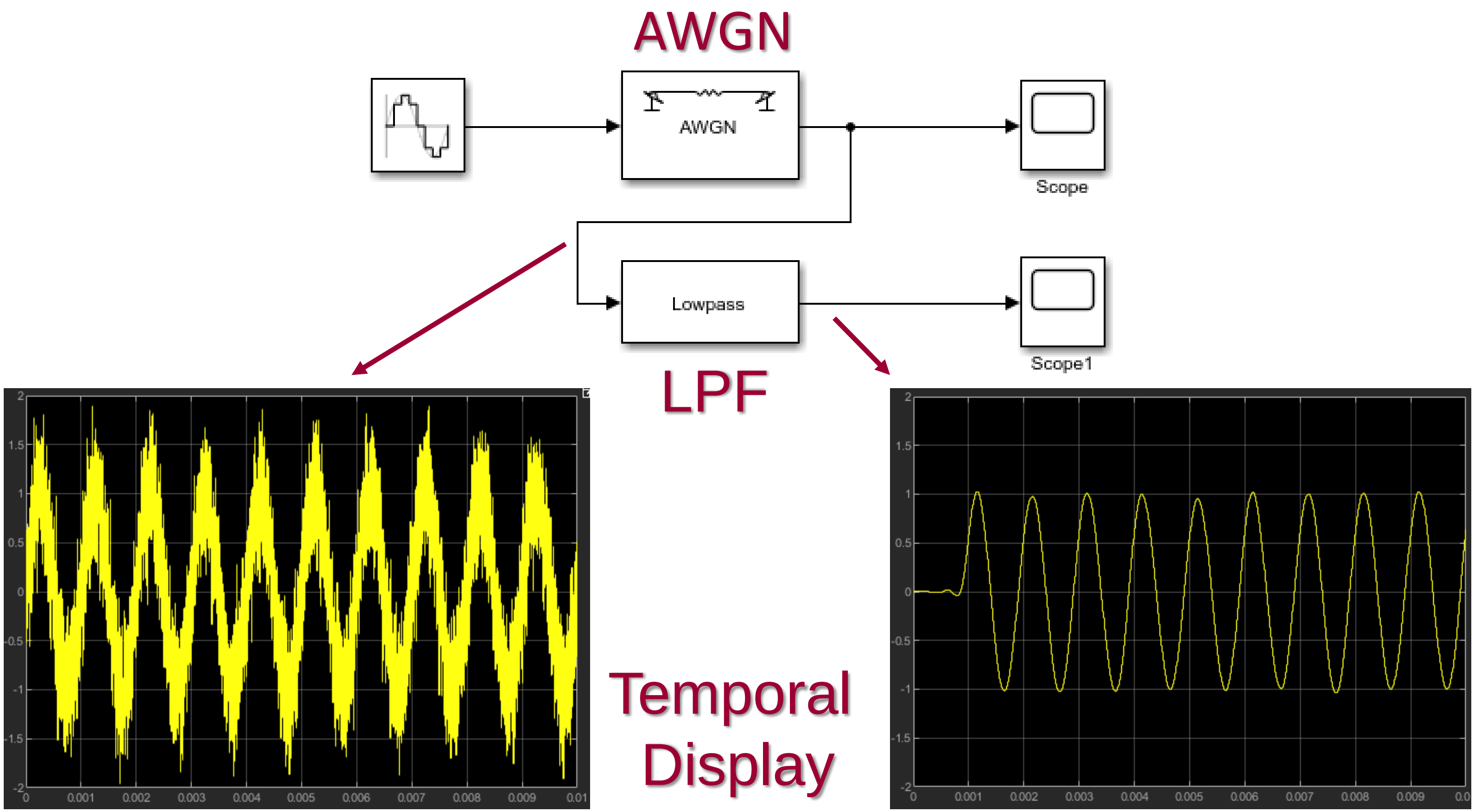
A *linear* operation for communications would be *filtering* in frequency within the range or *bandwidth* of the filter.





Mini-Workshop on SDR using RTL-SDR

Filtering in frequency within the bandwidth of the filter is shown here. A noisy 1 kHz sinusoid is processed by a *low pass filter* (LPF) in simulation using Simulink.



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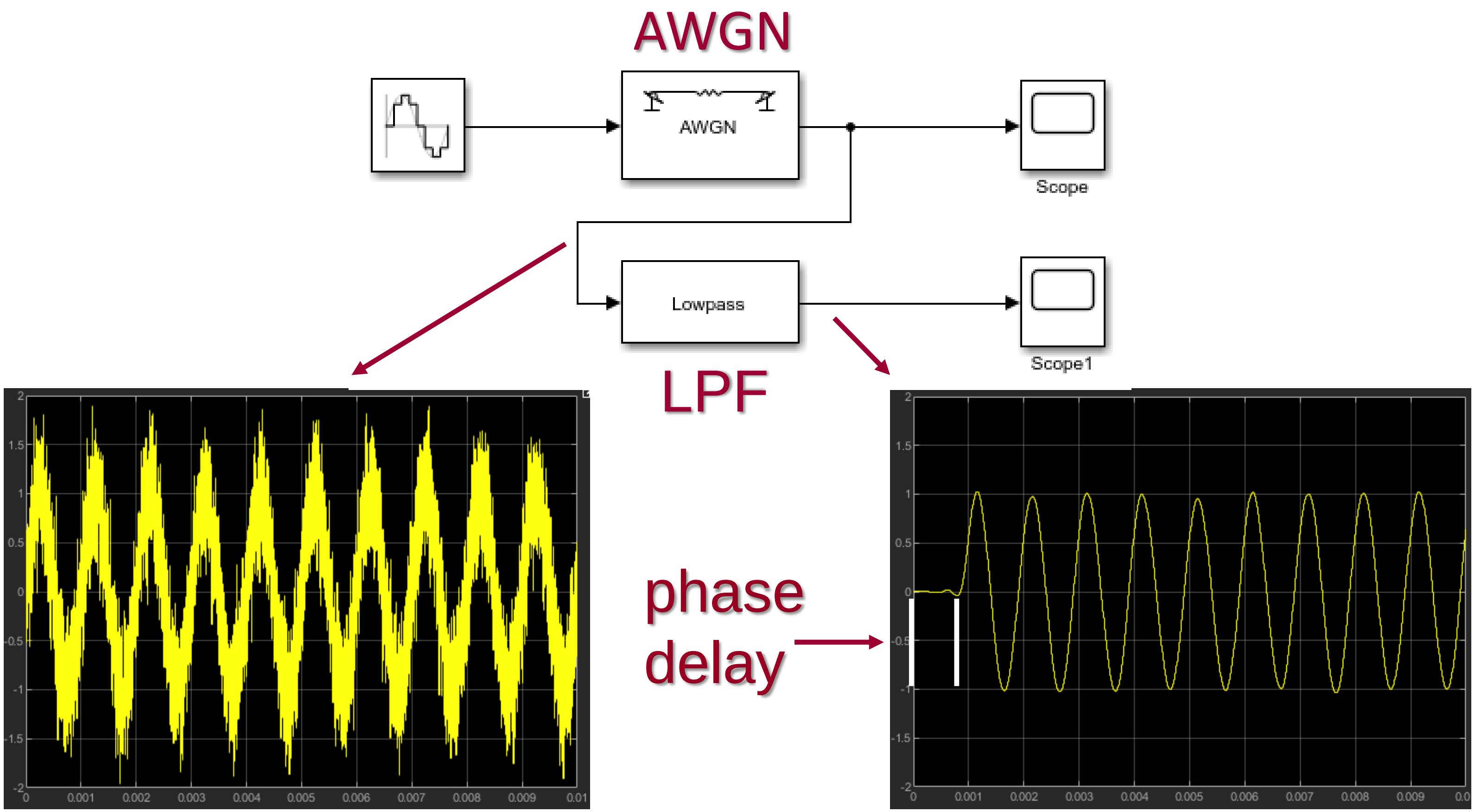
Two oscilloscopes (scope) display the input and output temporal signals. Note the *phase delay* of the output due to the LPF.



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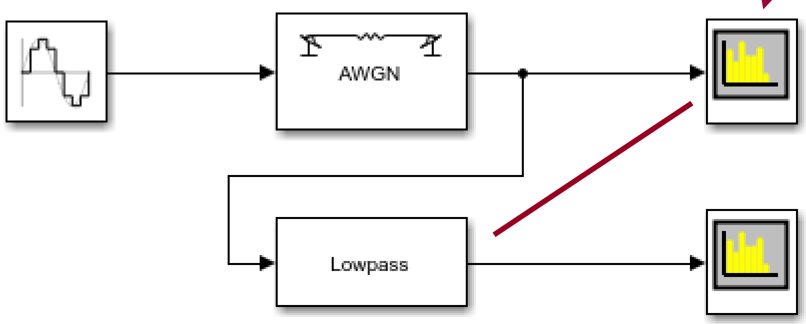
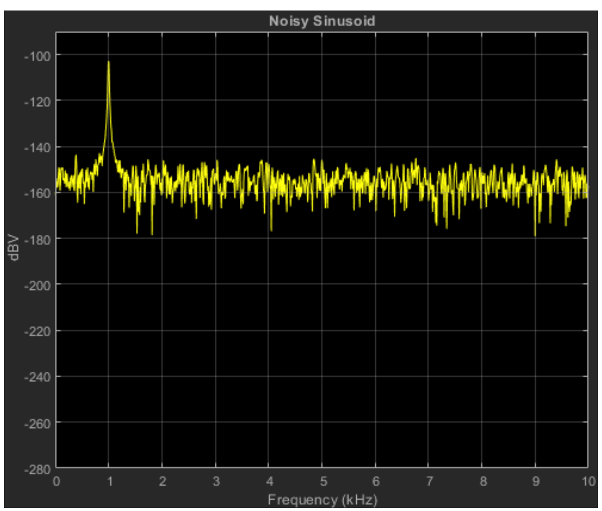
Replacing the temporal scopes with spectrum analyzers shows the frequency content.

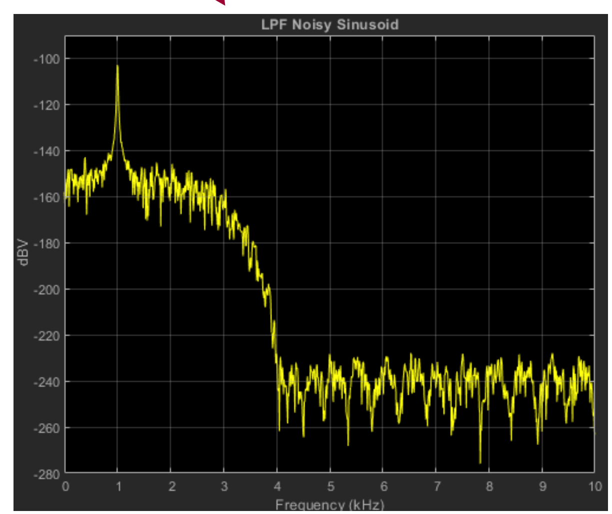
AWGN



LPF



Spectral Display



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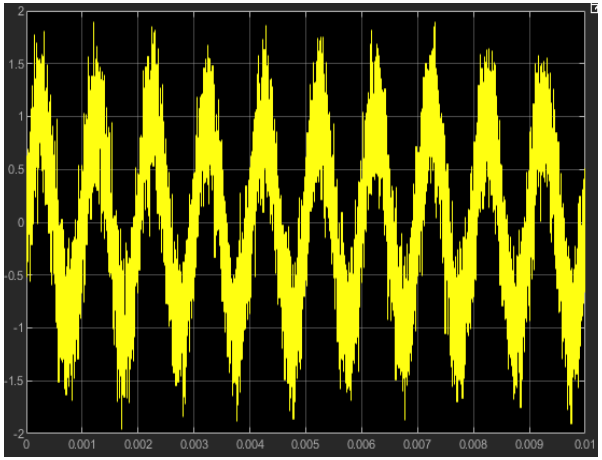
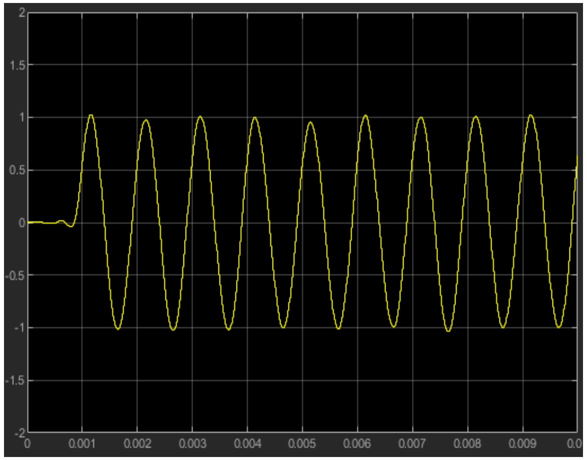
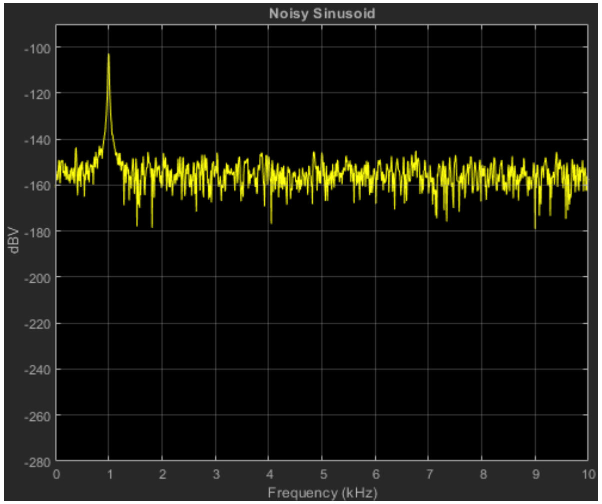
Noisy Sinusoid

LPF Noisy Sinusoid

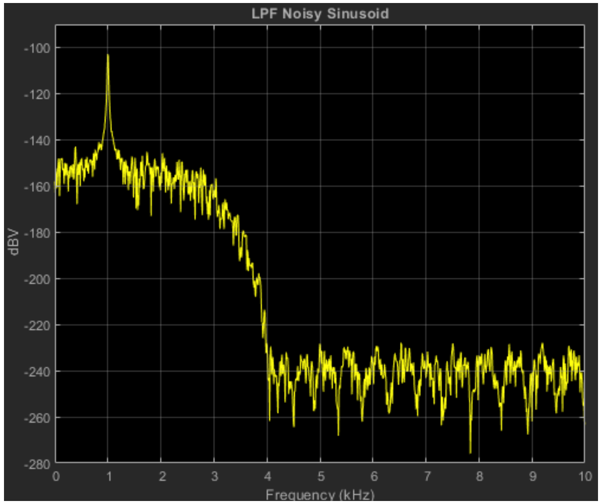


Temporal Display





Spectral Display



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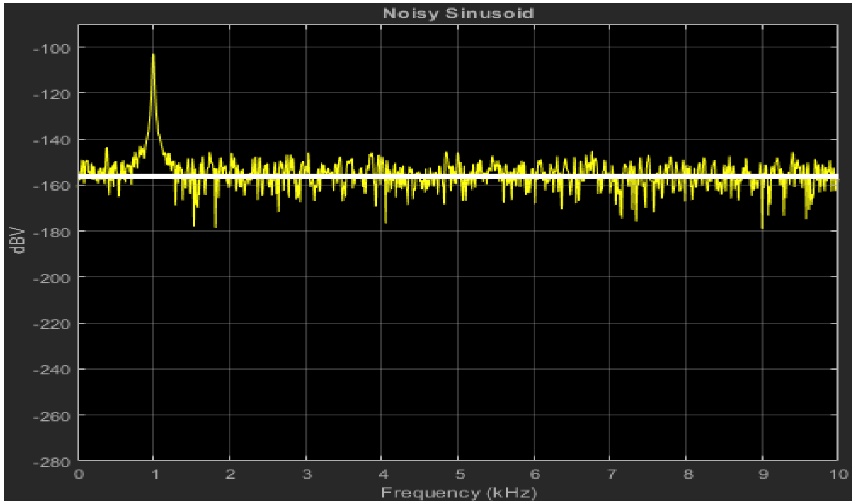
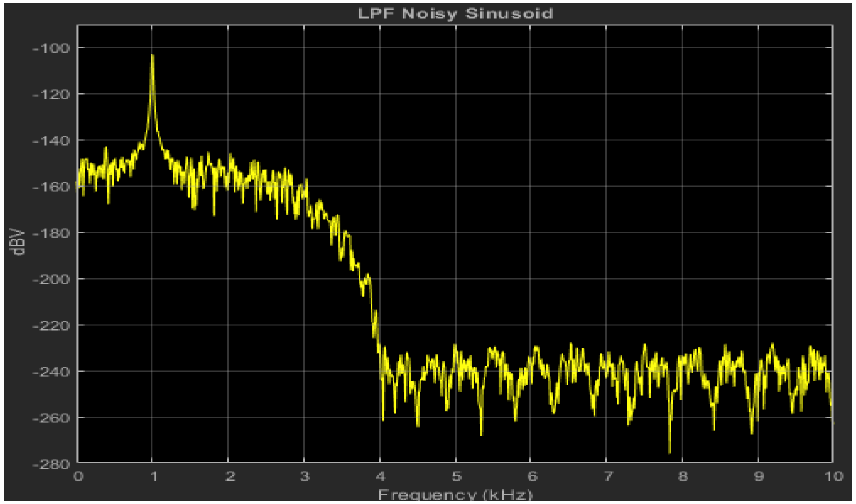
Noisy Sinusoid



AWGN has a *flat* frequency spectrum

Spectral Display

LPF Noisy Sinusoid



LPF does not affect the 1 kHz sinusoid but attenuates the AWGN

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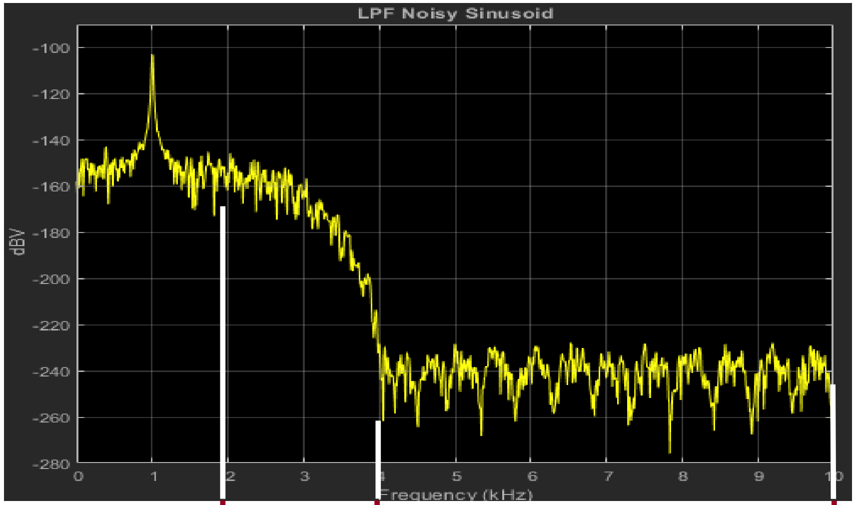
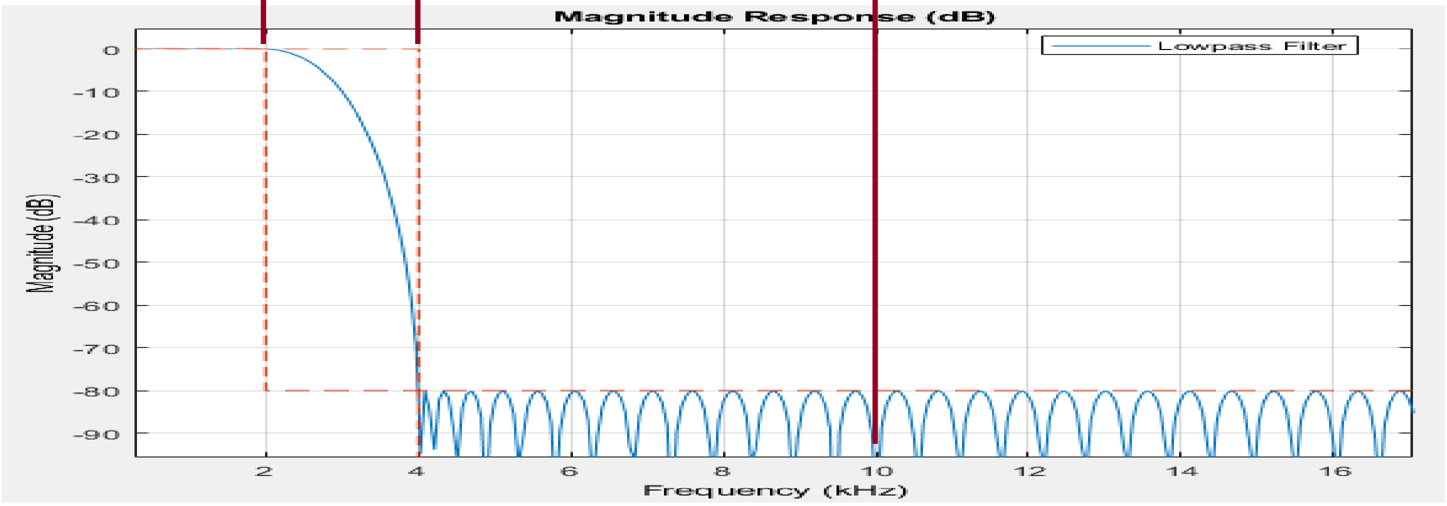
Spectral Display



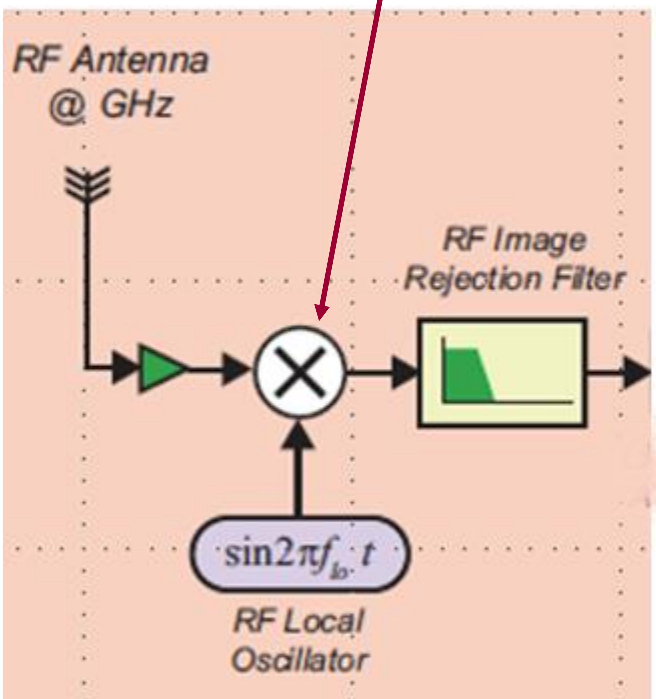
LPF Noisy Sinusoid, Shaped Filtering

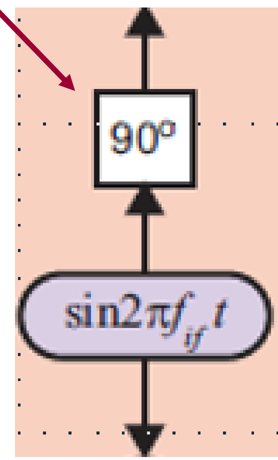
Filter Response

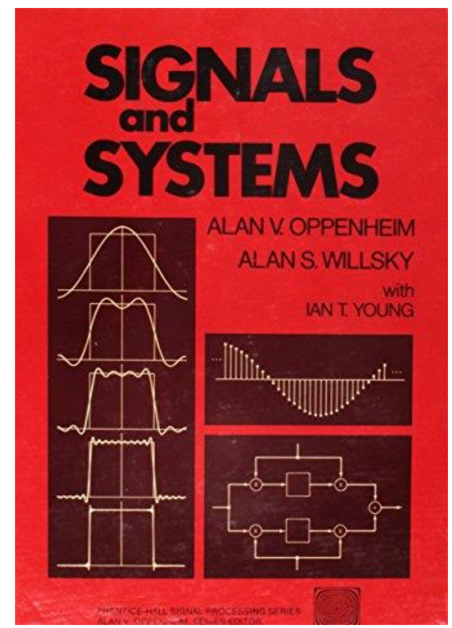


Mini-Workshop on SDR using RTL-SDR

Two common, *non-linear* operations for communications would be the *multiplication* of two sinusoids and the *phase shifting* of a sinusoid.







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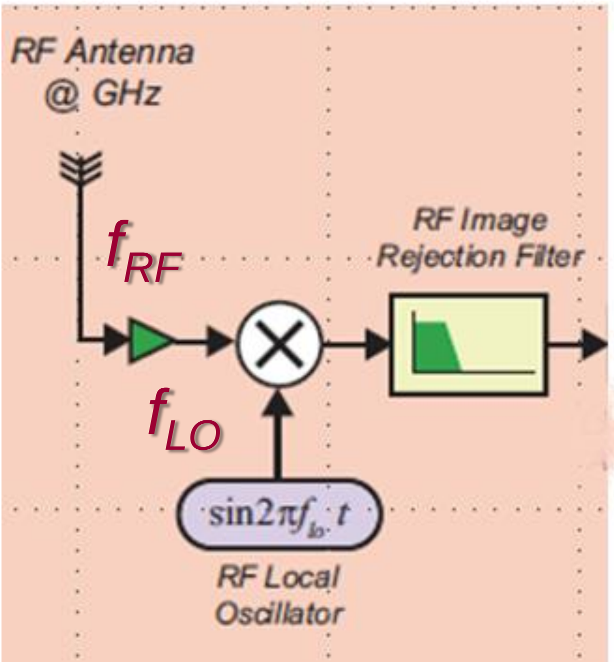
Two trigonometric identities are then key to understanding signal processing in communications and the SDR.

- Multiplication of sinusoids in a *mixer* results in an output as the *sum* and *difference* of the two frequencies. This is *frequency conversion* and is the first of the *trigonometric identities*:

$$\sin\alpha \sin\beta = \frac{\cos(\alpha - \beta) - \cos(\alpha + \beta)}{2}$$

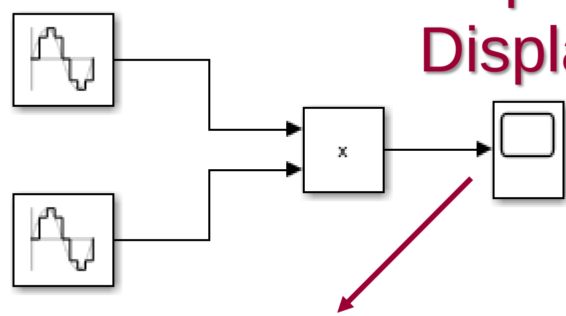


$$\sin(2\pi f_{RF} t) \text{ x } \sin(2\pi f_{LO} t) = [\cos(2\pi(f_{RF} - f_{LO})t) - \cos(2\pi(f_{RF} + f_{LO})t)] / 2$$

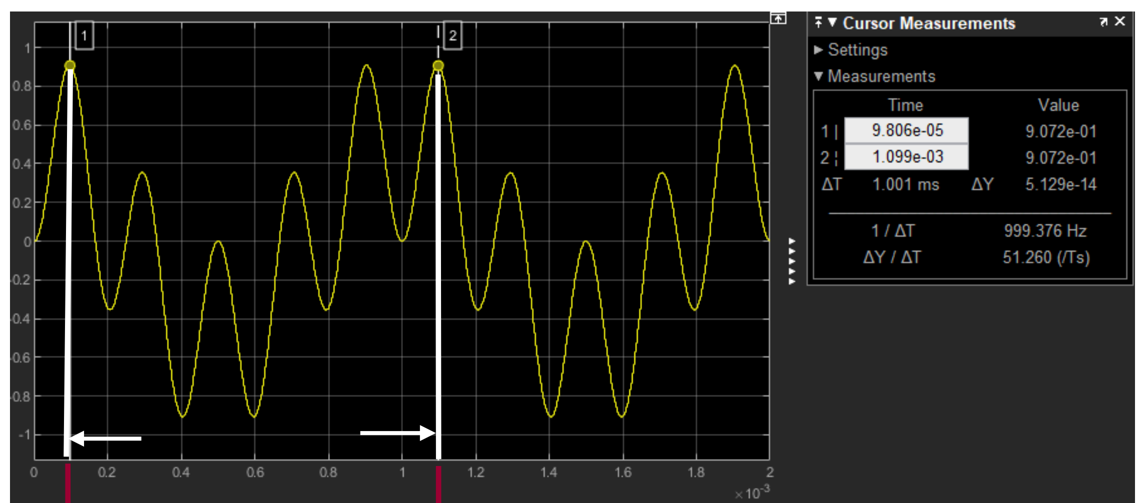
Mini-Workshop on SDR using RTL-SDR

The temporal display of the multiplication of a 1 V peak, 2 kHz and 1 V peak, 3 kHz sinusoid in simulation using Simulink is shown here.

Temporal Display



The temporal output signal is periodic with a period of 1 msec (1 kHz) *but what else is hard to discern*.



1 msec

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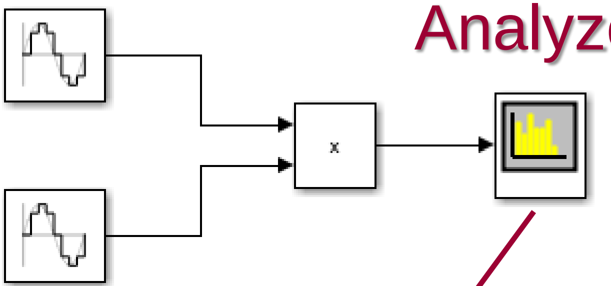
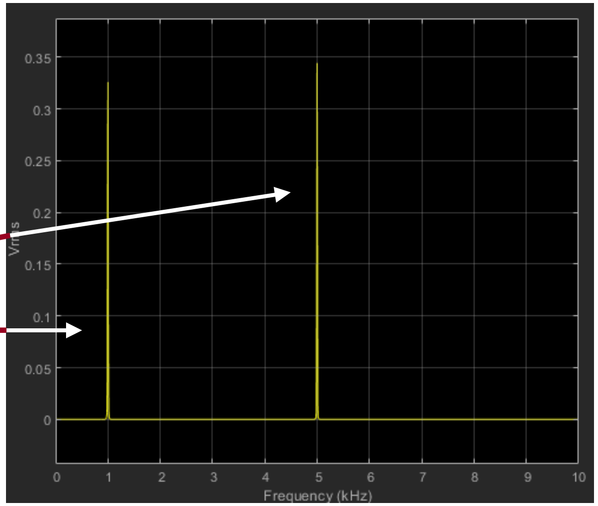
The spectral display of the multiplication of a 1 V peak, 2 kHz and 1 V peak, 3 kHz sinusoid in simulation using Simulink is shown here.

Spectrum Analyzer



The spectrum of the output signal clearly shows only two frequencies at the sum (5 kHz) and difference (1 kHz) frequencies.



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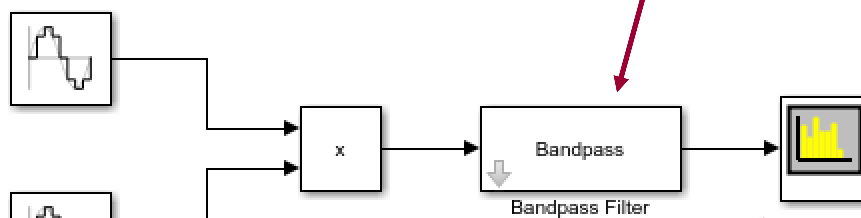
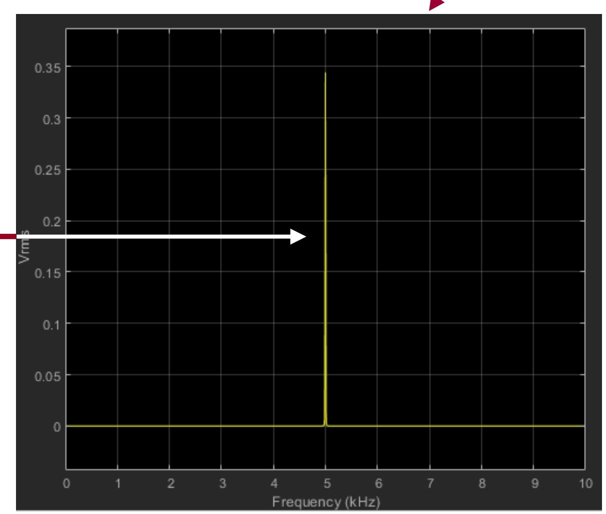
The spectral display of the multiplication of a 1 V peak, 2 kHz and 1 V peak, 3 kHz sinusoid then *bandpass filtered* (BPF) centered at 5 kHz is shown here.



BPF

The spectrum of the bandpass filtered output shows only the desired 5 kHz signal.



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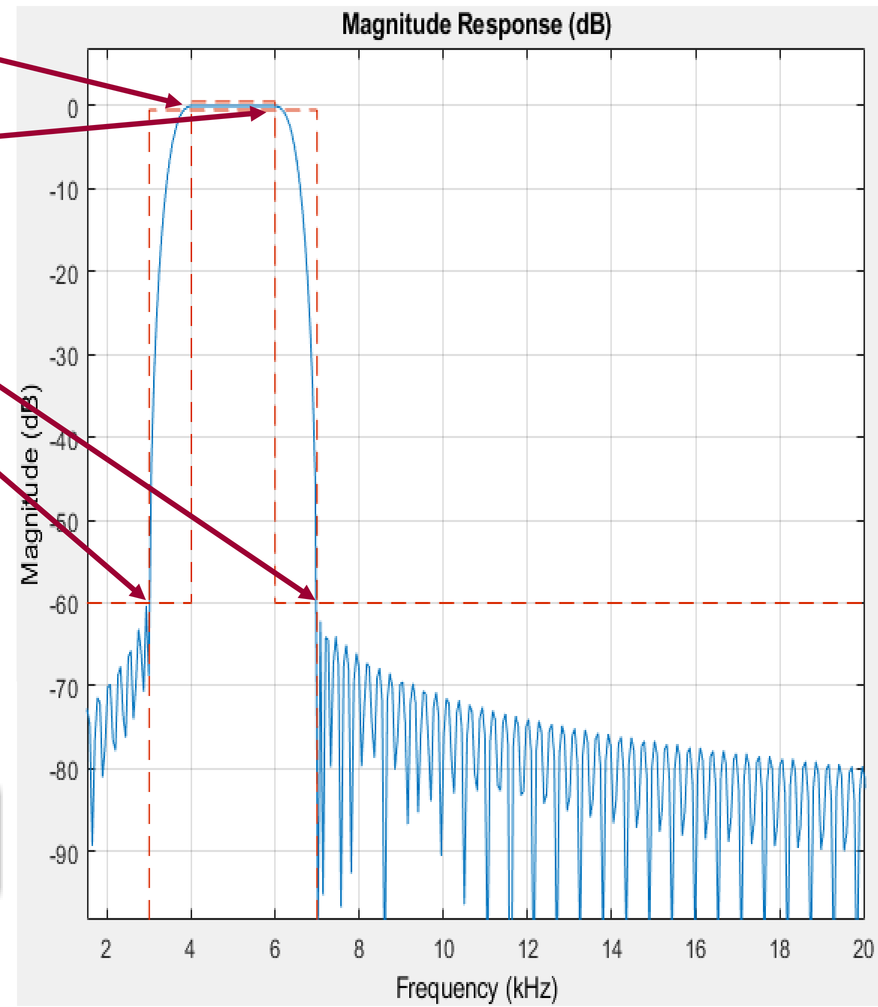
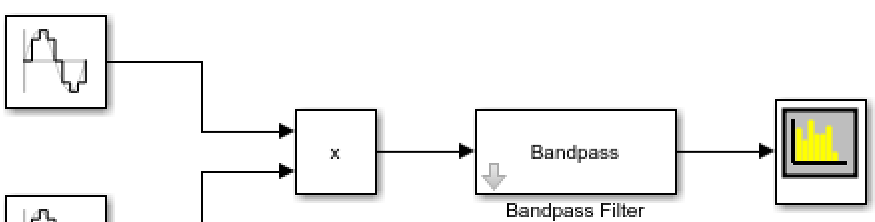
Bandpass filter with *passbands* between 4 kHz and 6 kHz, *stopbands* at 3 kHz and 7 kHz, and with minimal *ripple* and specified *attenuation*.





BPF

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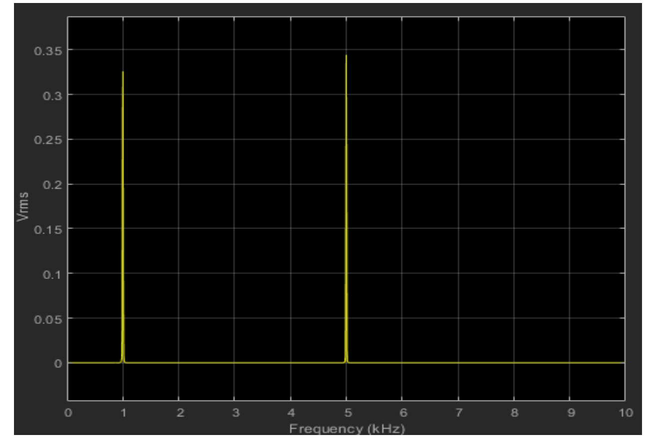
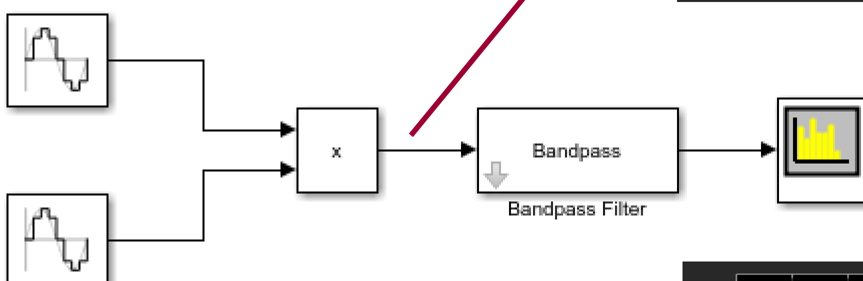
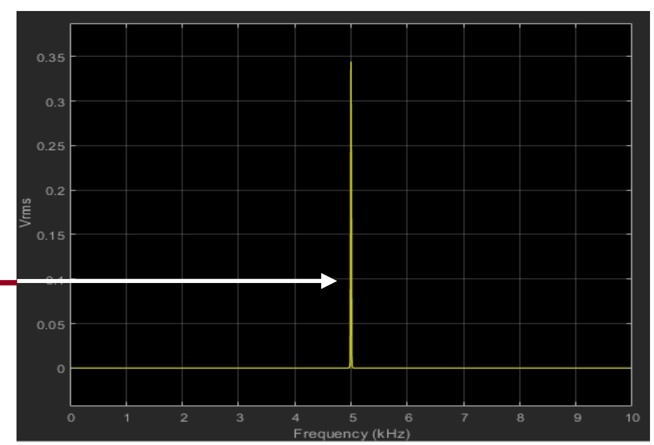
The multiplication of a 2 kHz sinusoid and a 3 kHz sinusoid then bandpass…





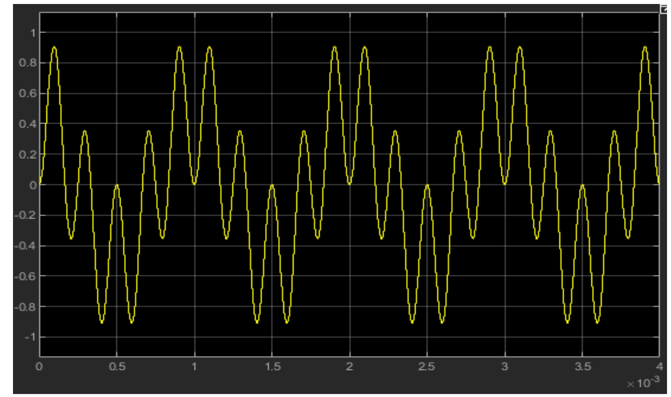
Spectral Display

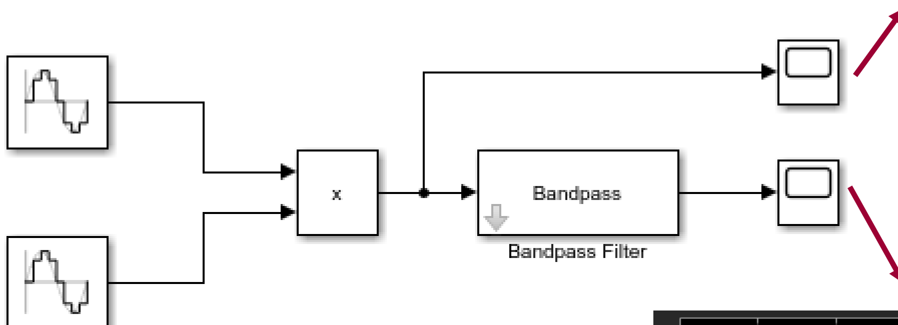


…filtered centered at 5 kHz (sum) produces the desired *upconverted* 5 kHz sinusoidal spectrum.

Mini-Workshop on SDR using RTL-SDR

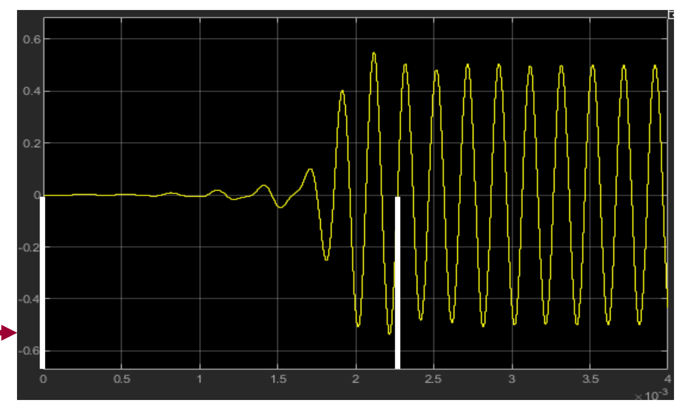
The multiplication of a 2 kHz sinusoid and a 3 kHz sinusoid then bandpass…





Temporal Display

…filtered centered at 5 kHz (sum) produces the desired *upconverted* 5 kHz sinusoid. Note the phase delay output.

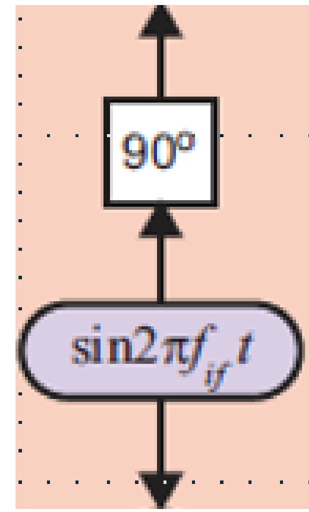


Mini-Workshop on SDR using RTL-SDR

- A 90º *phase shift can* generate a cosinusoid signal from a sinusoid signal (*β* = 90º)

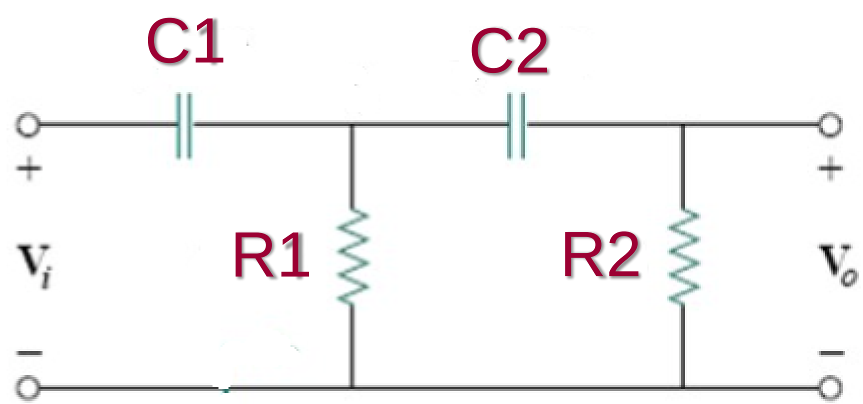
$$\sin(\alpha+\beta) = \sin\alpha\ \overset{0}{\cancel{\cos}}\,\beta + \cos\alpha\ \overset{1}{\cancel{\sin}}\,\beta$$

$$\sin(2\pi f_{IF} t + 90^{O}) = \cos(2\pi f_{IF})$$



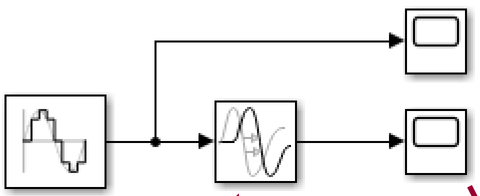
This is *phase shifting* and is the second of the *trigonometric identities.*

A 90º phase shift at a fixed frequency can be configured as a cascade of *RC* circuits.

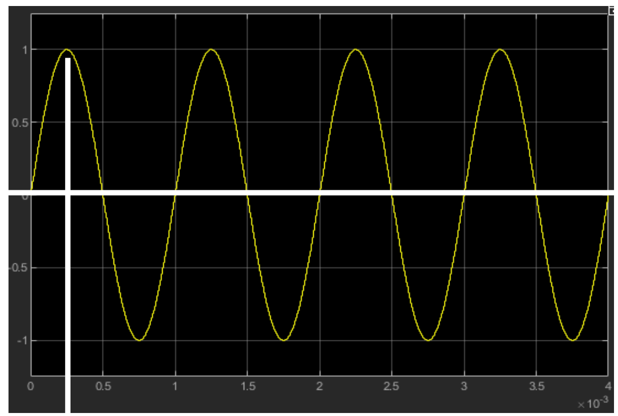


Mini-Workshop on SDR using RTL-SDR

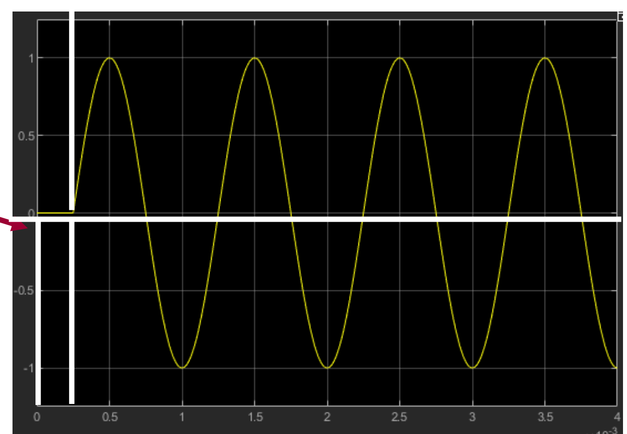
The temporal display of a 1 V peak, 1 kHz sinusoid phase shifted by 90º in simulation using Simulink is shown here.



Transport Delay

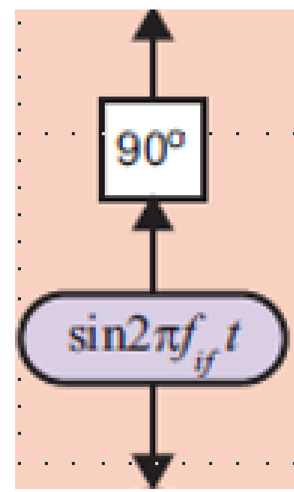


$\sin(2\pi(1000)t)$



Note the simulation delay

$$\sin(2\pi(1000)t + 90^{O}) = \cos(2\pi(1000)t)$$



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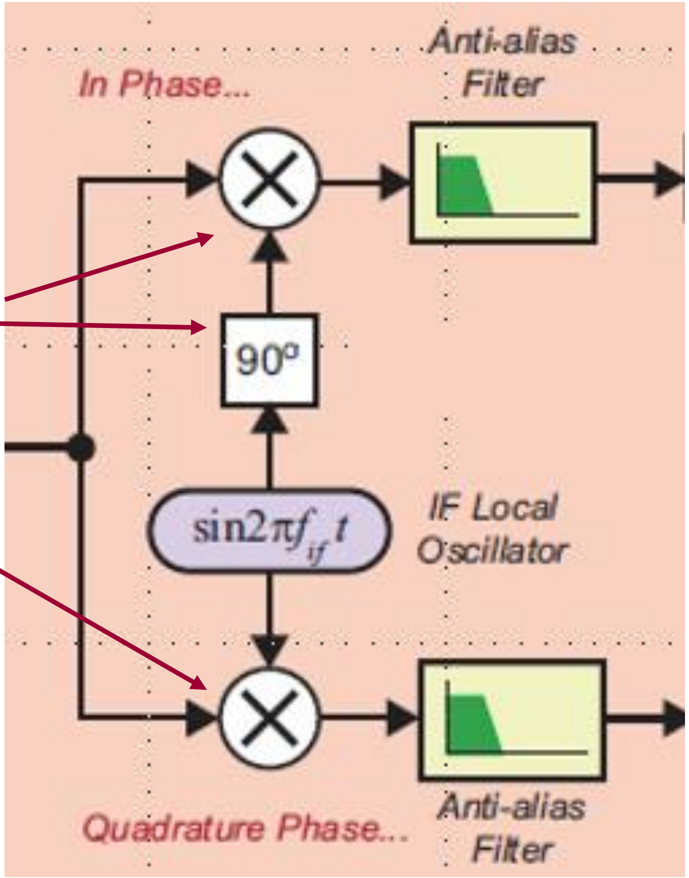
Mini-Workshop on SDR using RTL-SDR

The SDR is the modern approach to radio communication that has dominated recent technology.

For the SDR some of the radio components that had been typically implemented in *hardware* (mixers, phase shifters, filters, modulators, demodulators, and detectors) are now implemented in *software*.

The *inphase* (I, cosine) and *quadrature* (Q, sine) signal components are basic to understanding the modulation (transmission) and demodulation (reception) of both analog and digital communication signals.

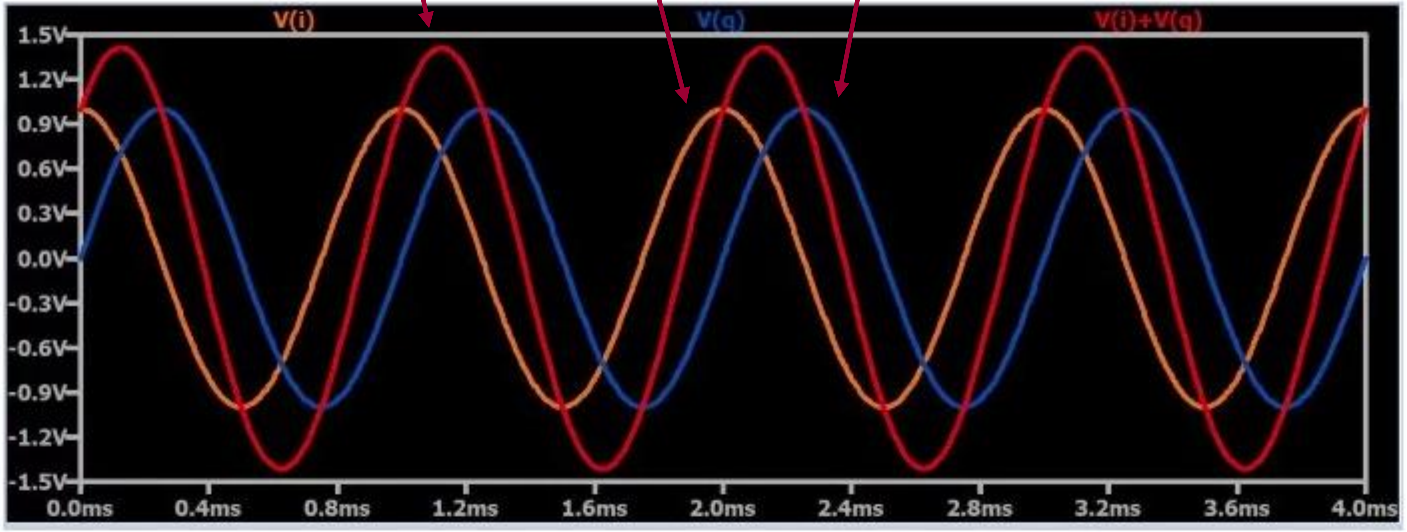
The I and Q signal components are generated by a *phase shifter* and two *mixers* (multipliers).



Mini-Workshop on SDR using RTL-SDR

I and Q refer to two sinusoids that have the same frequency and are 90° out of phase but are summed together to form a signal *s*(*t*).

$$s(t) = A_I \cos(2\pi f_C t) + A_Q \sin(2\pi f_C t)$$

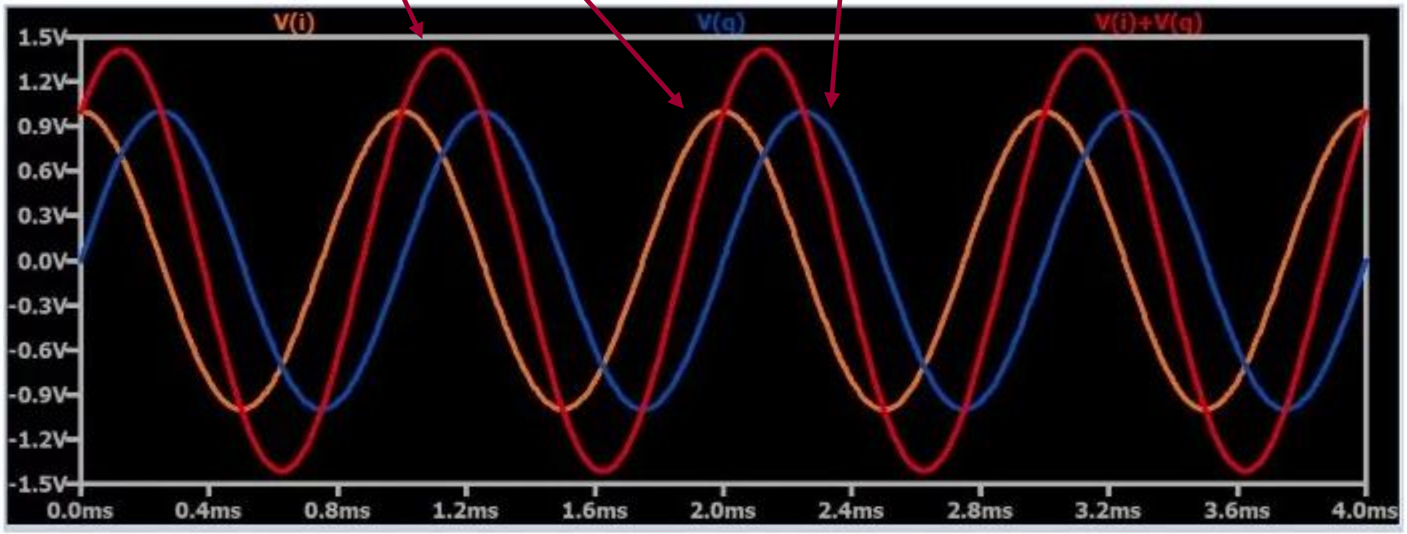


Mini-Workshop on SDR using RTL-SDR

I/Q signals are always *amplitude-modulated*, not frequency or phase modulated.

The amplitude components A_I and A_Q represent the information content for a symbol.

$$s(t) = A_I \cos(2\pi f_C t) + A_Q \sin(2\pi f_C t)$$

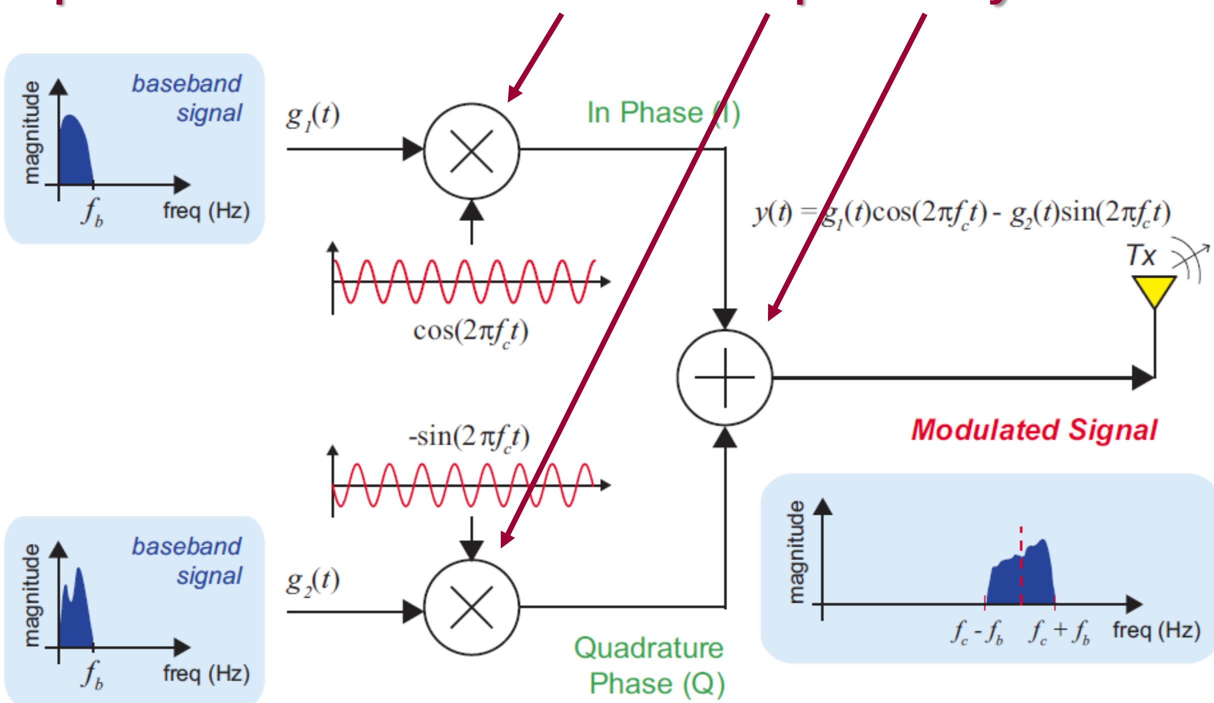


Mini-Workshop on SDR using RTL-SDR

The general form of a modulated, transmitted signal has an inphase (I, cosine) and quadrature (Q, sine) components where $g_1(t)$ and $g_2(t)$ are the information signals.

$$y(t) = g_1(t)\cos(2\pi f_c t) - g_2(t)\sin(2\pi f_c t)$$

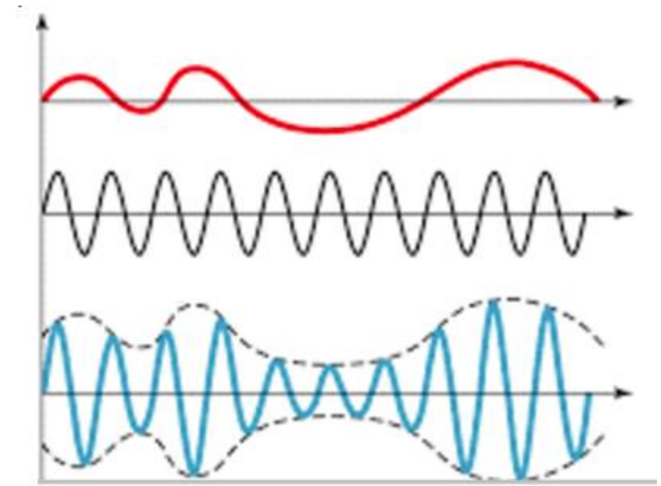
The components are modulated separately then summed.

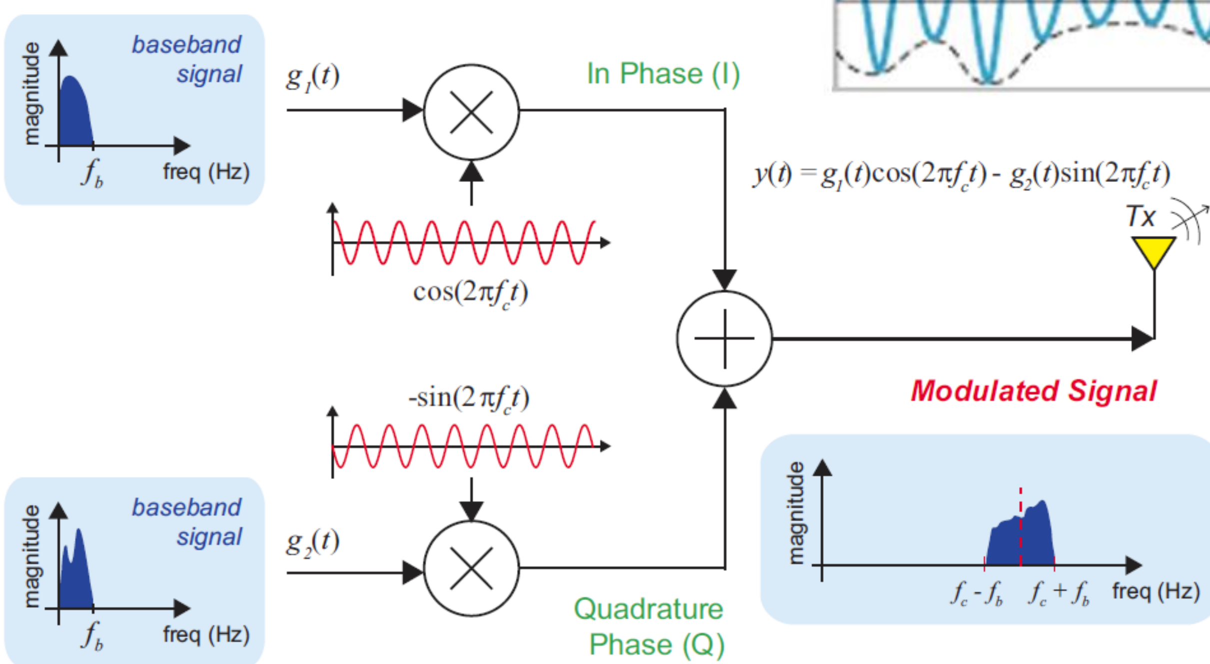


Mini-Workshop on SDR using RTL-SDR

An *amplitude modulated* (AM) signal would have no quadrature component.

$$y(t) = g_1(t)\cos(2\pi f_c t) - \cancelto{0}{g_2(t)\sin(2\pi f_c t)}$$



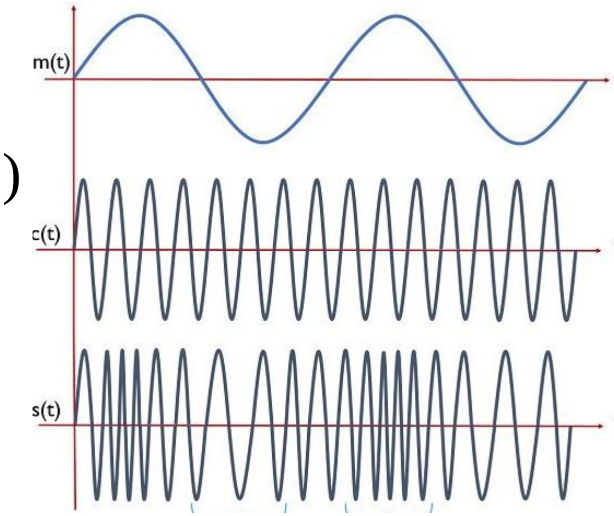


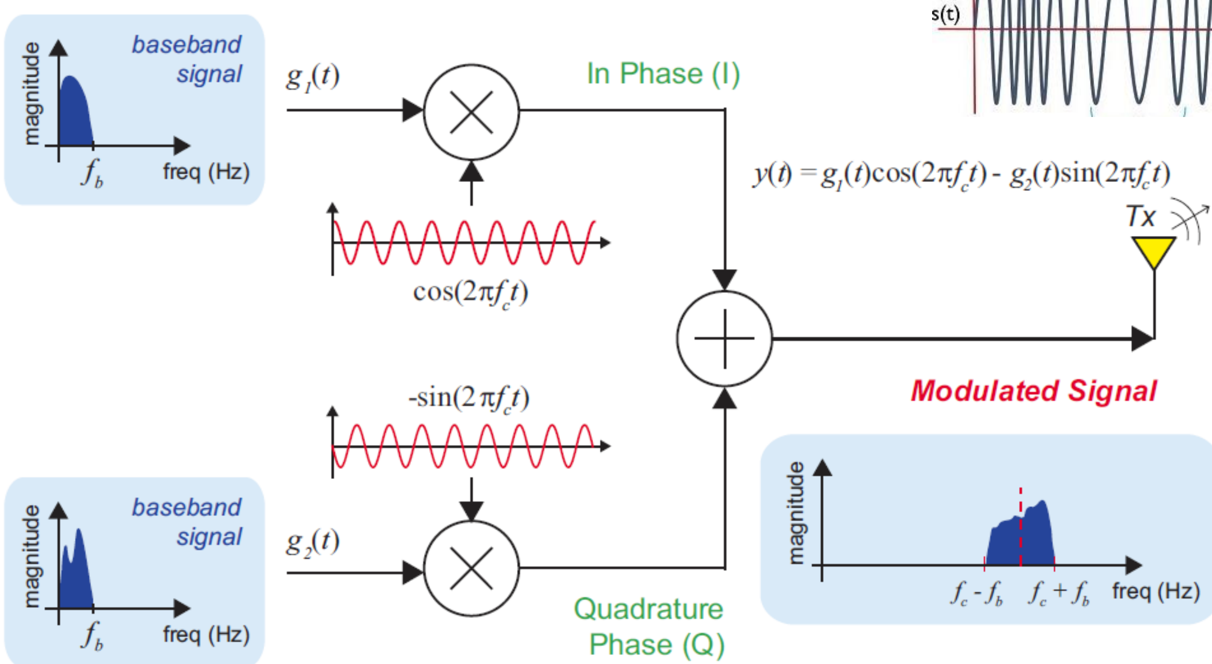
Mini-Workshop on SDR using RTL-SDR

A *phase modulated* (PM) signal would have a constant amplitude and time varying phase

$$\sqrt{g_1^2(t)+g_2^2(t)} = const \quad \theta(t) = \tan^{-1}(g_2(t)/g_1(t))$$

$$y(t) = g_1(t)\cos(2\pi f_c t) - g_2(t)\sin(2\pi f_c t)$$



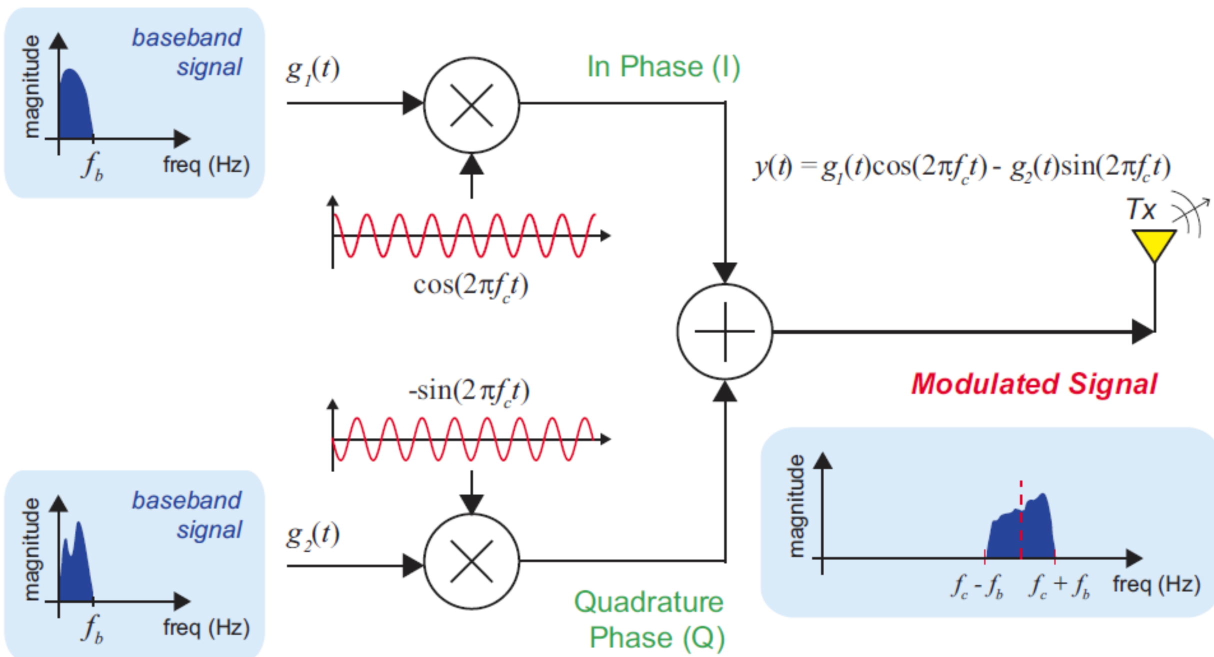


Mini-Workshop on SDR using RTL-SDR

An *amplitude and phase modulated* signal would have both a time varying amplitude and time varying phase

$$\sqrt{g_1^2(t)+g_2^2(t)} = V(t) \qquad \theta(t) = \tan^{-1}(g_2(t)/g_1(t))$$

$$y(t) = g_1(t)\cos(2\pi f_c t) - g_2(t)\sin(2\pi f_c t)$$

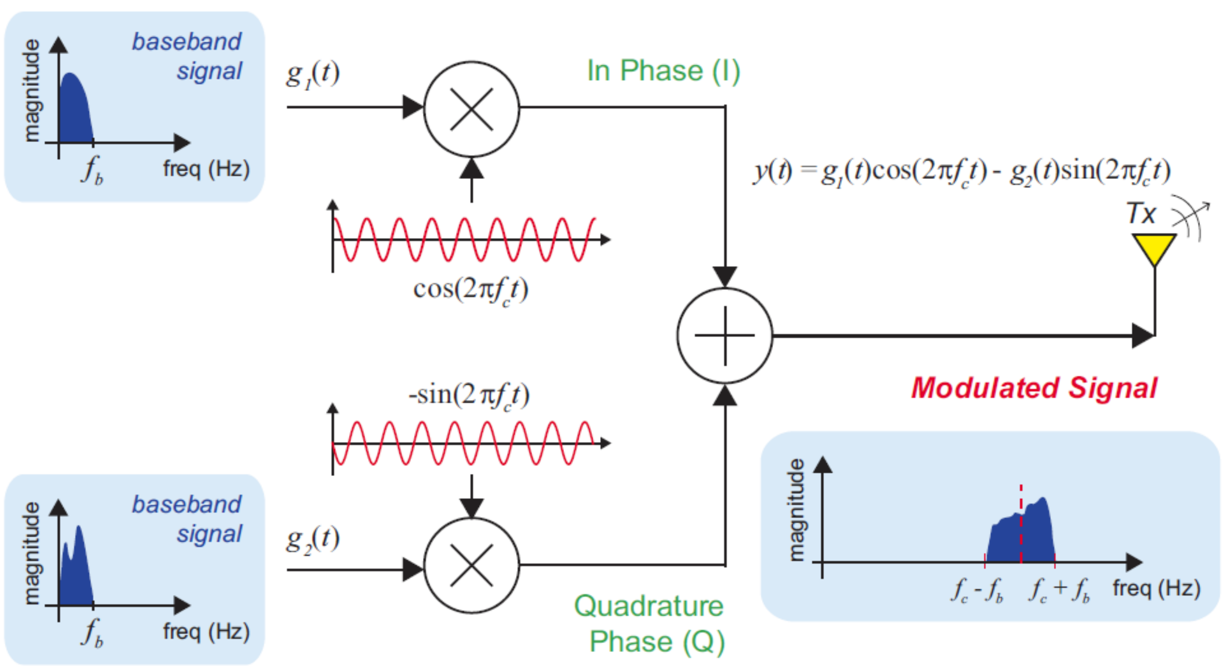


Mini-Workshop on SDR using RTL-SDR

Amplitude and phase modulation is also called *quadrature amplitude modulation* (QAM) and used in digital communication.

$$\sqrt{g_1^2(t)+g_2^2(t)} = V(t) \qquad \theta(t) = \tan^{-1}(g_2(t)/g_1(t))$$

$$y(t) = g_1(t)\cos(2\pi f_c t) - g_2(t)\sin(2\pi f_c t)$$

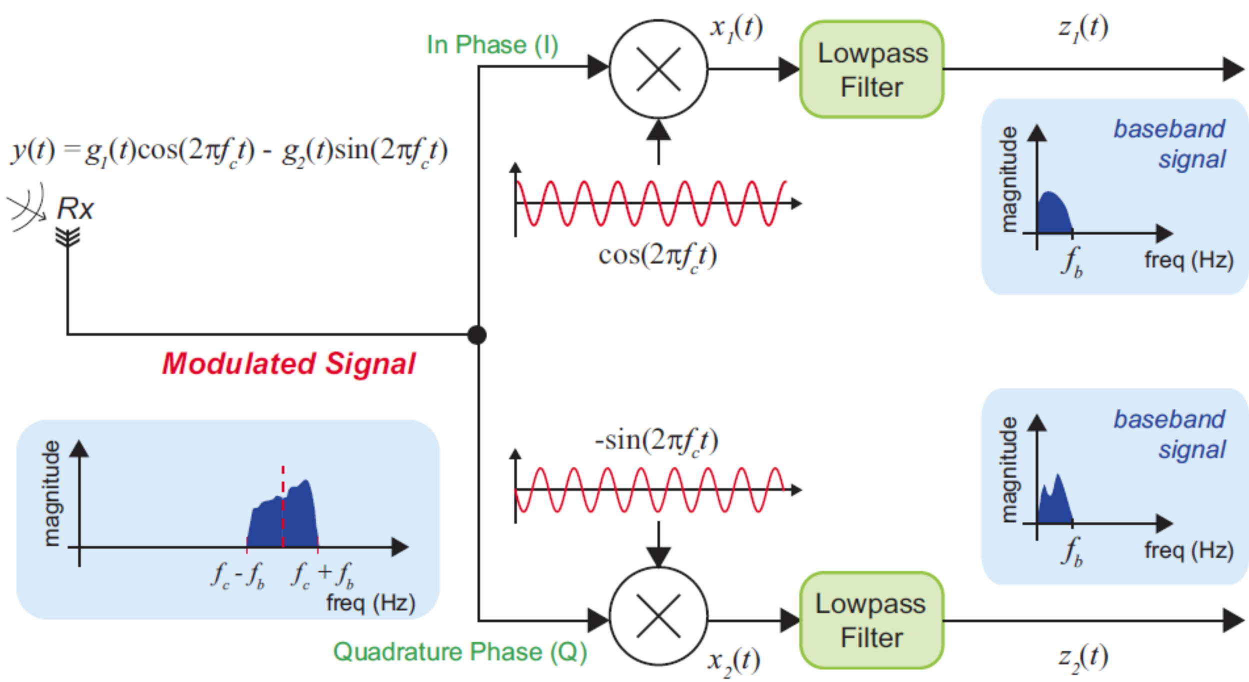


Mini-Workshop on SDR using RTL-SDR

Demodulation of the inphase (I, cosine) and quadrature (Q, sine) components recovers the information signals $g_1(t)$ and $g_2(t)$. If the relative phase shift $\theta = 0^0$ then:

$$z_1(t) = 0.5[g_1(t)\cos(\theta) + g_2(t)\cancel{\sin(\theta)}] = 0.5g_1(t)$$

$$z_2(t) = 0.5[-g_1(t)\cancel{\sin(\theta)} + g_2(t)\cos(\theta)] = 0.5g_2(t)$$



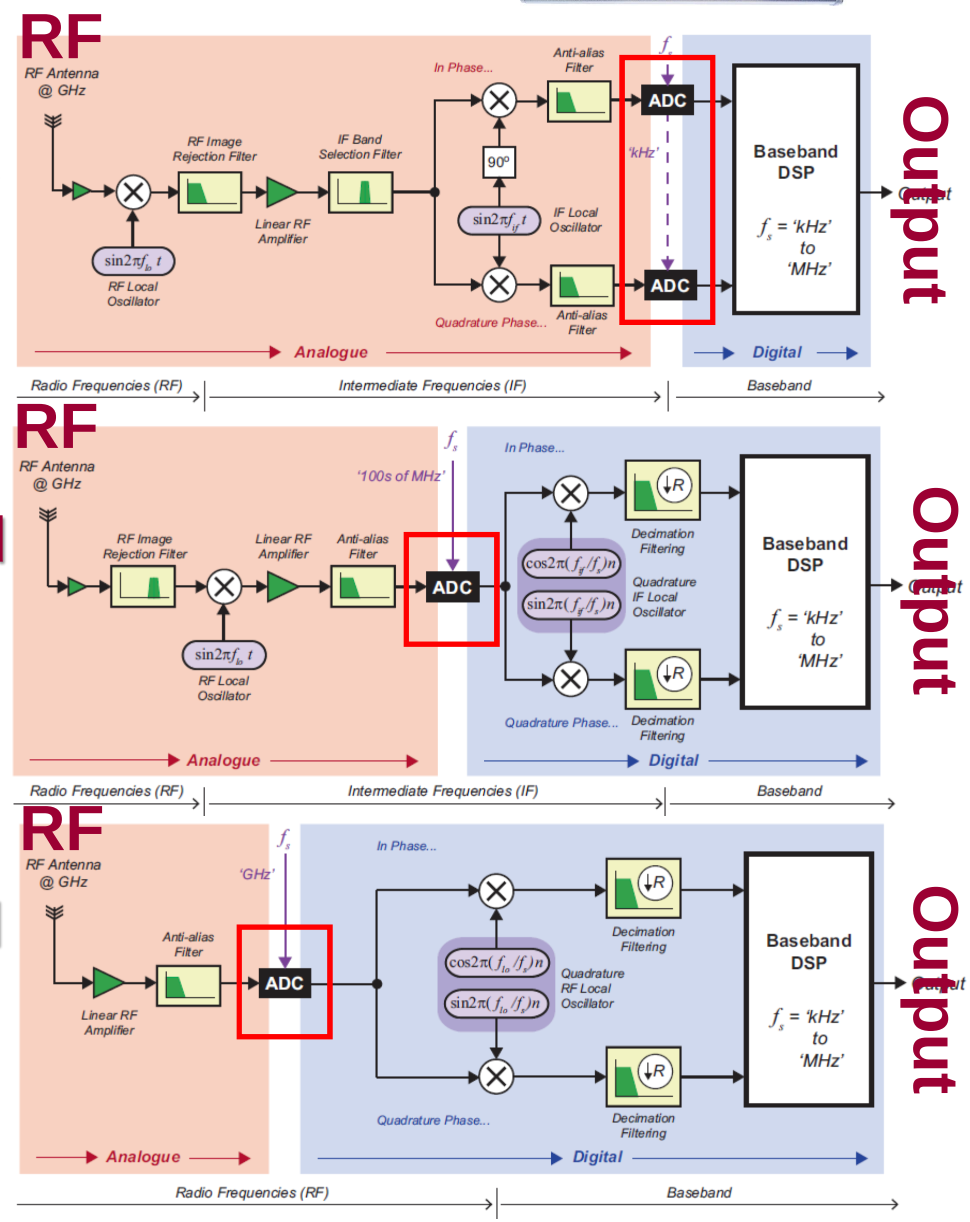
Mini-Workshop on SDR using RTL-SDR

There are three generations of the SDR receiver which are based on the location of the *analog-to-digital converter* (ADC) with respect to the *radio frequency* (RF) input and the *baseband* output.

1st

2nd

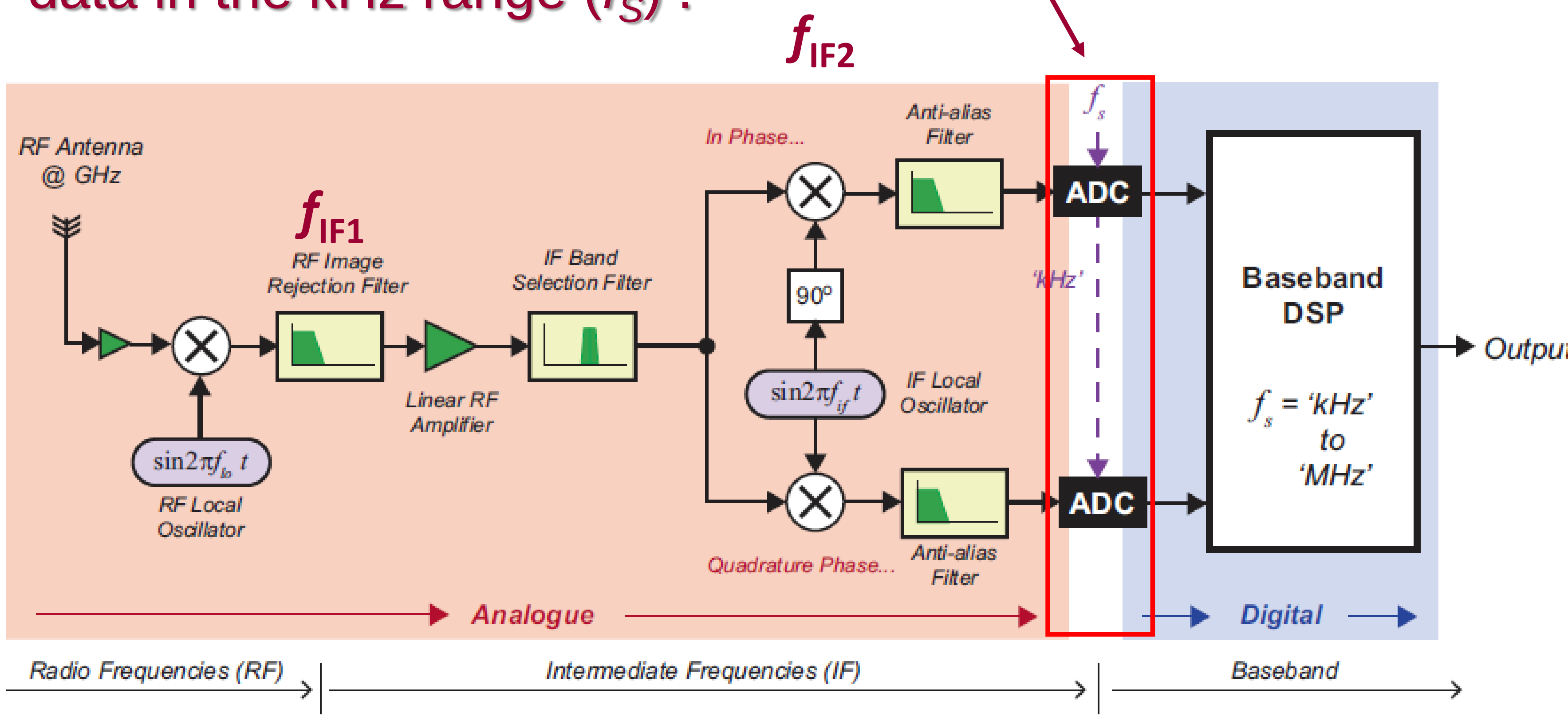
3rd



Mini-Workshop on SDR using RTL-SDR

Evolution of the SDR Receiver: First Generation

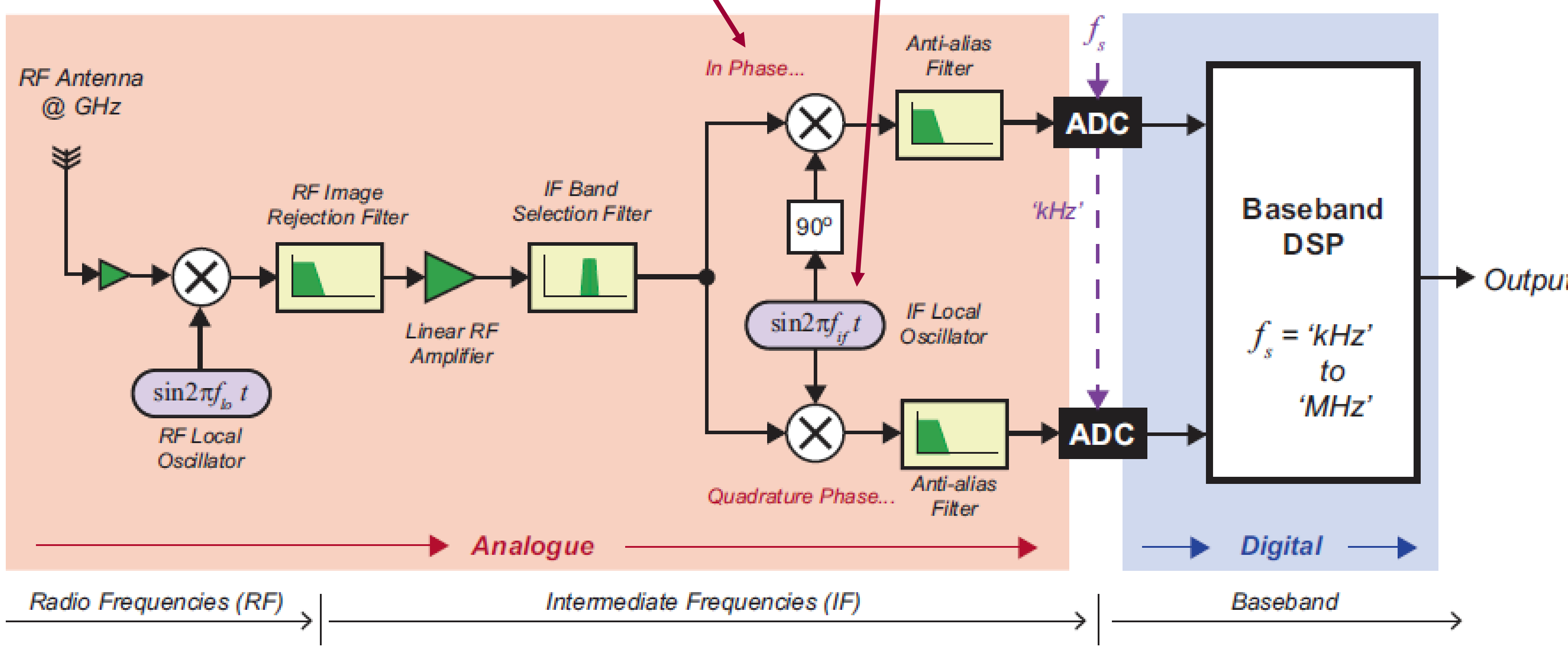
The ADC processes the signal at a second *intermediate frequency* (IF) (f_{IF2}) after the first IF (f_{IF1}) and samples data in the kHz range (f_S) .



Mini-Workshop on SDR using RTL-SDR

Evolution of the SDR Receiver: First Generation

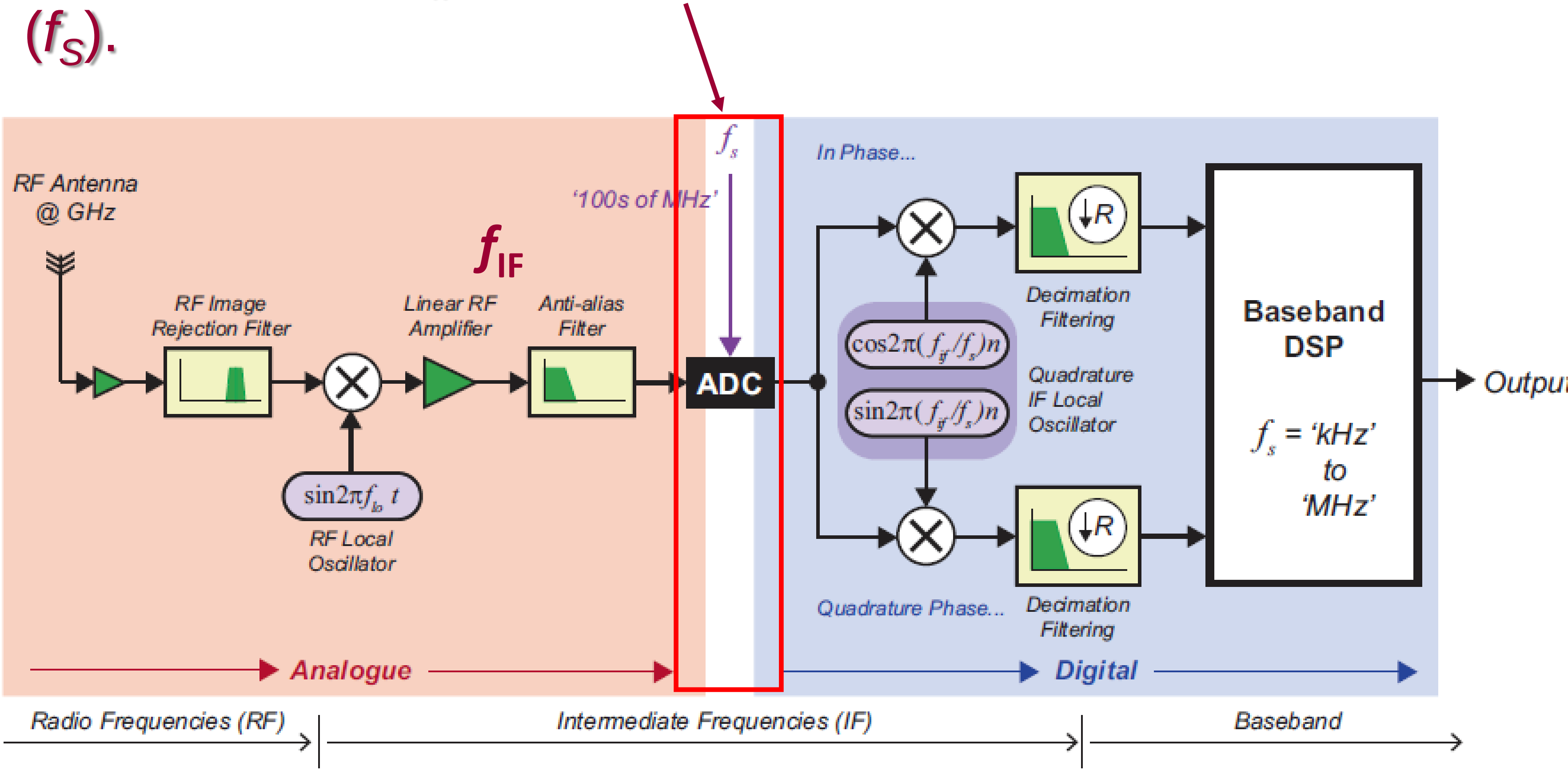
A signal *inphase* (I, cosine) and *quadrature* (Q, sine) demodulator is used in the SDR.



Mini-Workshop on SDR using RTL-SDR

Evolution of the SDR Receiver: Second Generation

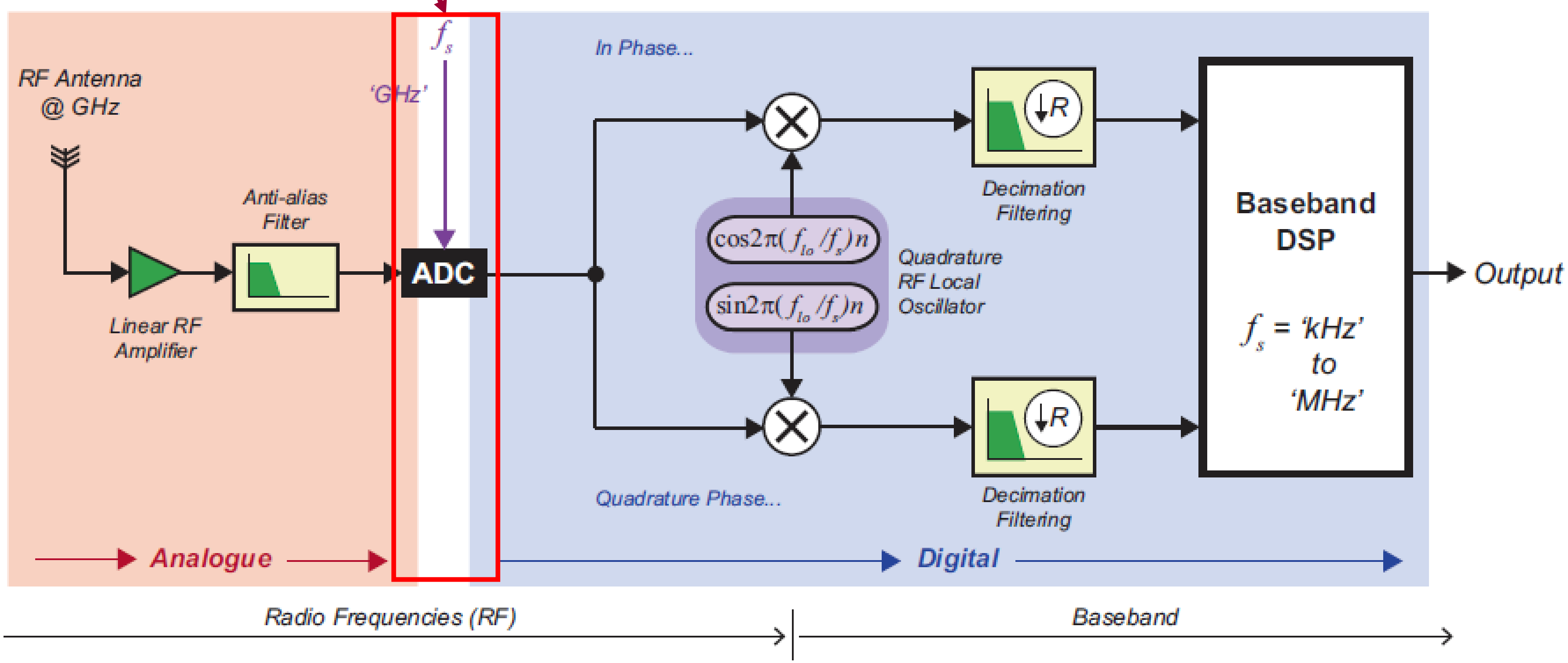
The ADC processes the signal at a single intermediate frequency (IF) (f_{IF}) and samples data in the MHz range (f_S).



Mini-Workshop on SDR using RTL-SDR

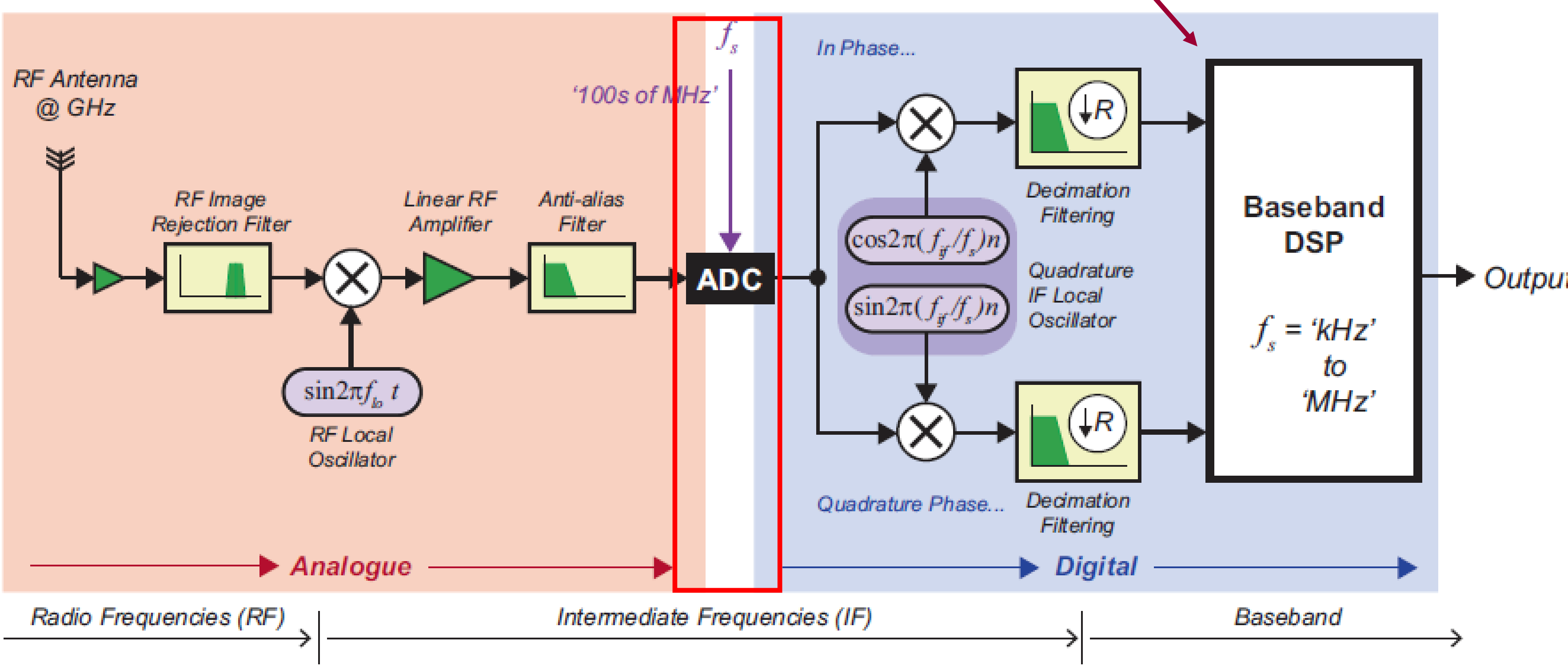
Evolution of the SDR Receiver: Third Generation

The ADC samples data at the RF input frequency which could be in the MHz or GHz range (f_S). The signal is directly converted to *baseband* without an IF.



Mini-Workshop on SDR using RTL-SDR

A popular example of a *receive only* SDR is the second generation RTL-SDR, consisting of a tunable and controllable *RF front end* and baseband signal processing in a PC.

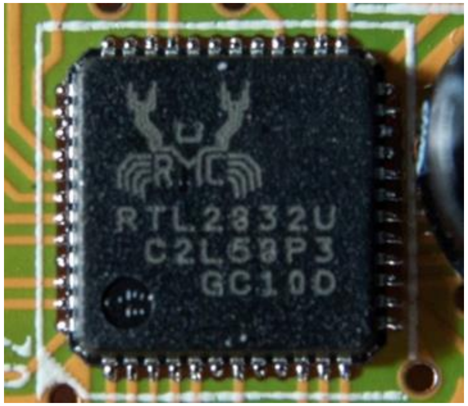


Mini-Workshop on SDR using RTL-SDR

The RTL-SDR uses an RF tuner and demodulator originally intended for decoding European HDTV broadcasts.

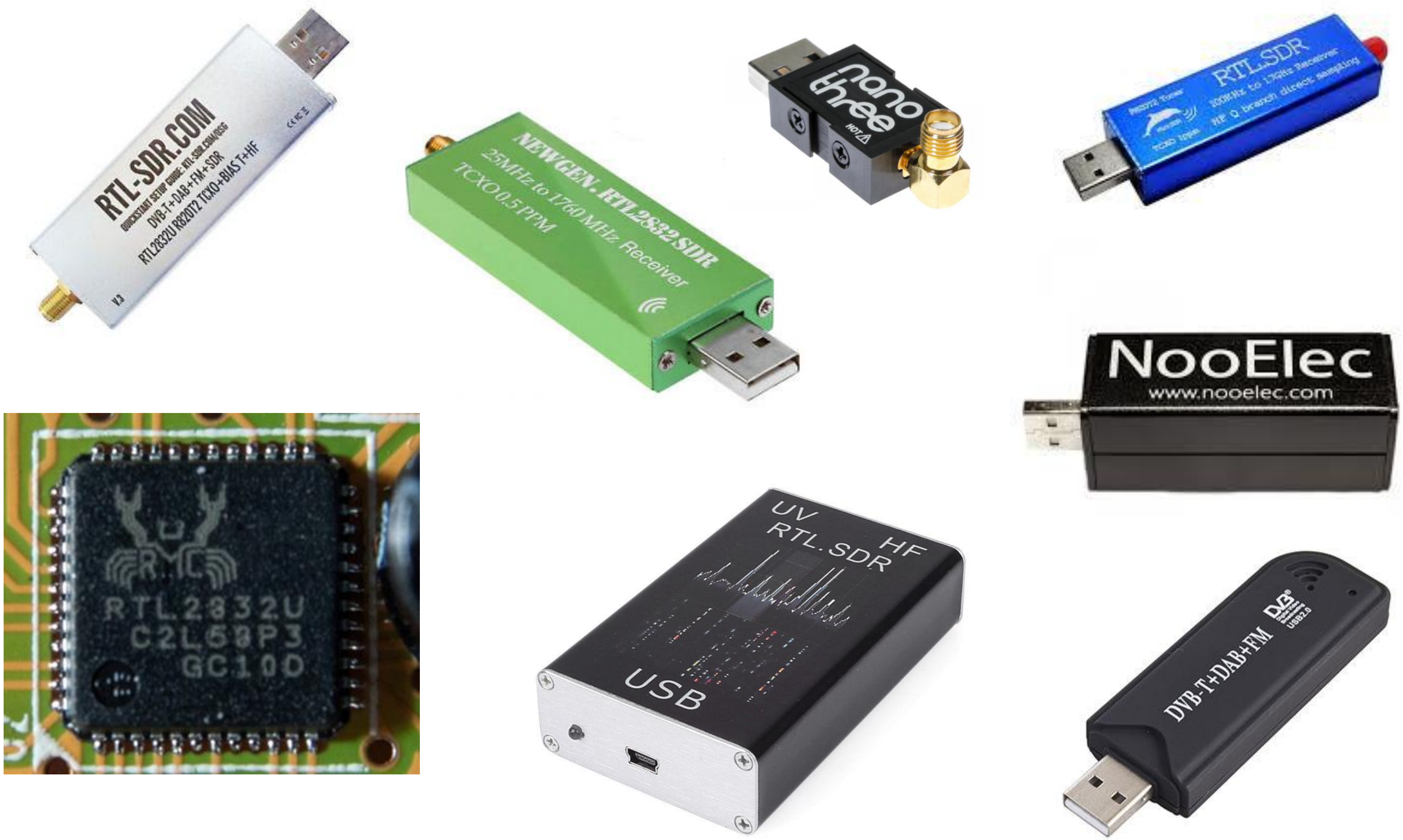
Host access to the baseband binary data stream produced rapid development starting in 2010.

Currently there are over 20 variants but all are based on the *Realtek RTL2832U* demodulator.



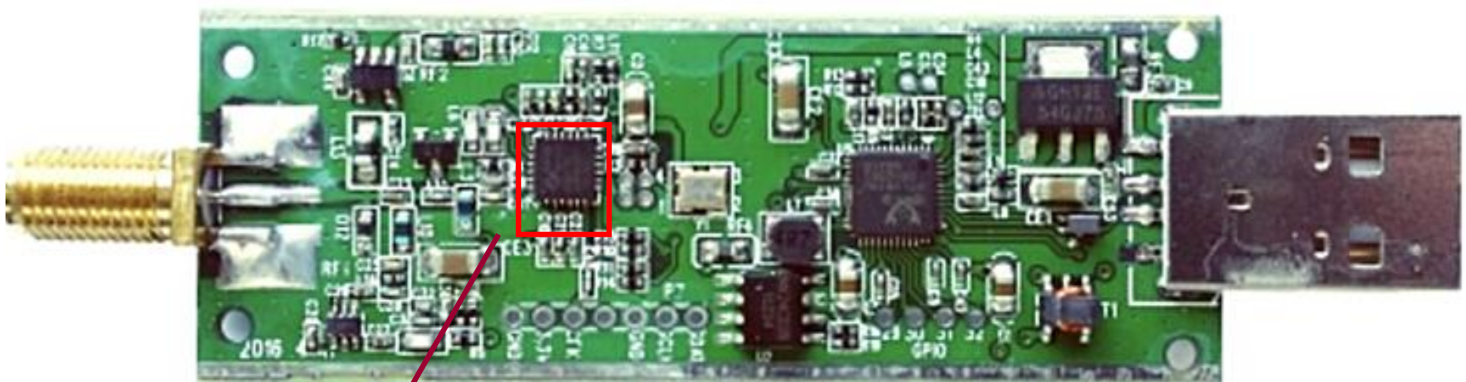
Mini-Workshop on SDR using RTL-SDR

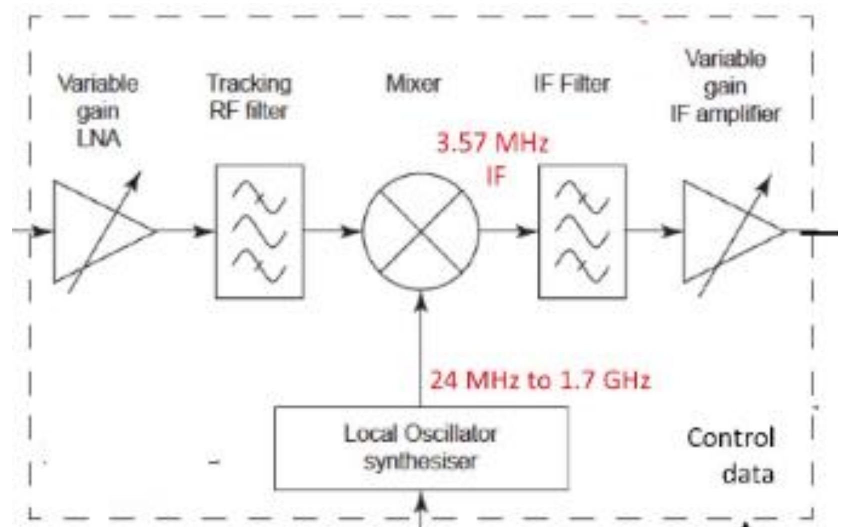
With the RTL2832U demodulator commonly used, this SDR implementation is known as the *RTL-SDR.*



Mini-Workshop on SDR using RTL-SDR

Several different RF tuners can be use but the Rafael Micro R820T is the most common and versatile.



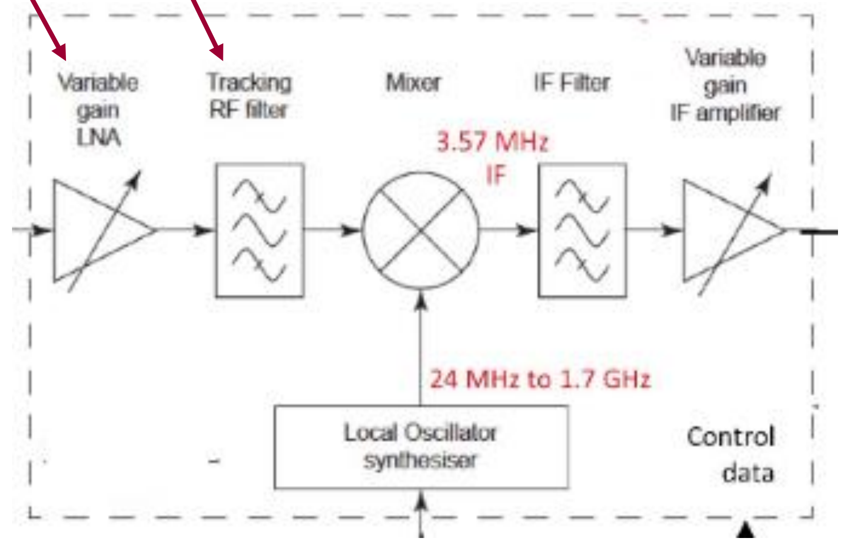


Mini-Workshop on SDR using RTL-SDR

The R820T analog tuner has the following components:

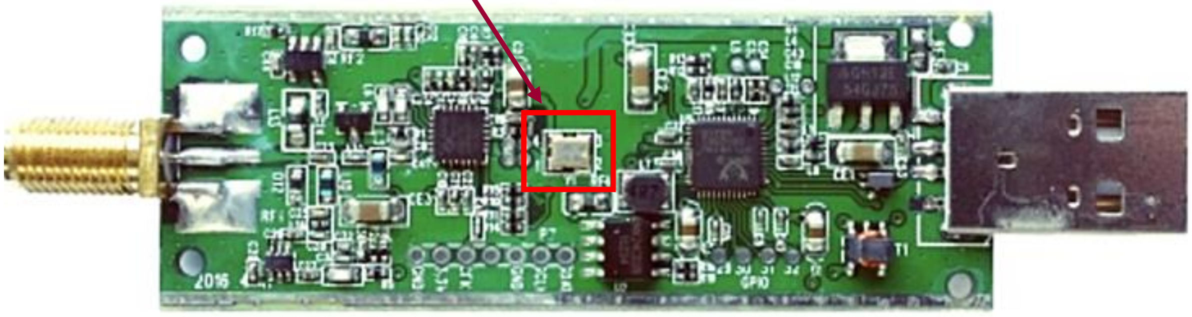
Variable gain *low noise amplifier* (LNA) with a frequency range from 25 to 1725 MHz

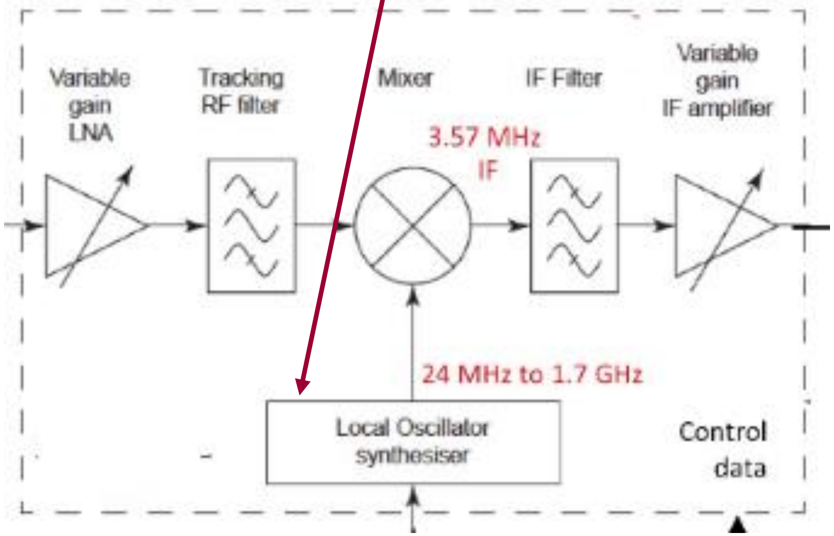
RF filter *tracks* the local oscillator (LO) frequency



Mini-Workshop on SDR using RTL-SDR

The local oscillator (LO) is a *frequency synthesizer* that outputs a reference signal from 24 to 1700 MHz from an external 28.8 MHz crystal.

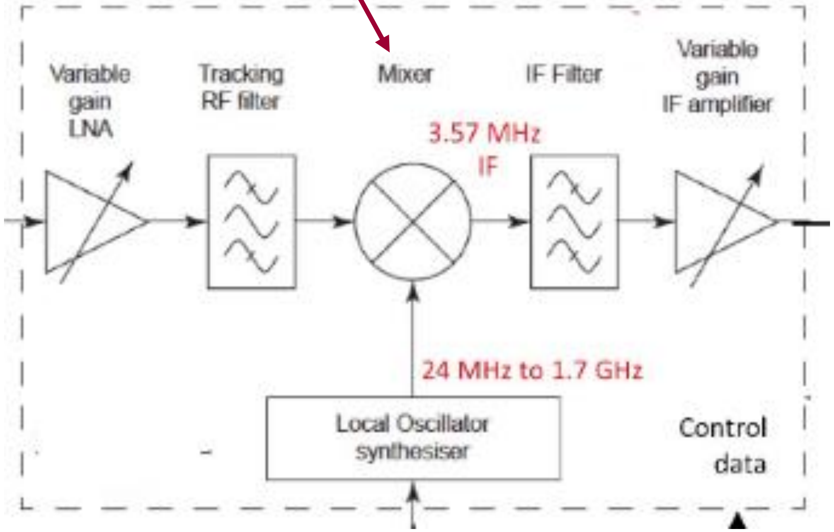




Mini-Workshop on SDR using RTL-SDR

The mixer multiplies the RF signal and the LO producing a sum and difference *intermediate frequency* (IF)

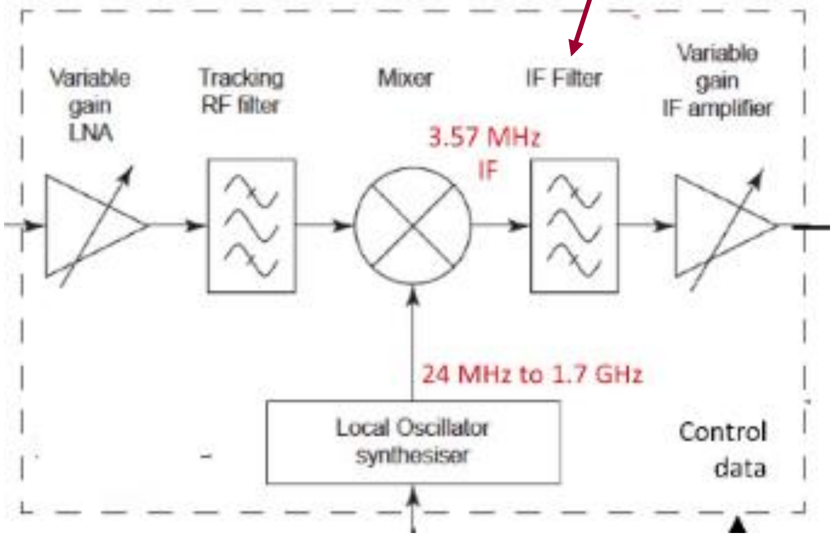
$$\sin(2\pi f_{RF}t)\ \mathrm{x}\ \sin(2\pi f_{LO}t) = [\cos(2\pi(f_{RF}+f_{LO})t) - \cos(2\pi(f_{RF}-f_{LO})t)]/2$$



Mini-Workshop on SDR using RTL-SDR

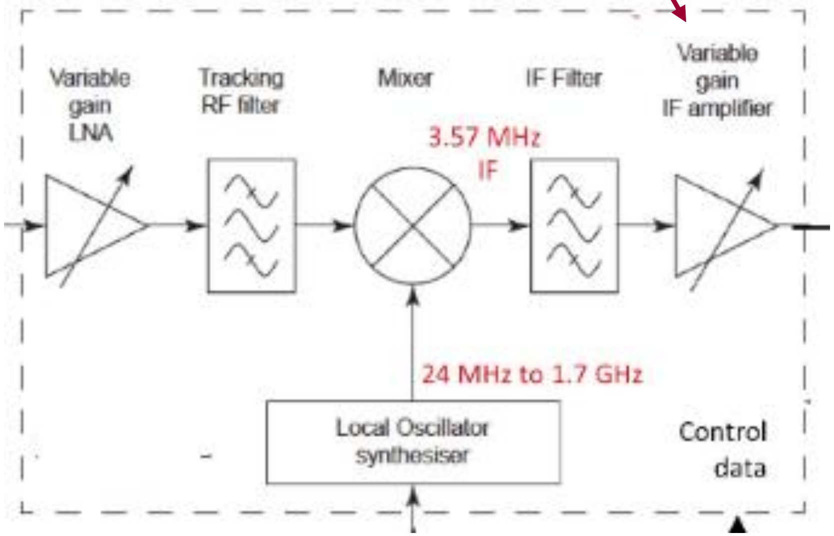
The IF bandpass filter selects the difference frequency at 3.57 MHz with a variable bandwidth of up to 1.2 MHz and suppresses the sum frequency.

$$\sin(2\pi f_{RF} t) \text{ x } \sin(2\pi f_{LO} t) = [\cos(2\pi(f_{RF} + f_{LO})t) - \cos(2\pi(f_{RF} - f_{LO})t)]/2$$



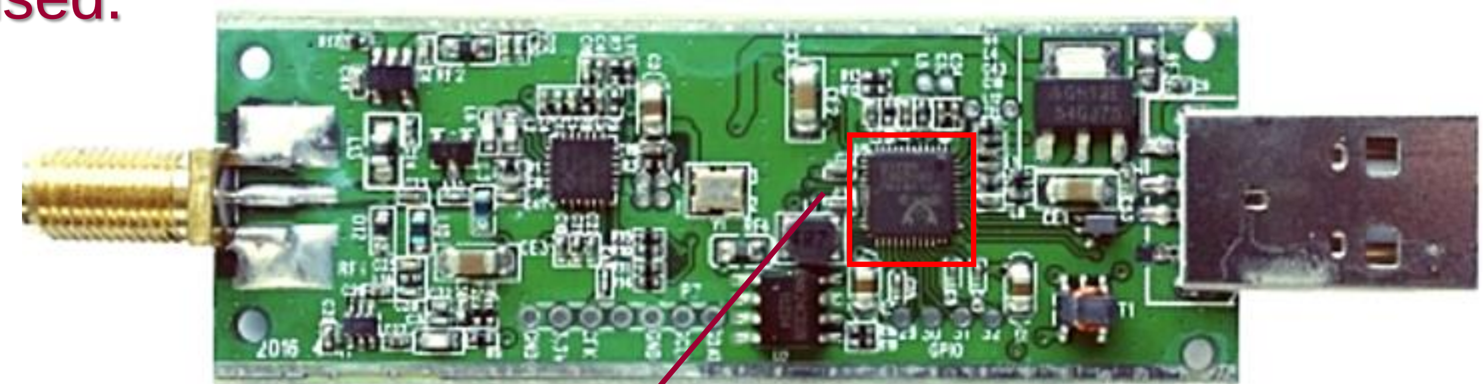
Mini-Workshop on SDR using RTL-SDR

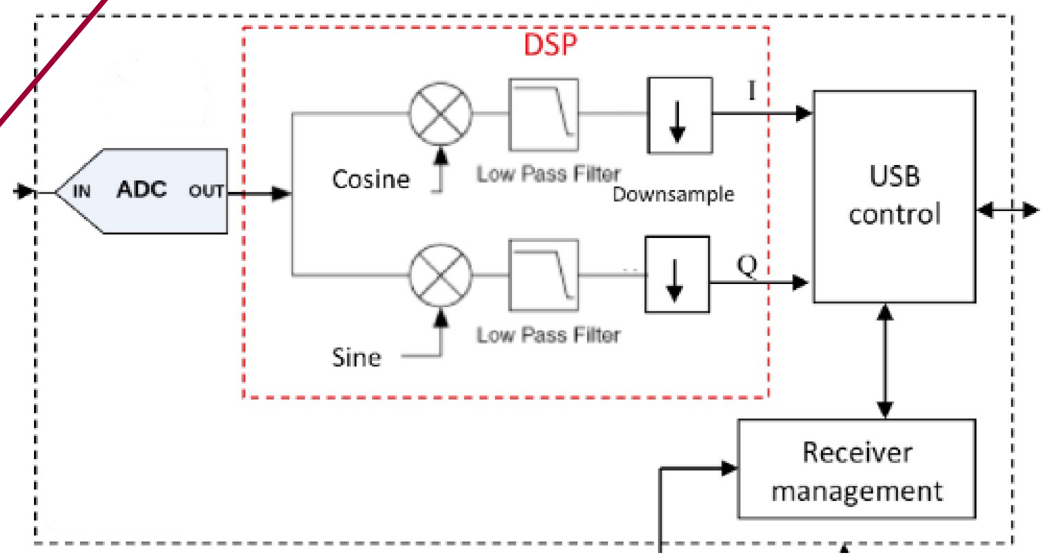
The variable gain IF amplifier at 3.57 MHz with a bandwidth of up to 1.2 MHz outputs an analog signal with an appropriate amplitude for digitization by the follow-on *demodulator*.



Mini-Workshop on SDR using RTL-SDR

The Realtek RTL2832U demodulator is commonly used.

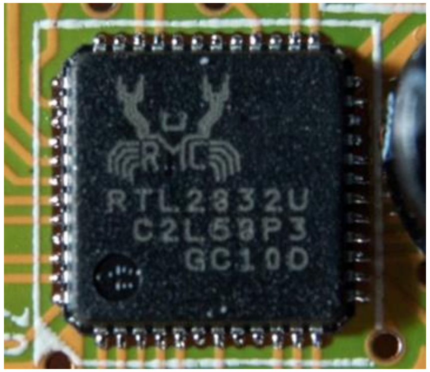


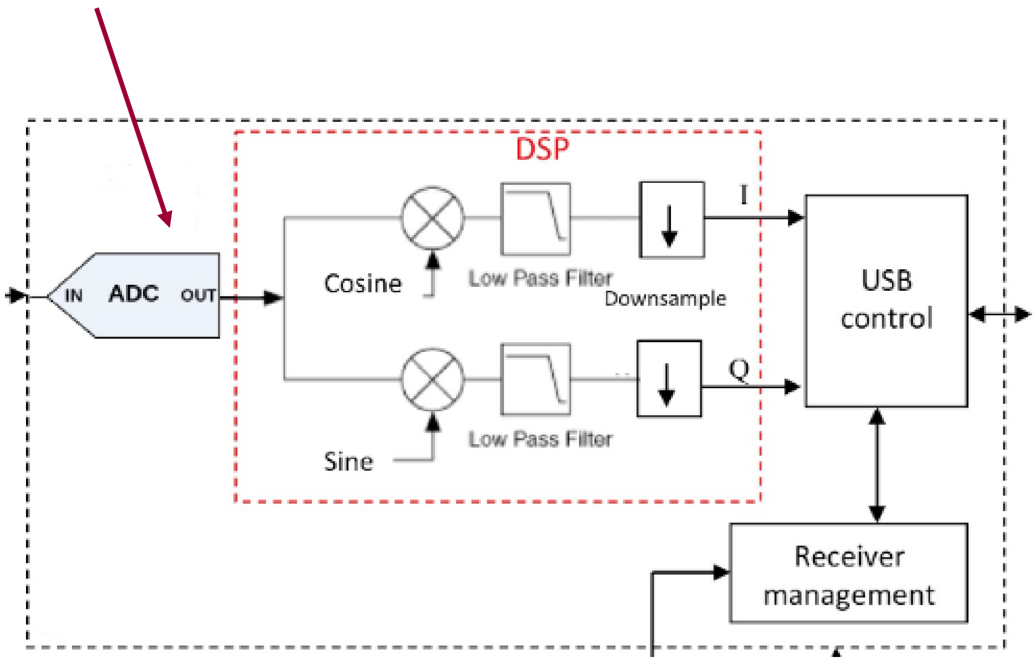


Mini-Workshop on SDR using RTL-SDR

Technical information for the RTL2832U is not available but has been reverse engineered to have the following components:

8-bit analog-to-digital converter (ADC) digitizes the IF signal from the R820T RF tuner at a maximum of 28.8 Msamples/sec

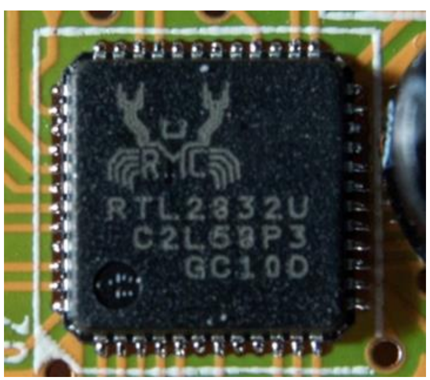


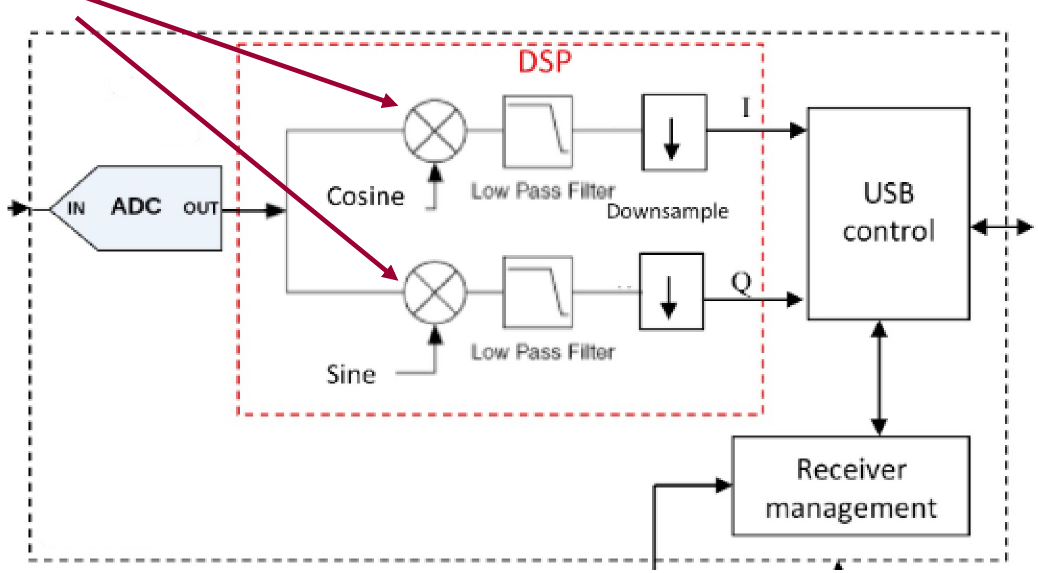


Mini-Workshop on SDR using RTL-SDR

Digital signal processing (DSP) is used to obtained the *inphase* (I) and *quadrature* (Q) signal components.

Two digital multipliers process the digital data with a cosine (I) and sine (Q) reference signal.

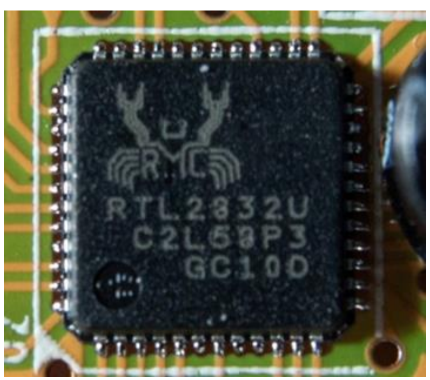


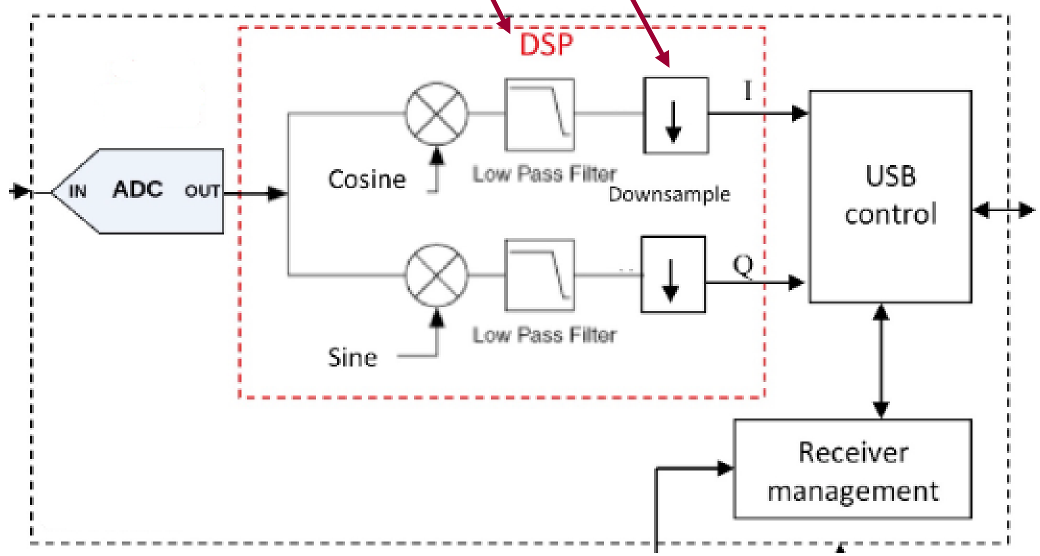


Mini-Workshop on SDR using RTL-SDR

DSP low pass filters select the *baseband* difference frequency I and Q digital data streams.

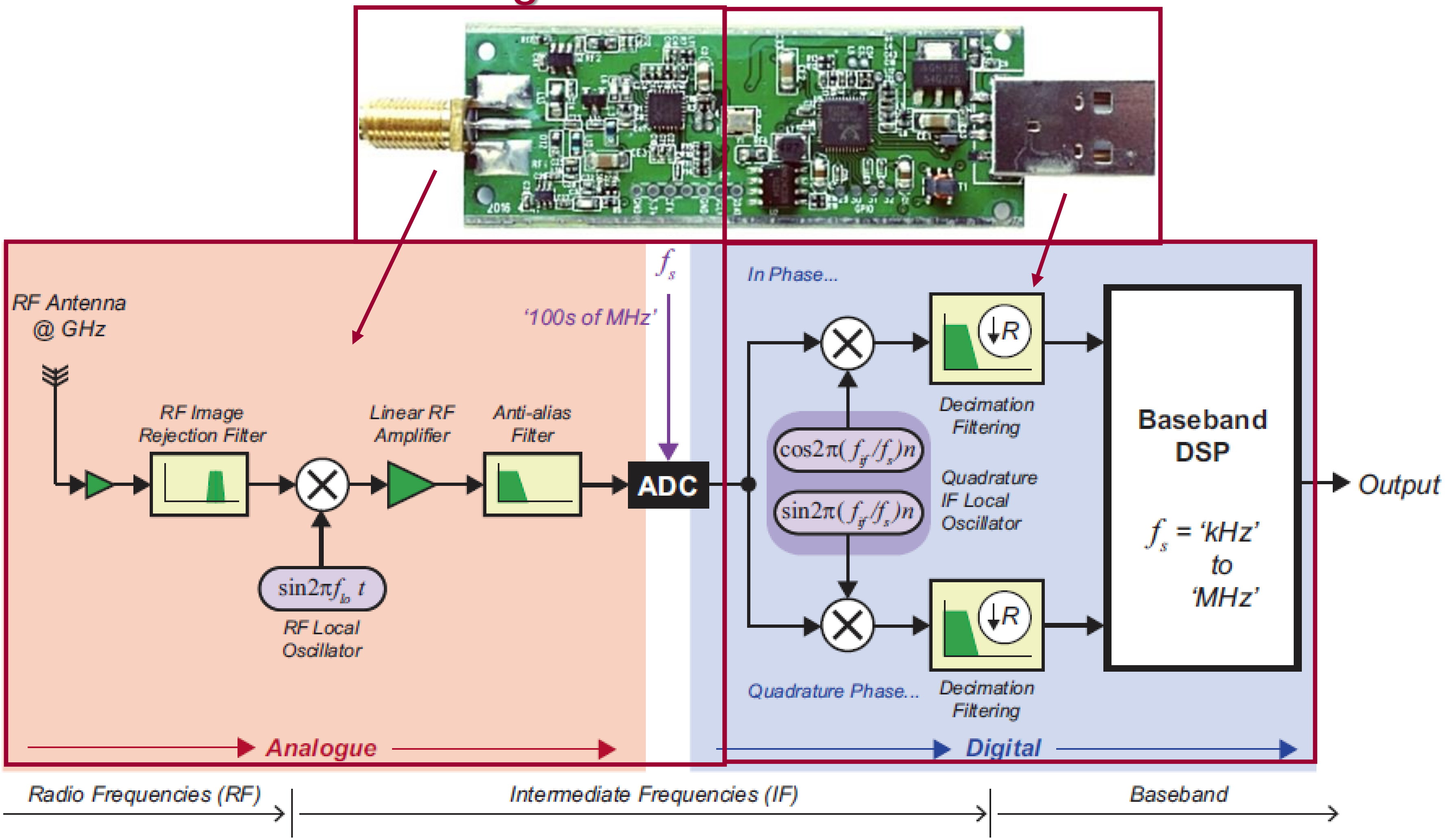
Downsampling reduces the data rate from 2 x 28.8 Msamples/sec (460.8 Mb/sec) to 2.4 Msamples/sec (19.2 Mb/sec) for the USB 2.0 interface.





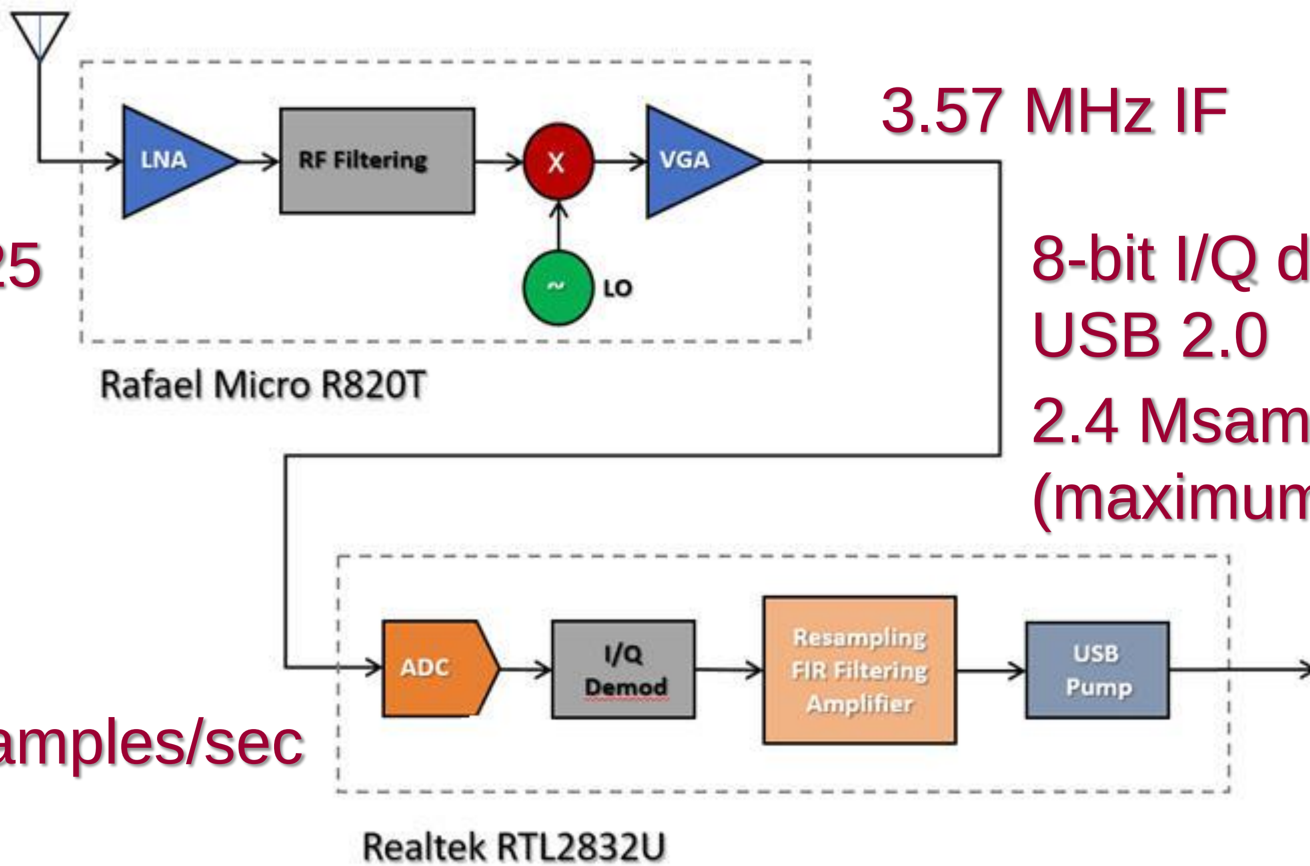
Mini-Workshop on SDR using RTL-SDR

The R820T RF tuner and RTL2832U are interfaced and form the second generation SDR.



Mini-Workshop on SDR using RTL-SDR

The nominal RF frequency range, the down-converted IF and the digital data rate and resolution of the RTL-SDR is shown here.



25-1725 MHz

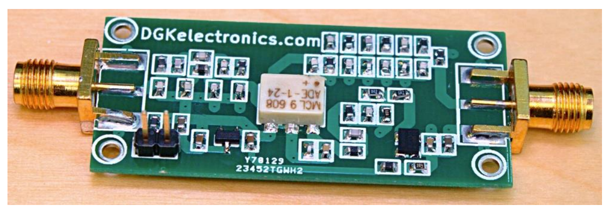
3.57 MHz IF

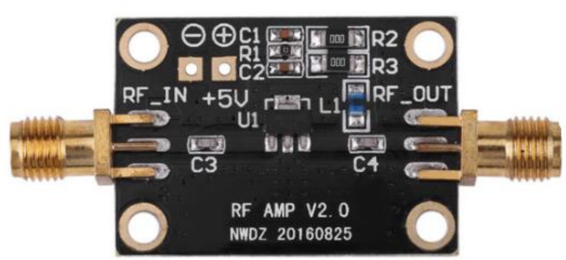
8-bit I/Q data
USB 2.0
2.4 Msamples/sec (maximum)

28.8 Msamples/sec

Mini-Workshop on SDR using RTL-SDR

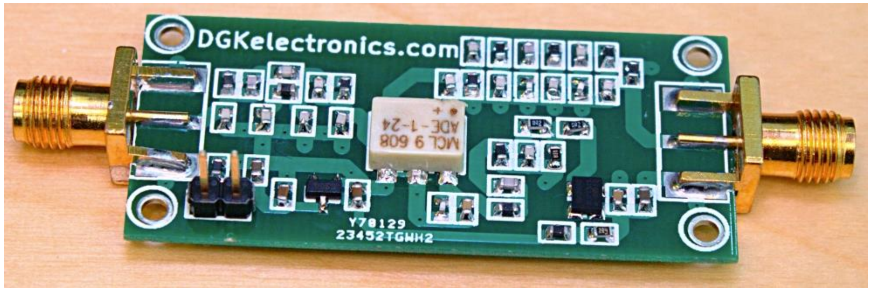
There are several *add-ons* to the basic RTL-SDR to extend its nominal RF frequency range (25−1725 MHz) and to improve performance.





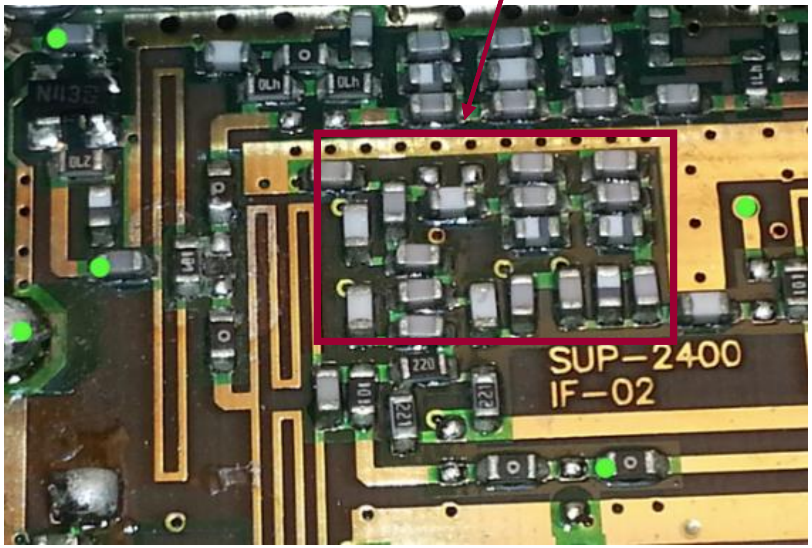
Mini-Workshop on SDR using RTL-SDR

An *upconverter* allows the RTL-SDR to receive signals in the 0.1-60 MHz frequency range. The upconverter is available as an internal *add-on* with a UHF/VHF and HF or an external add-on with only an HF antenna port.



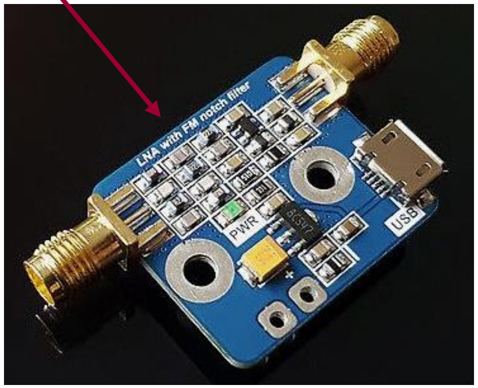
Mini-Workshop on SDR using RTL-SDR

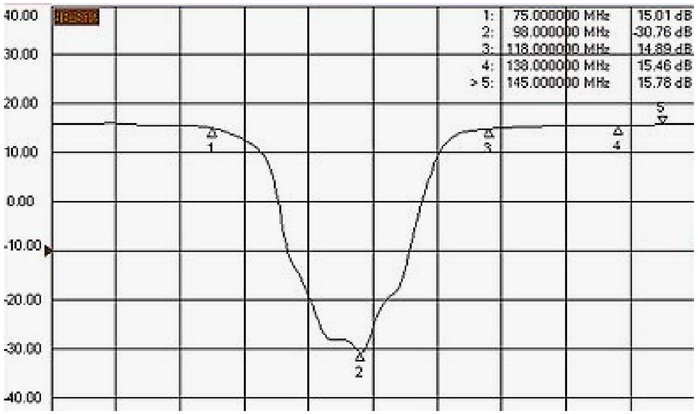
A *downconverter* allows the RTL-SDR to receive signals in the 1800-4500 MHz frequency range. The downconverter is modified from an inexpensive ($5) and readily available device (DirectTV SUP-2400) by removing passive filters.

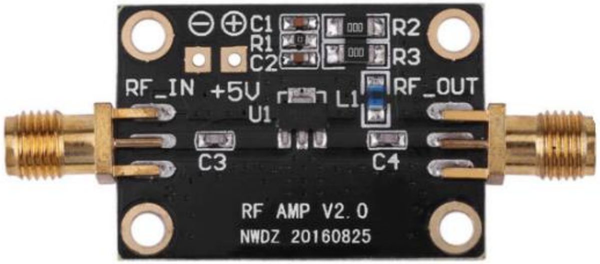


Mini-Workshop on SDR using RTL-SDR

Low noise amplifiers (LNA) are available for narrow or broad band applications. An LNA with a broadcast FM *notch* filter mitigates strong interference.



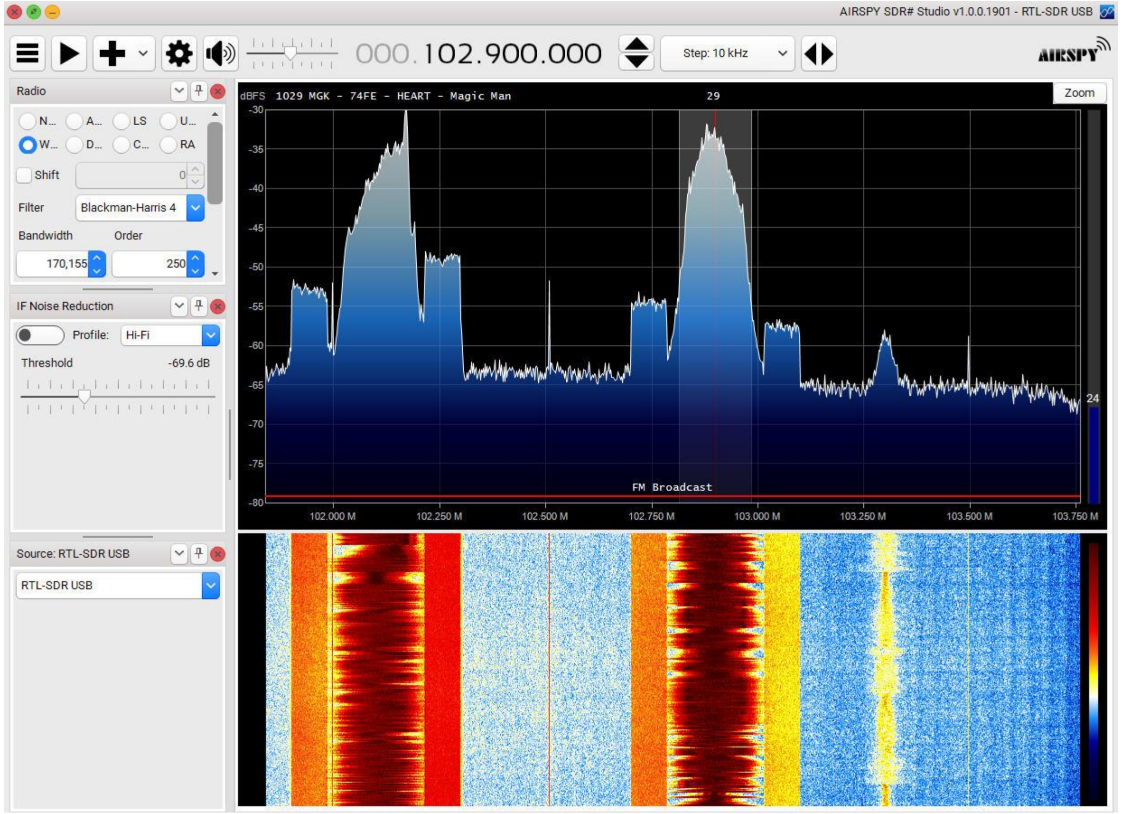




Mini-Workshop on SDR using RTL-SDR

Further demodulation of the I and Q digital data streams is provided by the PC using application software. Freeware (usually) software is available for the RTL-SDR. SDR# (pronounced “SDR Sharp”) is popular.

SDR#



Mini-Workshop on Software Defined Radio using the RTL-SDR

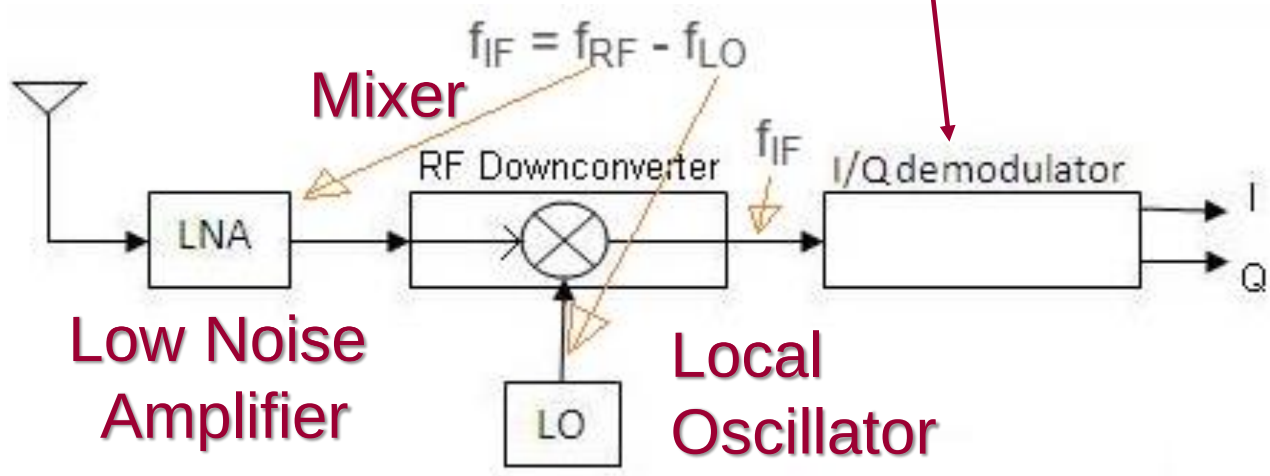
- Signals and Systems
- I/Q Signals, SDR and the RLT-SDR
- Direct Conversion to Baseband
- RTL-SDR Hands-On and Applications
- Additional Topics

Mini-Workshop on SDR using RTL-SDR

As described earlier, the general form of a modulated signal has an inphase (I, cosine) and quadrature (Q, sine) components with the *baseband* information signals $g_1(t)$ and $g_2(t)$.

$$y(t) = g_1(t)\cos(2\pi f_c t) - g_2(t)\sin(2\pi f_c t)$$

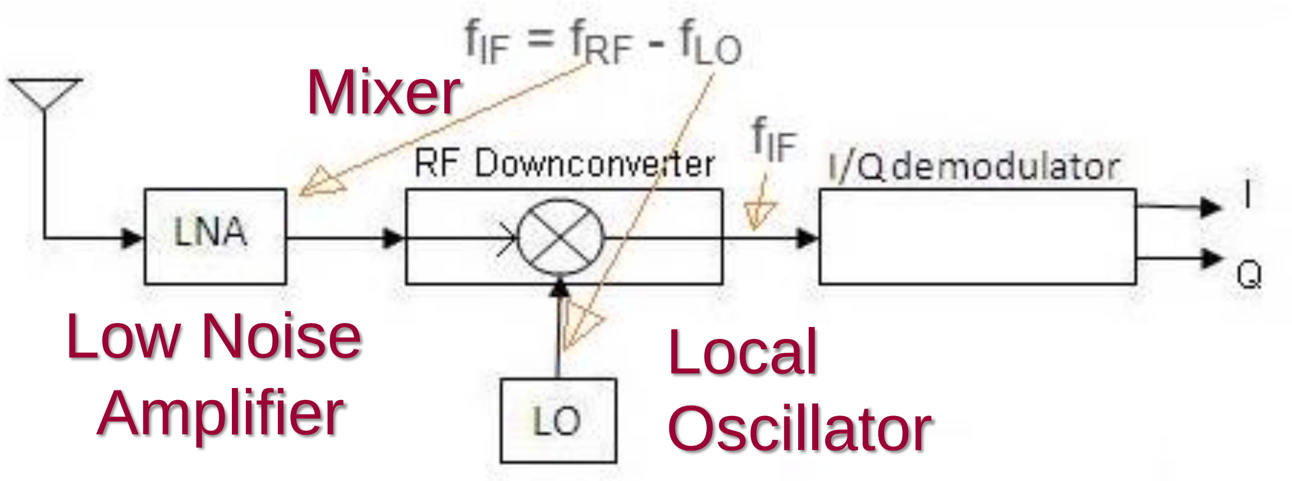
This is referred to as I/Q modulation for the transmitter followed by I/Q demodulation in the receiver.



Mini-Workshop on SDR using RTL-SDR

Receiver architecture has until recently used the *heterodyne* or *super heterodyne* architecture.

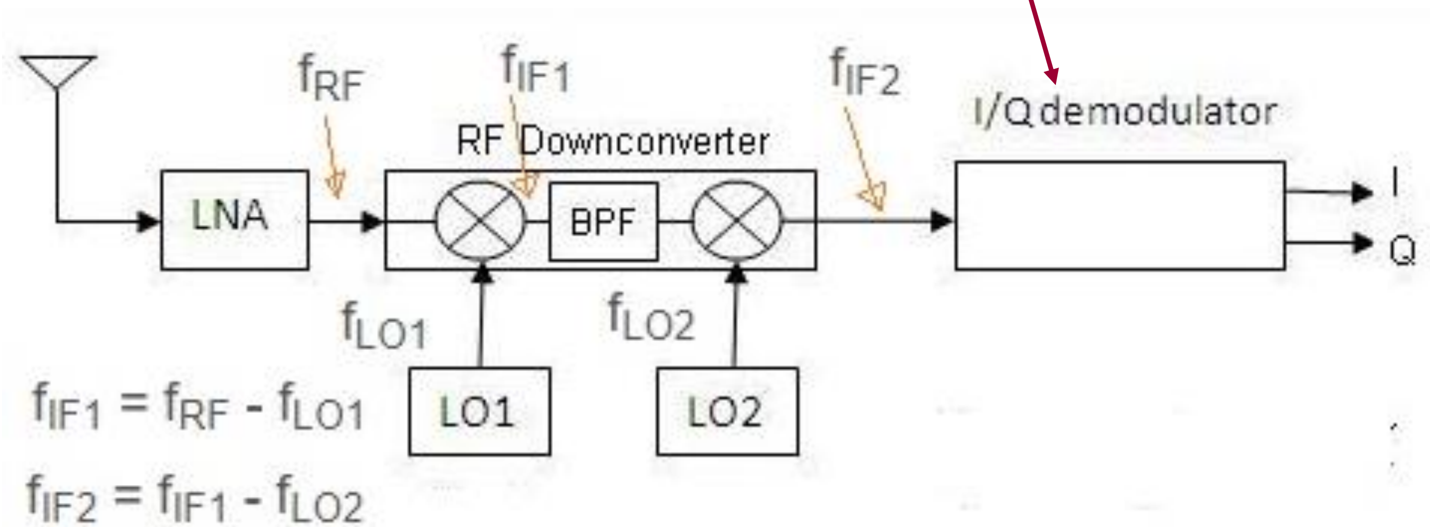
The *heterodyne* receiver uses *one mixer* to convert the modulated RF signal to a modulated IF signal. This signal is then applied to I/Q demodulator which brings the modulated low IF to baseband output frequencies.



Mini-Workshop on SDR using RTL-SDR

The *super heterodyne* receiver uses *two mixers* to bring the modulated RF signal to the modulated IF signal.

The first mixer brings the RF signal to the IF1 signal. The second mixer brings the IF1 signal to the IF2 signal. This IF2 signal is then applied to I/Q demodulator which brings the modulated low IF to baseband output frequencies.

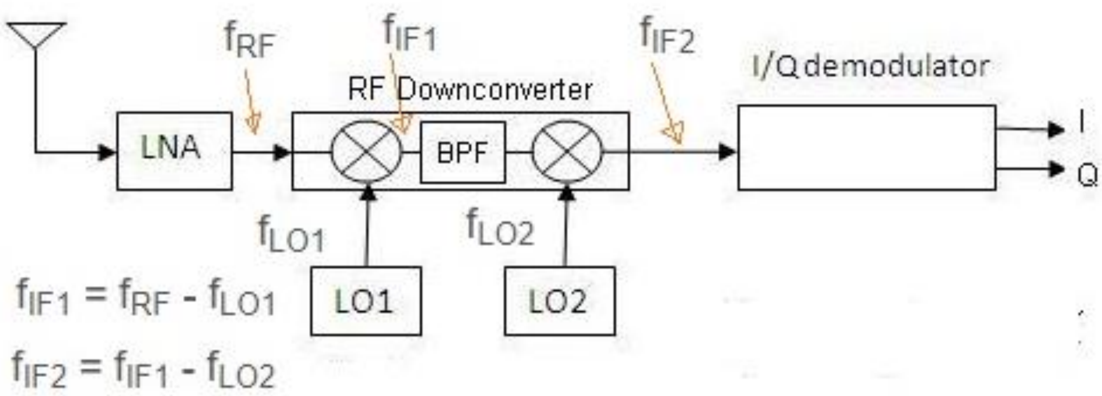


Mini-Workshop on SDR using RTL-SDR

The *advantages* of the heterodyne and super heterodyne receiver are that:

- Since it converts high frequency to low frequency, all processing takes place at lower frequencies. The devices are cheaper at such lower frequencies compare to higher frequencies.

- It is also easier to filter an IF signal compared to RF signal.

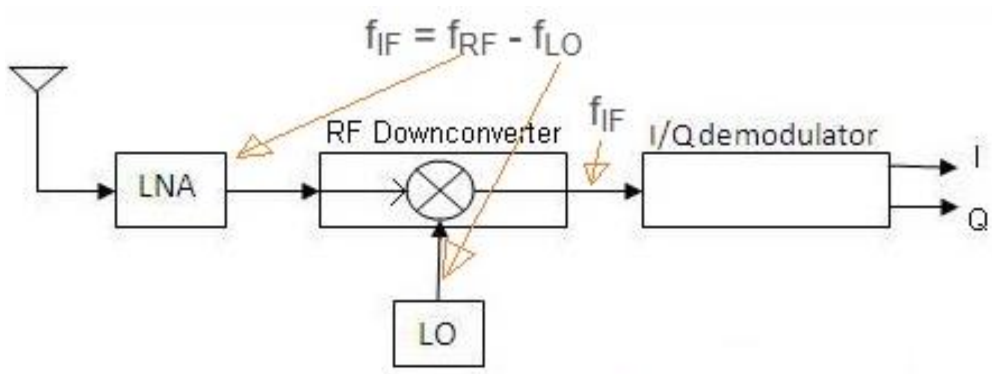


Mini-Workshop on SDR using RTL-SDR

The *disadvantages* of the heterodyne and super heterodyne receiver are that:

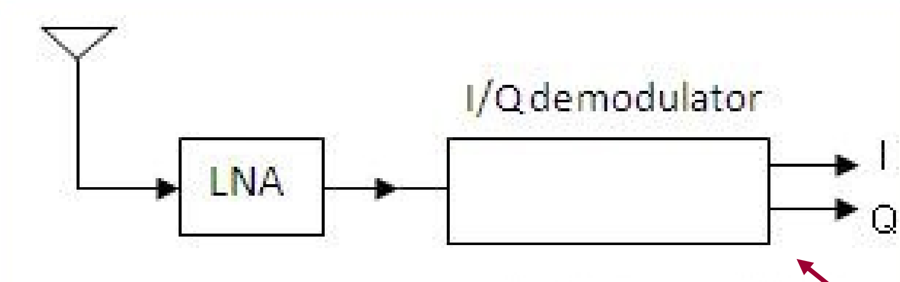
- They requires additional LOs and RF Mixers to convert the signal from RF to IF before conversion to baseband. This increases the cost.

- Filters are needed to remove any LO *leakage* as well as undesired frequency components to prevent *image* frequencies. This increases the complexity.

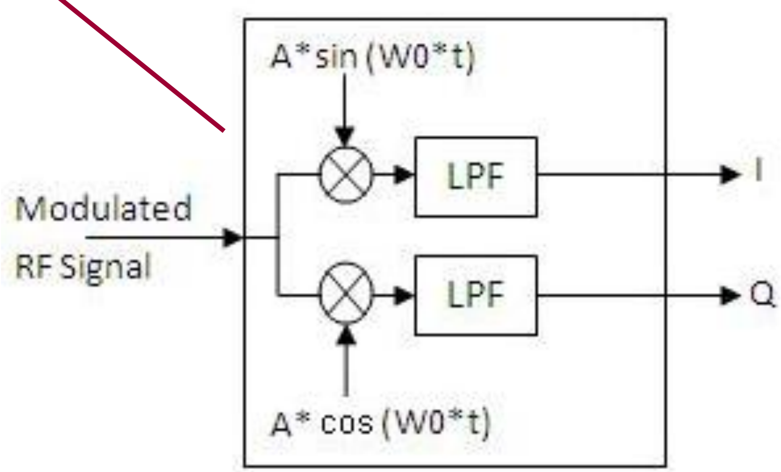


Mini-Workshop on SDR using RTL-SDR

The *homodyne* or *direct conversion* receiver does not require any mixers at the RF stage. The modulated RF signal is directly applied to I/Q demodulator which outputs the baseband information signals $g_1(t)$ and $g_2(t)$.



Low Noise Amplifier

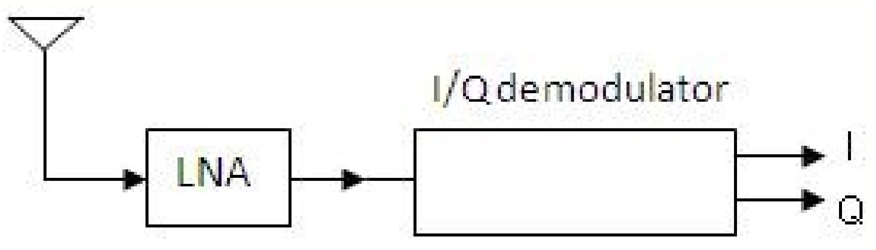


Mini-Workshop on SDR using RTL-SDR

The *advantages* of homodyne receiver are that:

- It uses same frequency for LO as the transmit RF frequency for conversion to the baseband information signal frequency. Thus, it is a very simple architecture for both transmit and receive.

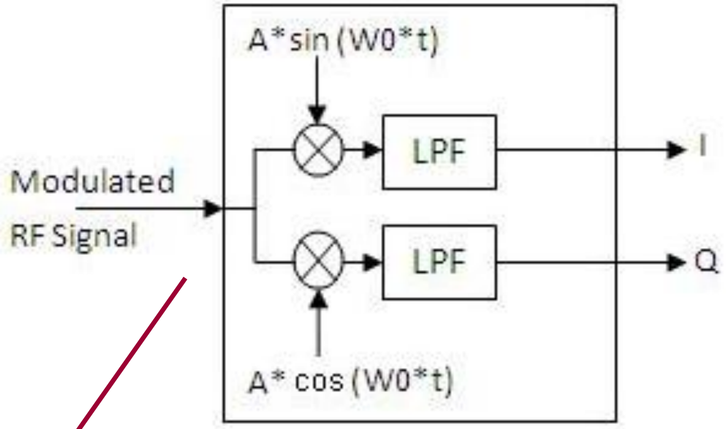
- The RF components such as LOs, RF mixers and filters are not needed as for the heterodyne receiver architecture. Hence the complexity is less.

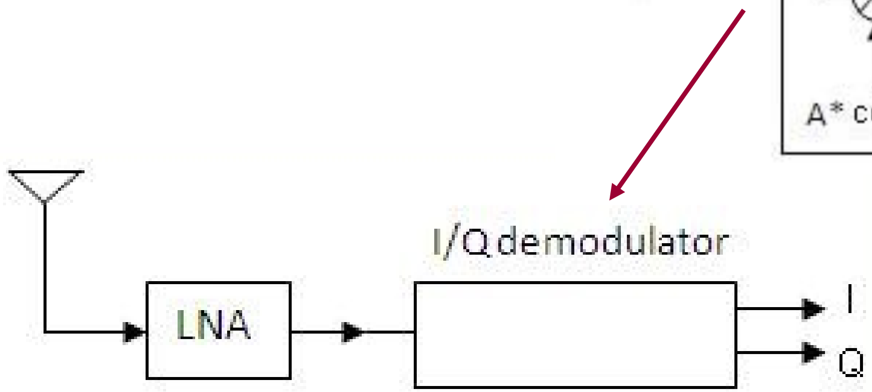


Mini-Workshop on SDR using RTL-SDR

The *disadvantage* of homodyne receiver is that:

- The homodyne receiver suffers from LO *leakage*. It should be as low as possible in order to properly demodulate I/Q signals at baseband information signal frequencies.



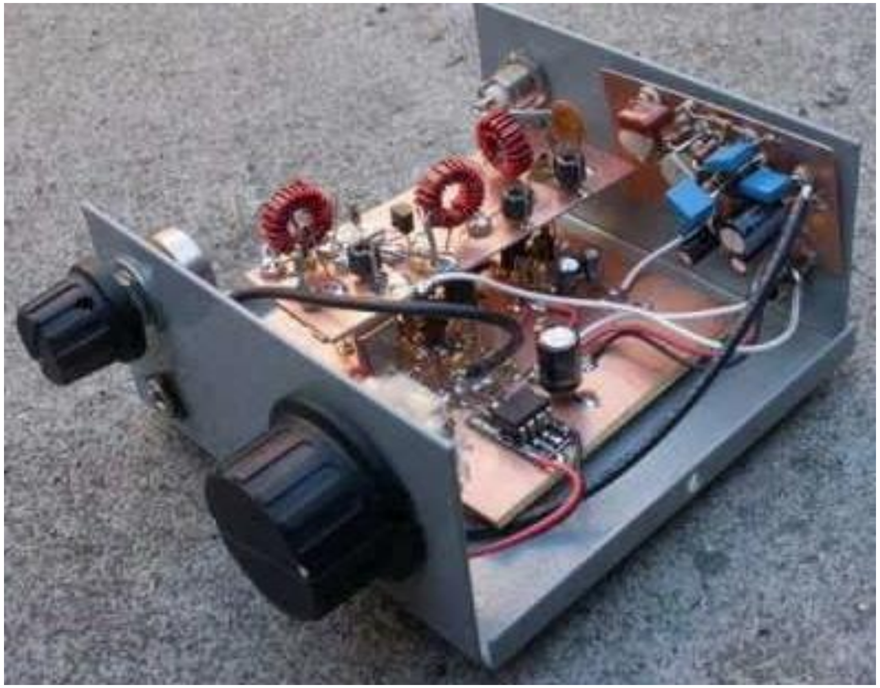


Mini-Workshop on SDR using RTL-SDR

The origins of the homodyne or direct conversion receiver date back to 1924 when a single down-conversion receiver was first described.

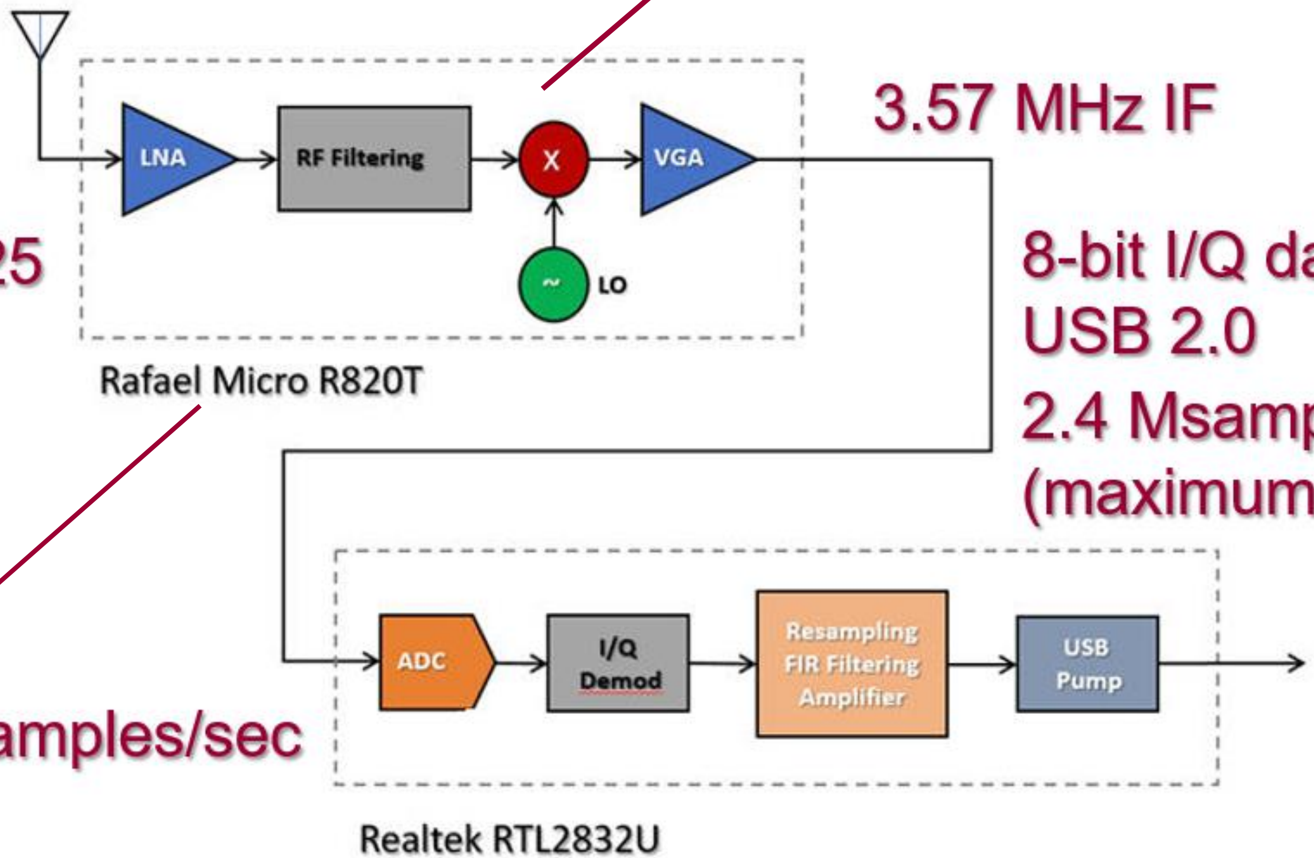
The homodyne is popular in Amateur Radio for simple portable HF receivers.

Homebrew 7 MHz CW (Continuous Wave using Morse code) direct conversion receiver and transmitter



Mini-Workshop on SDR using RTL-SDR

The RLT-SDR is a heterodyne receiver since it uses one mixer to convert the modulated RF signal to a modulated IF signal *near baseband* sampled at f_s as digital data.



25-1725 MHz

3.57 MHz IF

8-bit I/Q data

USB 2.0

2.4 Msamples/sec (maximum)

f_s = 28.8 Msamples/sec

Mini-Workshop on SDR using RTL-SDR

The sampling rate f_s is usually considered to be at least, but greater than, the *Nyquist rate* = $2\,W$ where W is the bandwidth of the signal.

For example, a 3 kHz bandwidth *baseband* voice signal is usually sampled at 8 kHz (>2 W) as in telephony.

Theorem

A signal having no frequency components above W Hertz is completely described by specifying the values of the signal at periodic time instants that are separated by at most $1/2W$ seconds.

Harry Nyquist
1889-1976

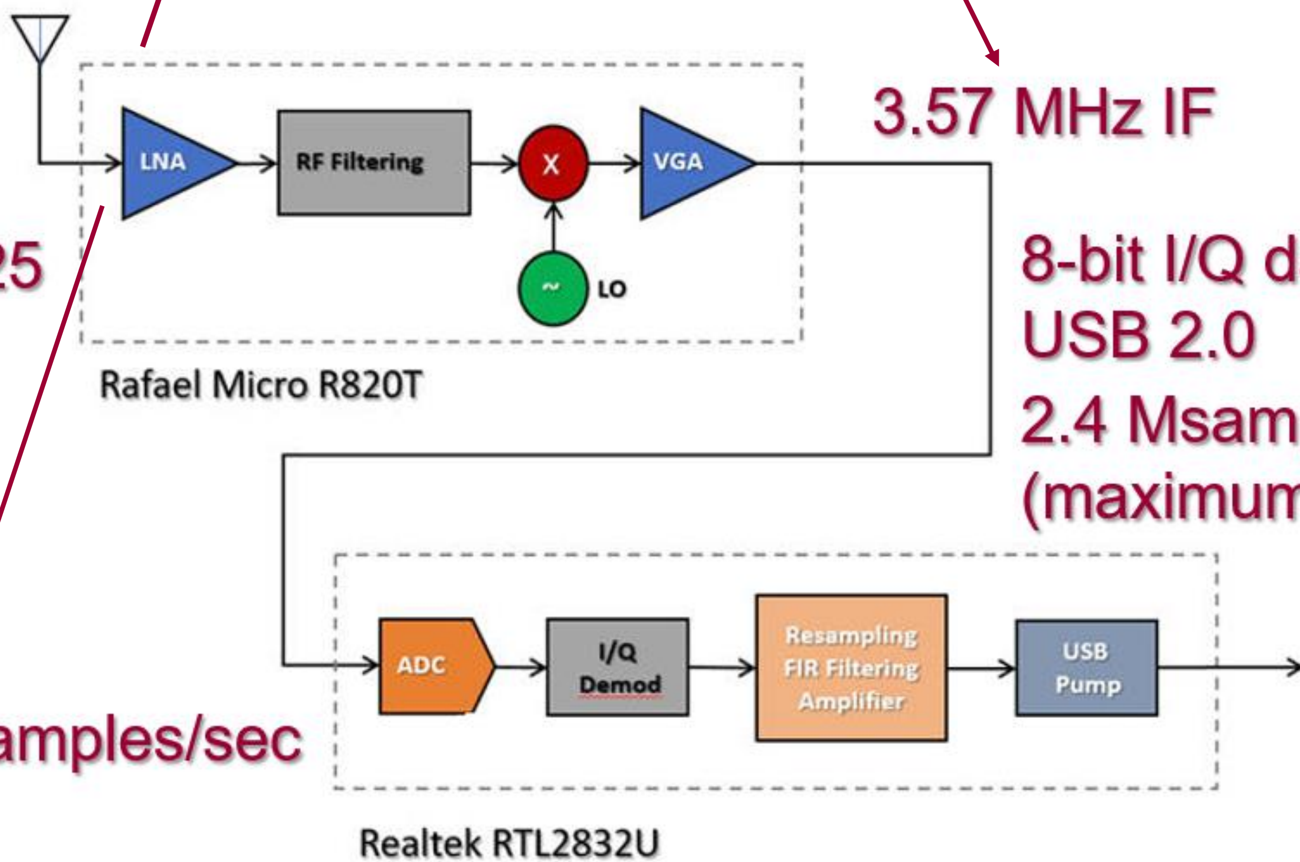
Mini-Workshop on SDR using RTL-SDR

The RLT-SDR has an IF signal 3.57 MHz and is sampled at f_s = 28.8 Msamples/sec. Here $W \approx$ 4.2 MHz (actually $\approx$ 3 to 4.2 MHz).

3.57 MHz IF

25-1725 MHz

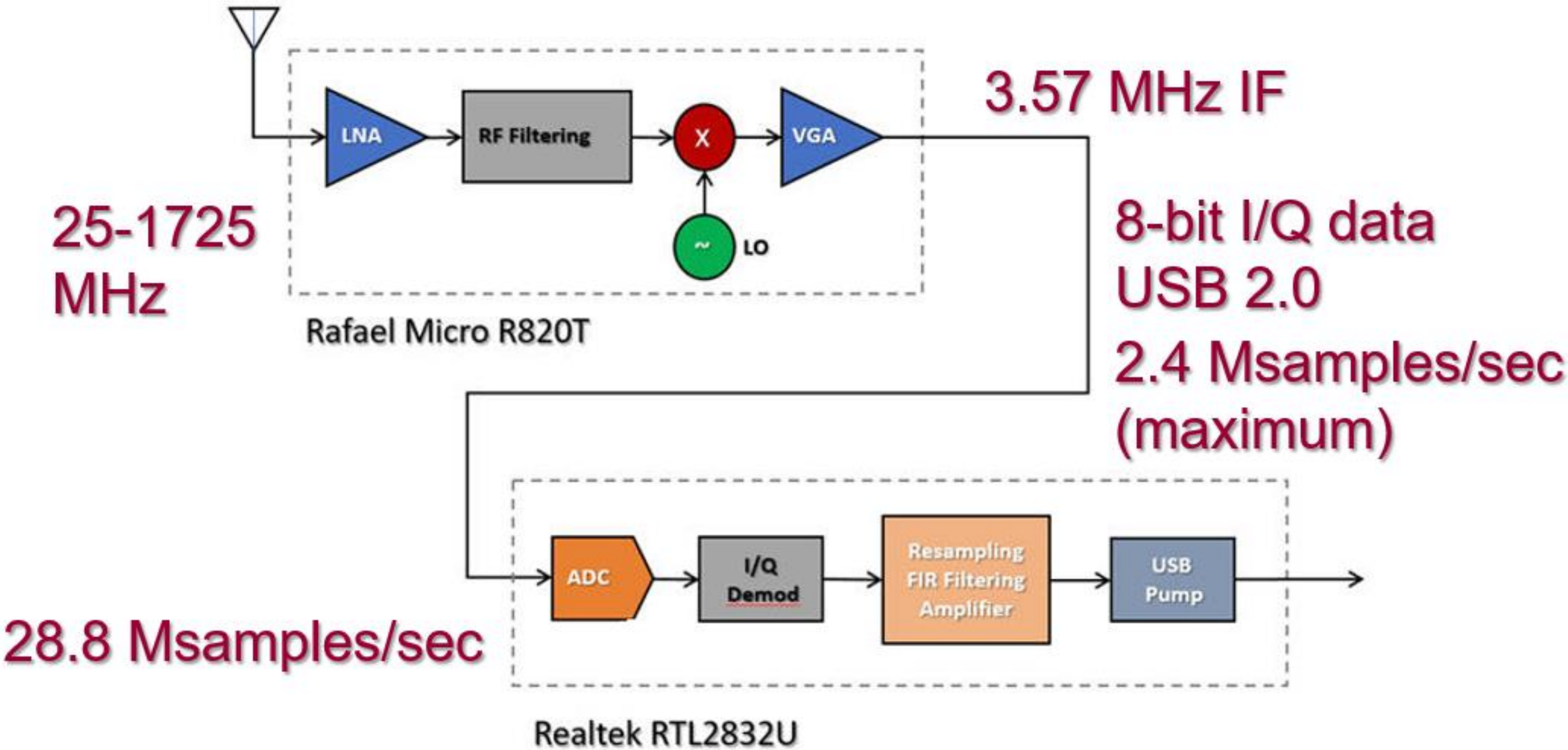
8-bit I/Q data
USB 2.0
2.4 Msamples/sec (maximum)



28.8 Msamples/sec

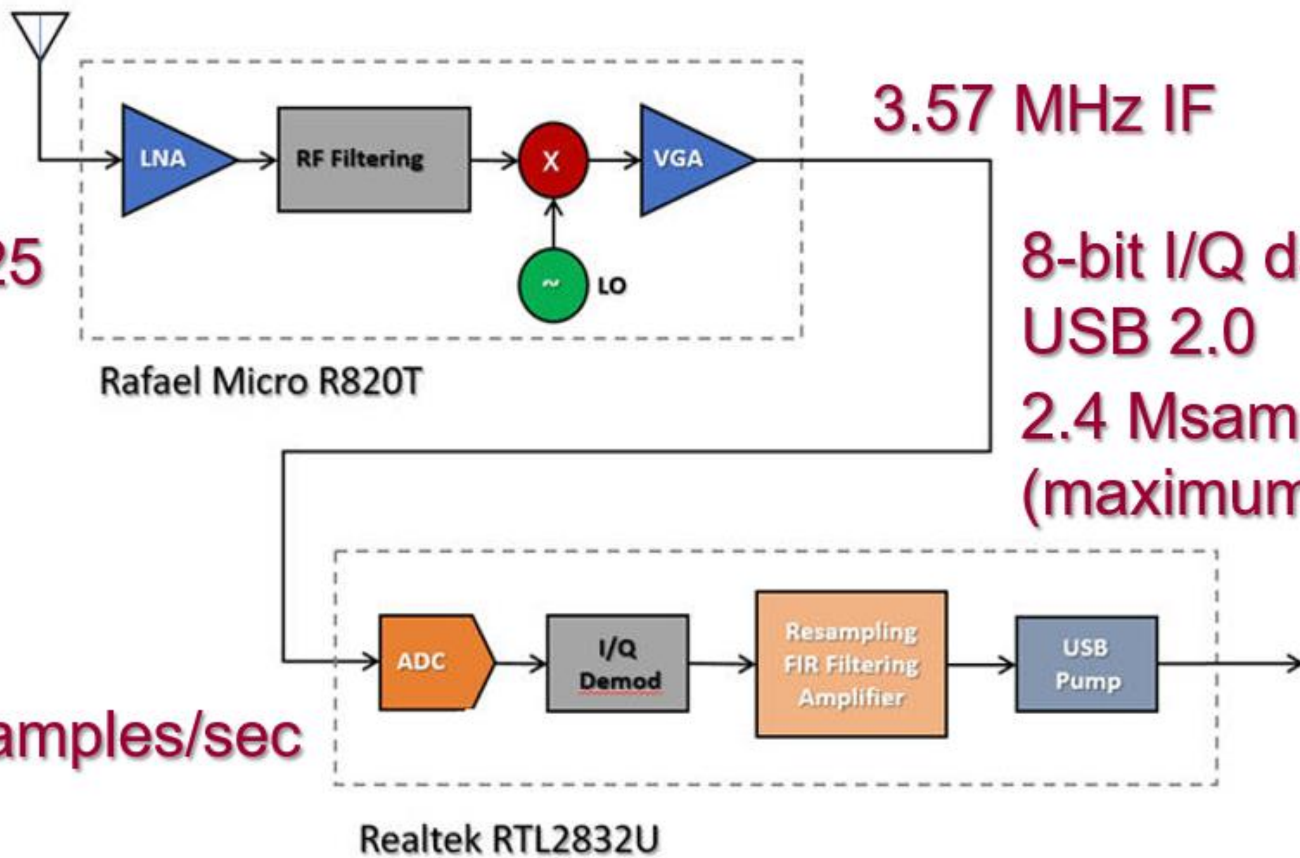
Mini-Workshop on SDR using RTL-SDR

The RTL-SDR is an example of *Nyquist sampling* where f_s = 28.8 Msamples/sec > 2 W = 8.4 MHz.



Mini-Workshop on SDR using RTL-SDR

The nominal IF bandwidth at 3.57 MHz of the RTL-SDR is about 1.2 MHz (≈ 3 to 4.2 MHz).



3.57 MHz IF

25-1725 MHz

8-bit I/Q data

USB 2.0

2.4 Msamples/sec (maximum)

28.8 Msamples/sec

Mini-Workshop on Software Defined Radio using the RTL-SDR

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- RTL-SDR Hands-On and Applications
- Additional Topics

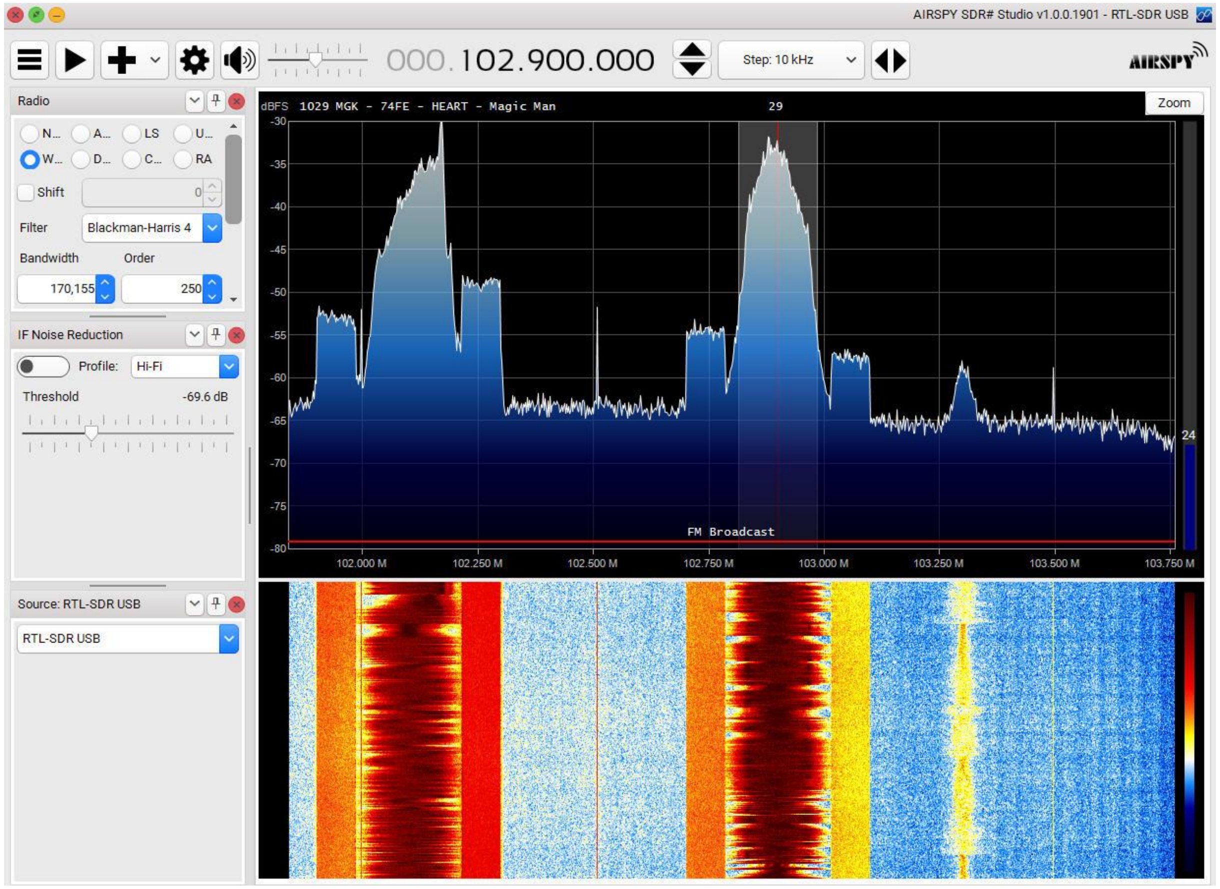
Mini-Workshop on SDR using RTL-SDR

Open and assemble the RLT-SDR device and its external antenna. Use the longer *dipole* antenna for VHF (30-300 MHz) reception. Connect the antenna to the RTL-SDR device using the SMA coaxial cable.

Mini-Workshop on SDR using RTL-SDR

There are several freeware applications for the RTL-SDR that are available. SDR# (pronounced "SDR Sharp") is used here. Now to complete its installation.

SDR#

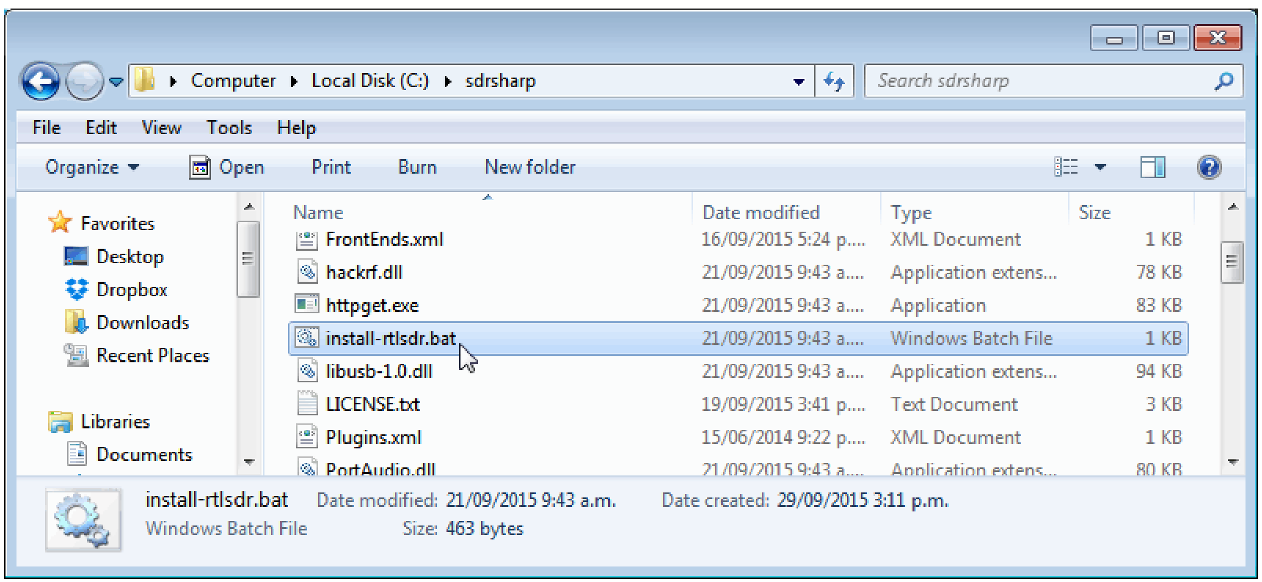


Mini-Workshop on SDR using RTL-SDR

The SDR# application should have been downloaded and extracted to the root directory as C:\sdrsharp following the instructions for steps 1 through 4 at:

https://www.rtl-sdr.com/rtl-sdr-quick-start-guide/

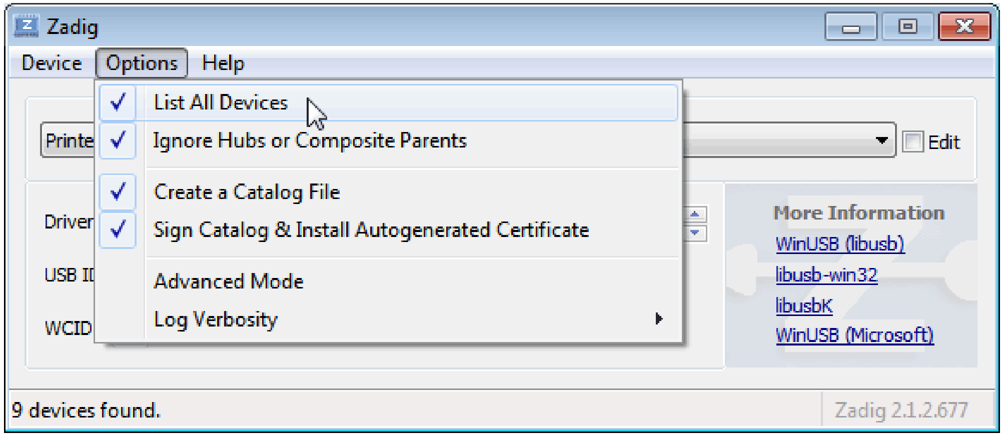
Run *install-rtlsdr.bat* as in step 5.



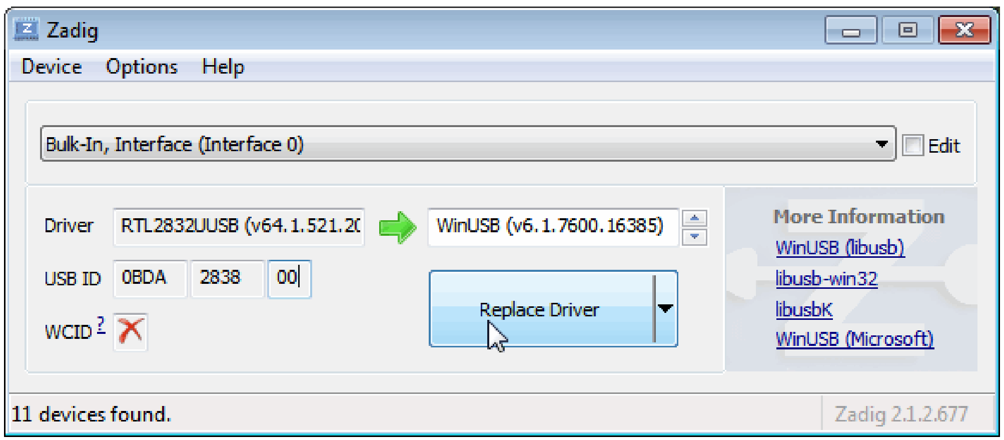
Mini-Workshop on SDR using RTL-SDR

The RTL-SDR device is now plugged in at a USB port as step 6. Run the *Zadig* application as described in steps 7 through 11. Close the *Zadig* application.

Steps 7 and 8



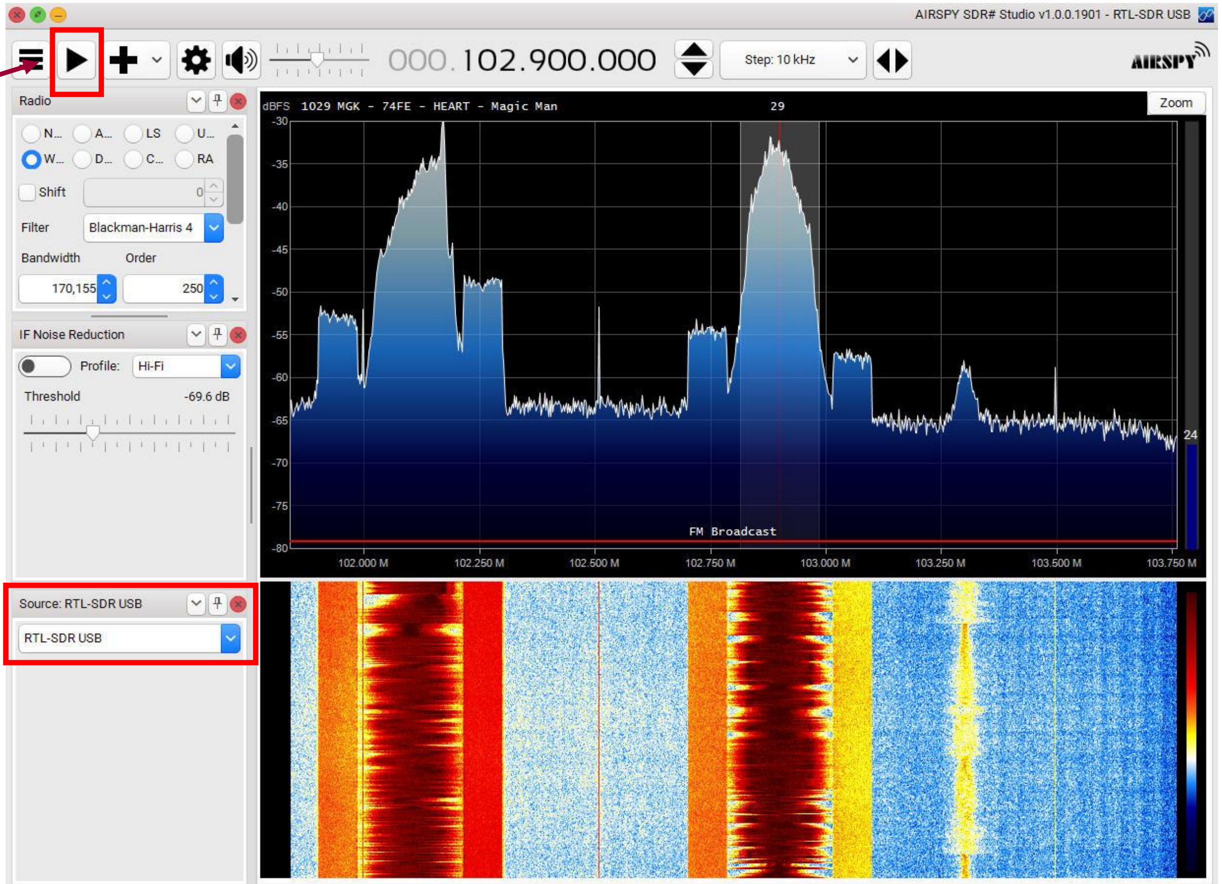
Steps 9, 10 and 11



Mini-Workshop on SDR using RTL-SDR

Open SDR# and set the *Source* to *RTL-SDR USB* as in step 12. Press the *Play* button ▶ to begin using the device as in step 13.

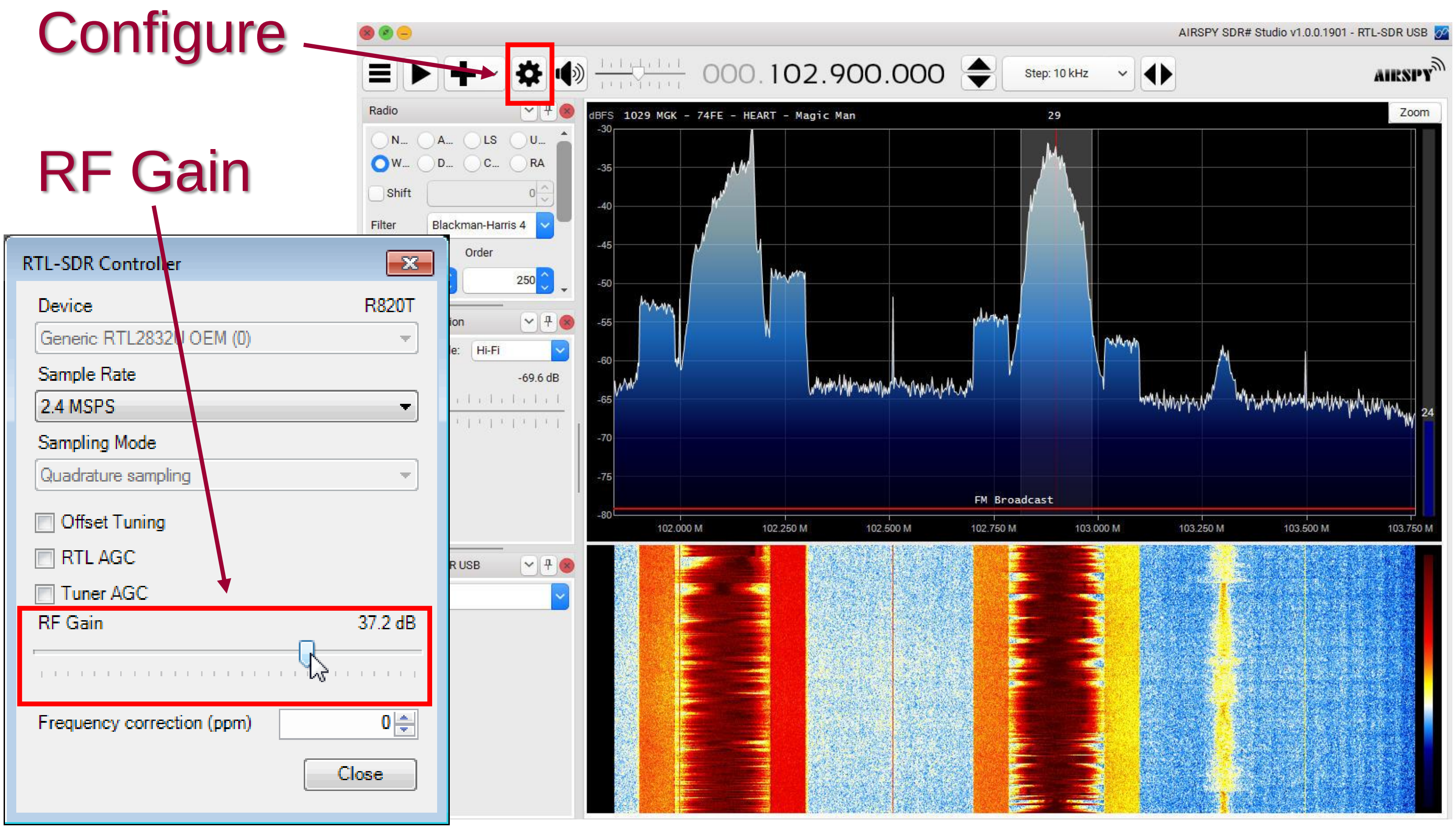
Play



Source set to RTL-SDR USB

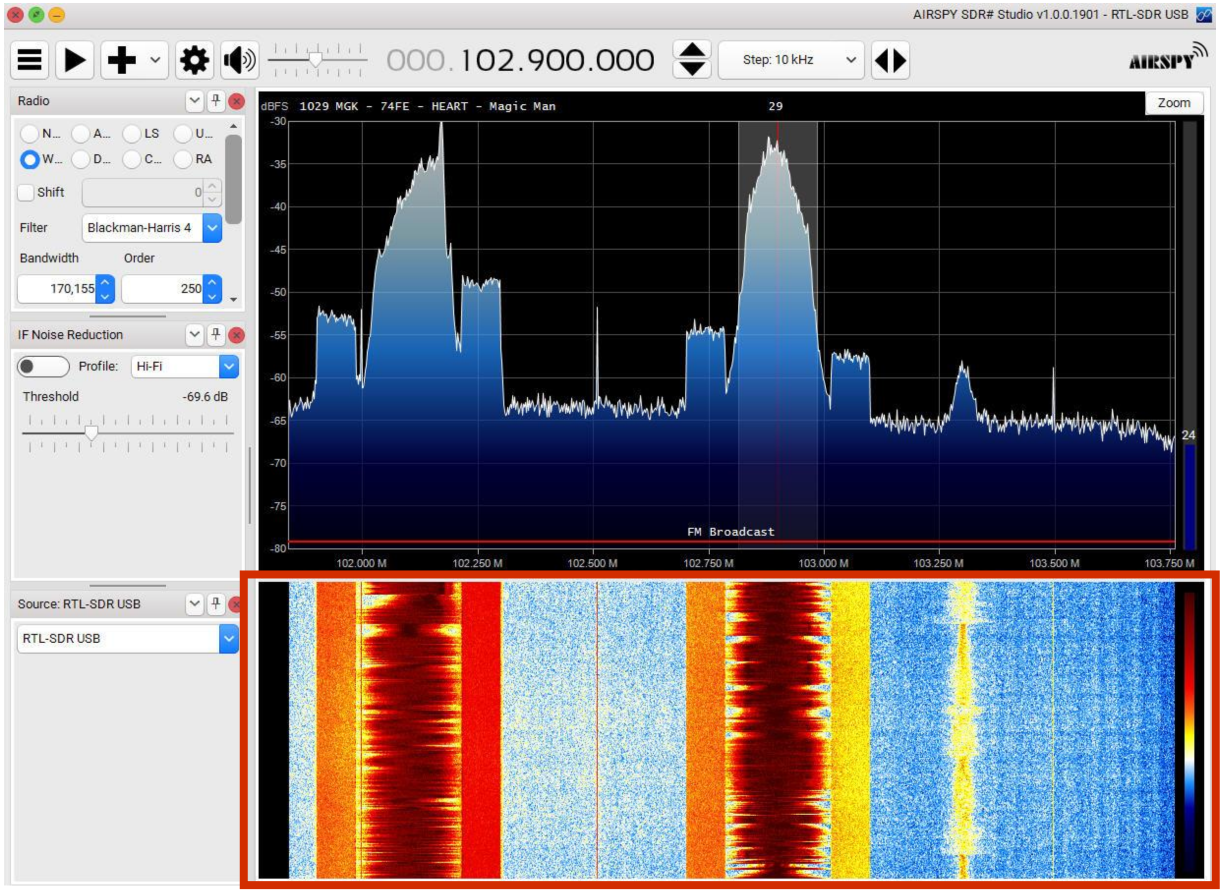
Mini-Workshop on SDR using RTL-SDR

Adjust the *RF Gain* setting to greater than 0 using the Configure button as in step 14.



Mini-Workshop on SDR using RTL-SDR

The SDR# application is described in a concise *Users Guide*: https://www.rtl-sdr.com/sdrsharp-users-guide/



Mini-Workshop on SDR using RTL-SDR

SDR# is a versatile (and complex) application. There is also a free manual that describes in detail all the capabilities and features of SDR#.

https://airspy.com/downloads/SDRSharp_Big_Book_v5.5.pdf

Additional references and software applications can be found at:

https://www.rtl-sdr.com/about-rtl-sdr/

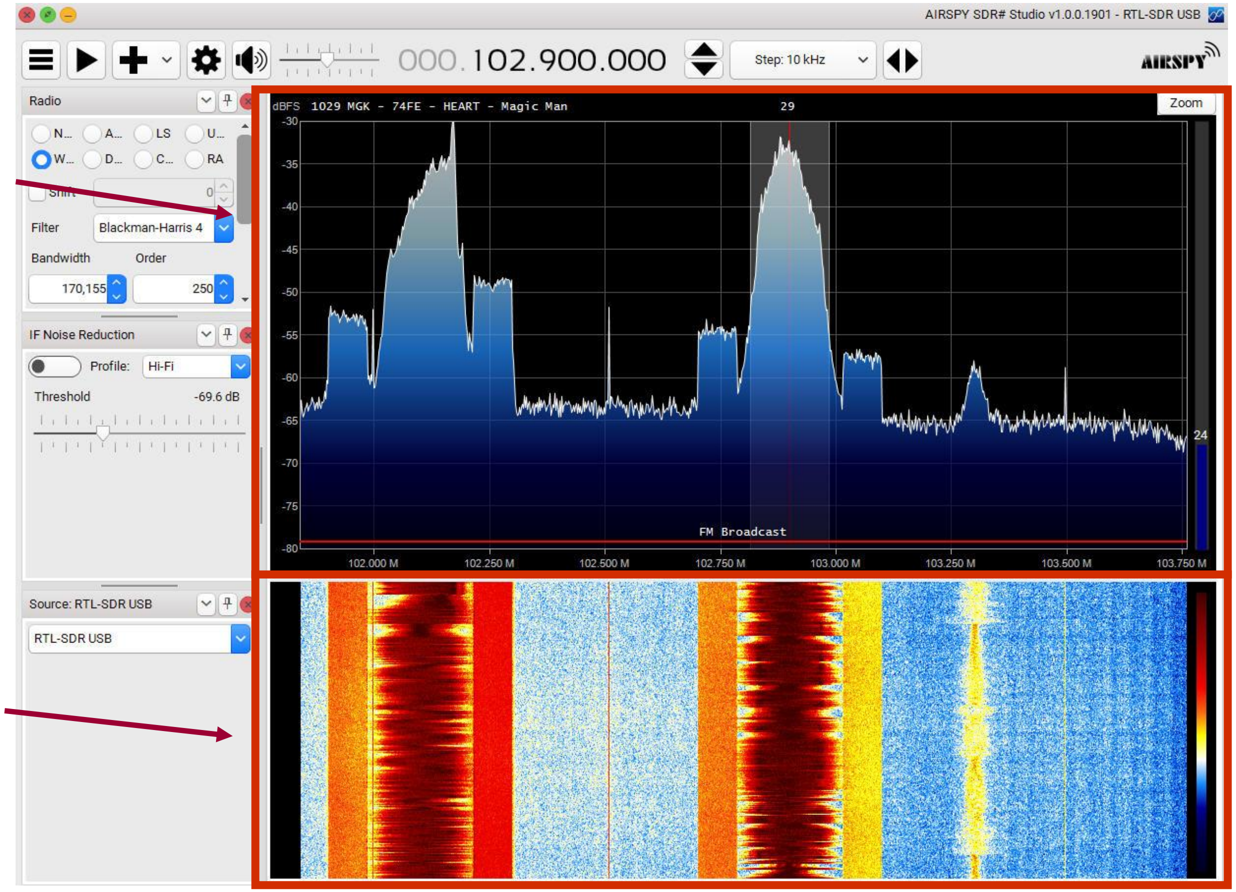
Mini-Workshop on SDR using RTL-SDR

SDR# includes a standard *spectrum* and *waterfall* display, a frequency manager and digital noise reduction.

Spectrum

SDR#

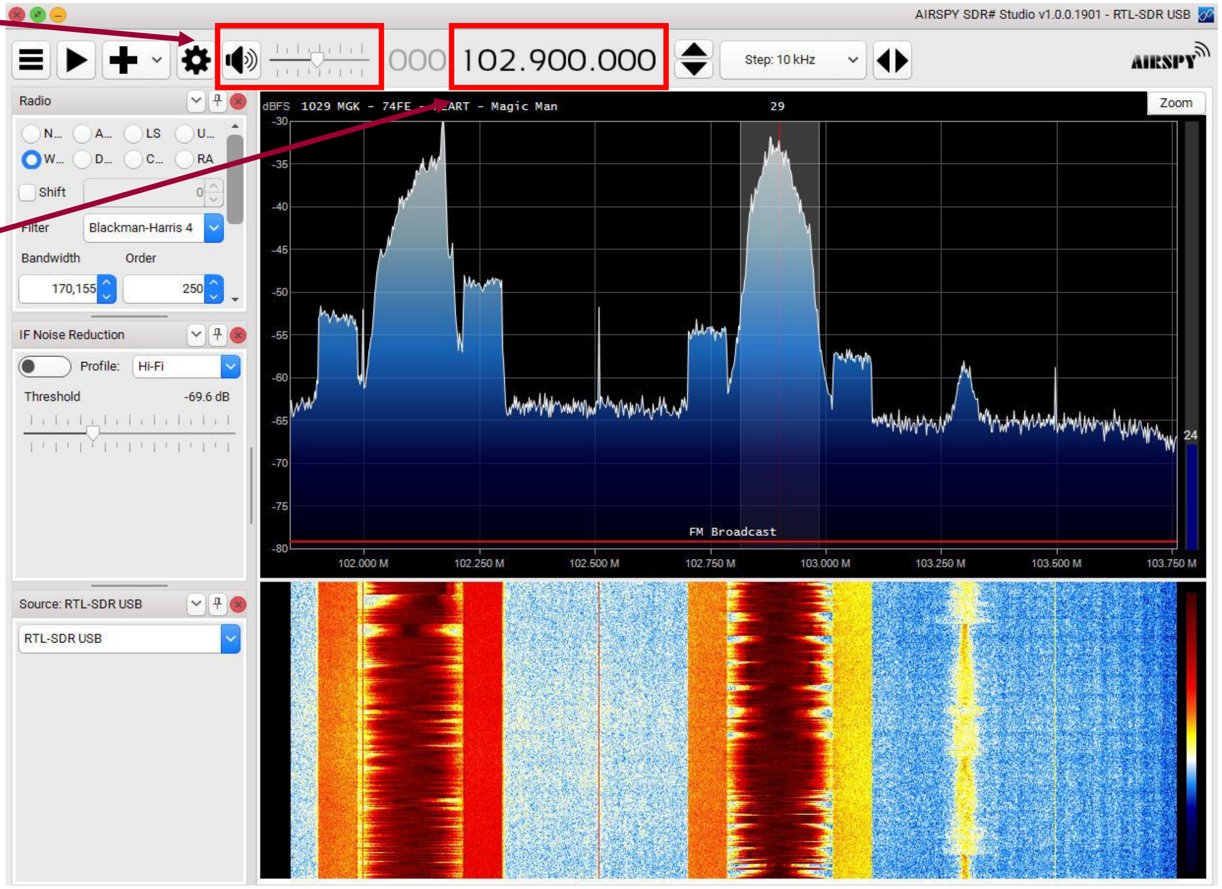
Waterfall



Mini-Workshop on SDR using RTL-SDR

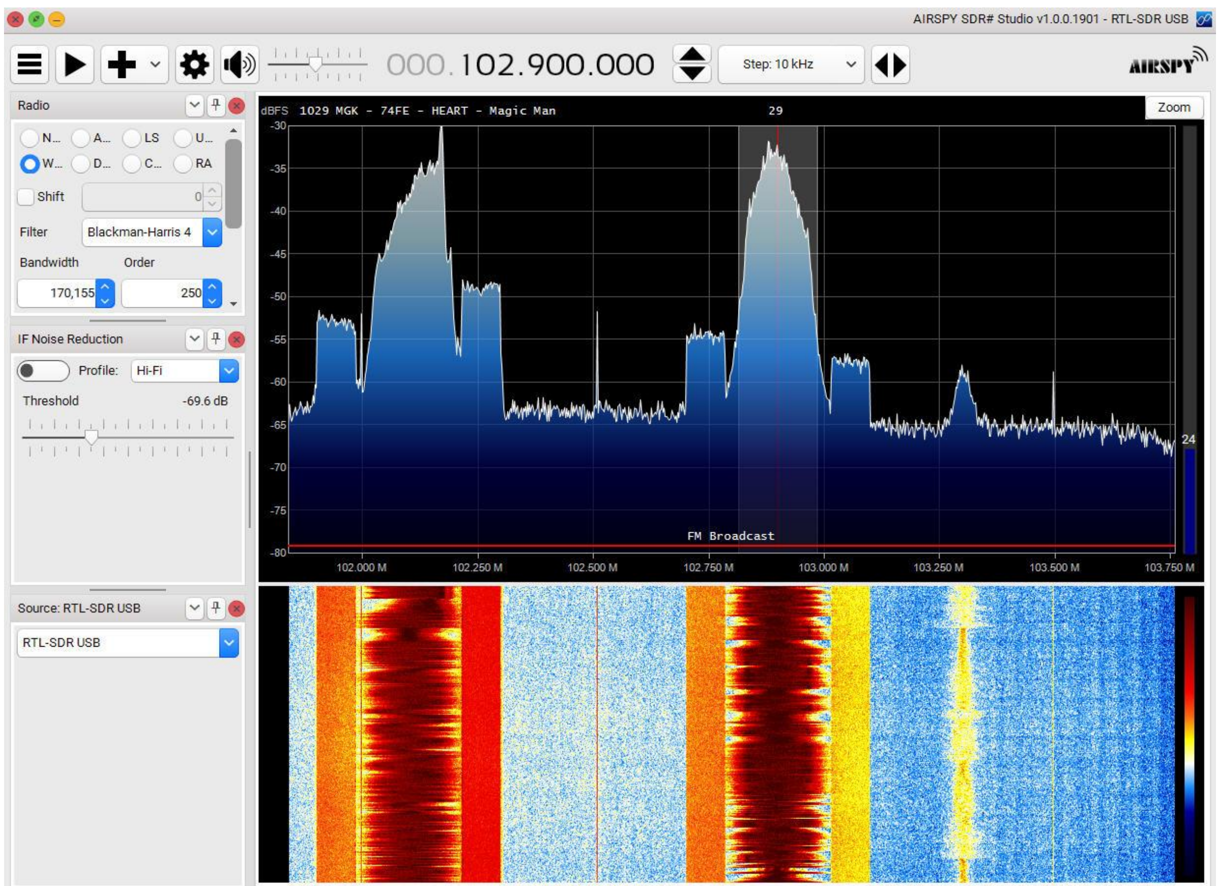
To verify the installation, use the RTL-SDR and SDR# for the *hands-on* reception of an analog FM broadcast (from 88 to 108 MHz). The demodulated audio can be played.

102.9 MHz
WMGK
Philadelphia



Mini-Workshop on SDR using RTL-SDR

Let’s take the time to see if we all can have the RTL-SDR receiving an FM broadcast (88-108 MHz) with help if necessary.



Mini-Workshop on SDR using RTL-SDR

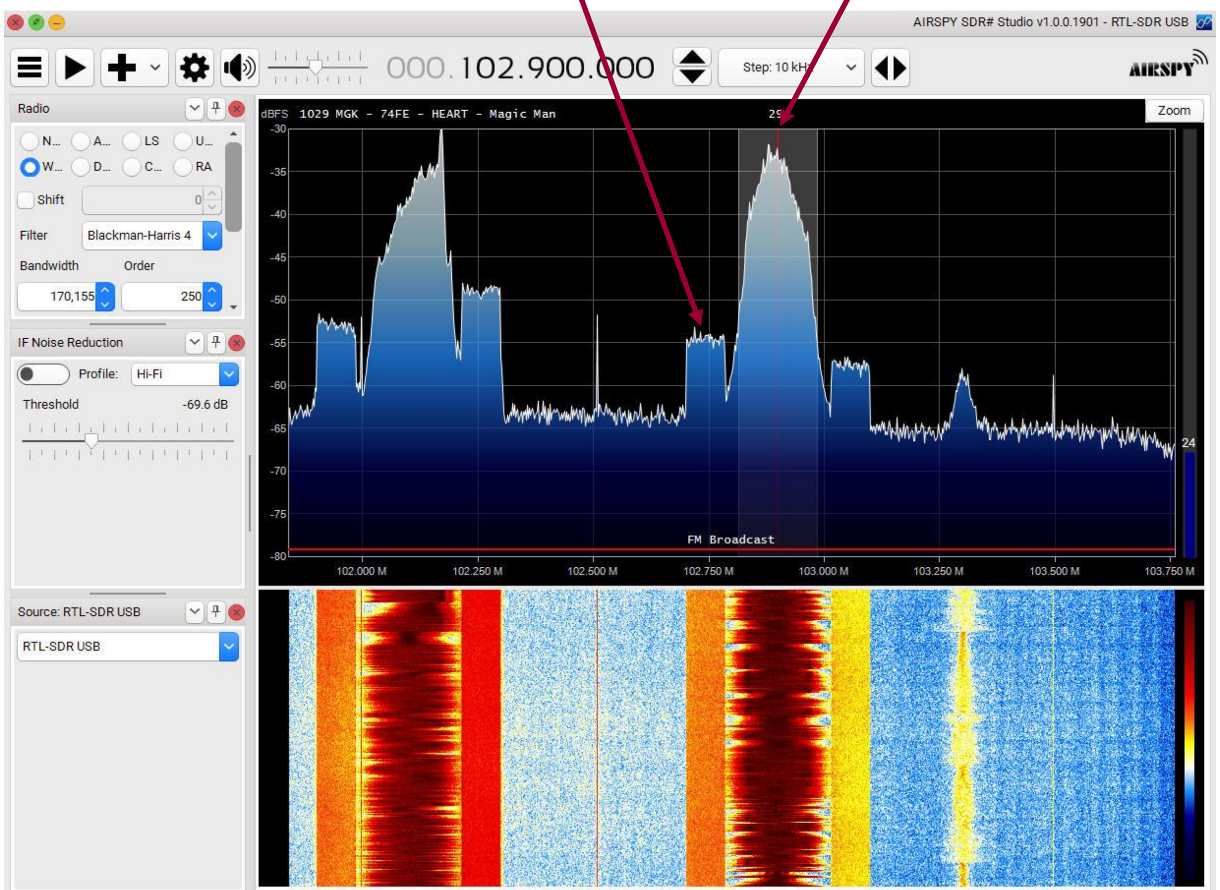
The RTL-SDR is a *frequency agile* receiver that can demodulate a variety of analog and digital signal from *over-the-air* broadcast and unicast sources and satellite images:

- FM broadcast, wide band FM (WBFM) with pre-emphasis and de-emphasis for noise reduction
- Radio Broadcast Data System (RBDS) for FM broadcast program information

https://www.rtl-sdr.com/about-rtl-sdr/

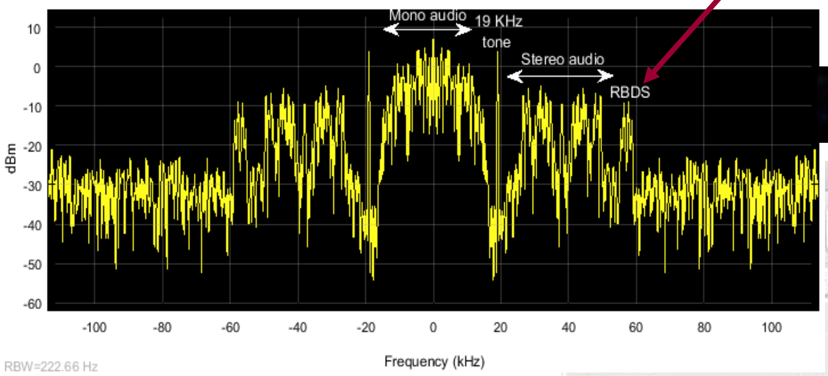
Mini-Workshop on SDR using RTL-SDR

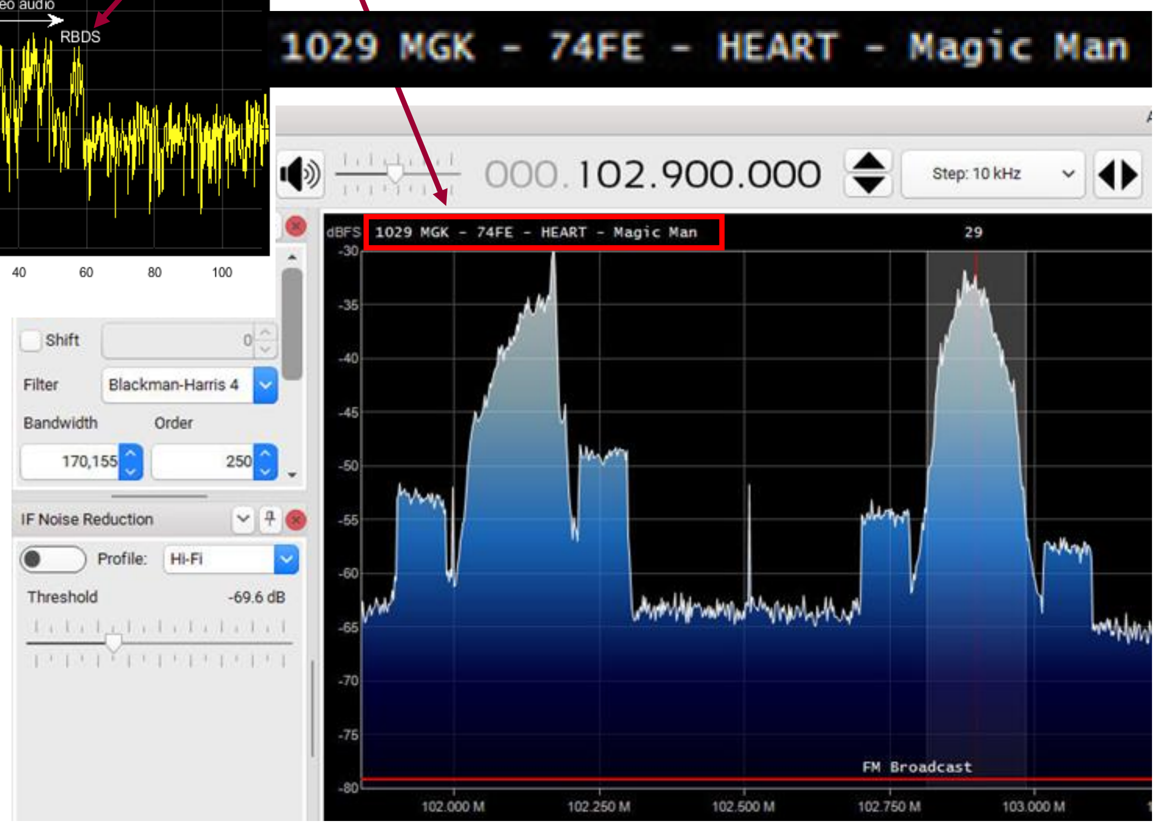
RTL-SDR and SDR# for the reception of analog WBFM (wide band FM) and HD digital broadcasts.



Mini-Workshop on SDR using RTL-SDR

RTL-SDR and SDR# for reception of the digital Radio Broadcast Data System (RBDS) information during an analog FM broadcast.





Mini-Workshop on SDR using RTL-SDR

Other applications for the RTL-SDR include:

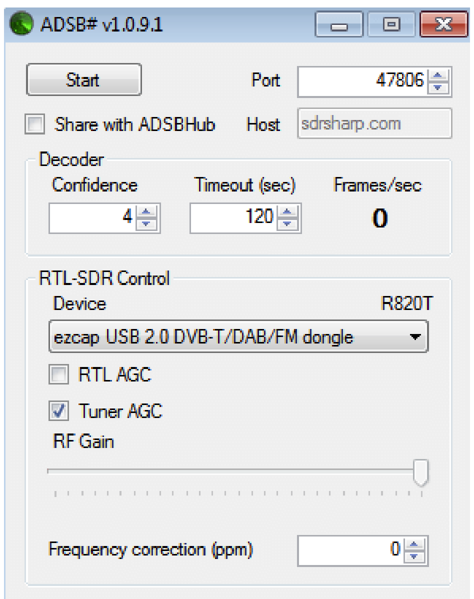
- Automatic Dependent Surveillance-Broadcast (ADS-B) aircraft flight identification
- Aircraft Communications Addressing and Reporting System (ACARS) for messages
- NOAA weather satellite images
- Shortwave digital broadcasts (DRM)
- Radio astronomy

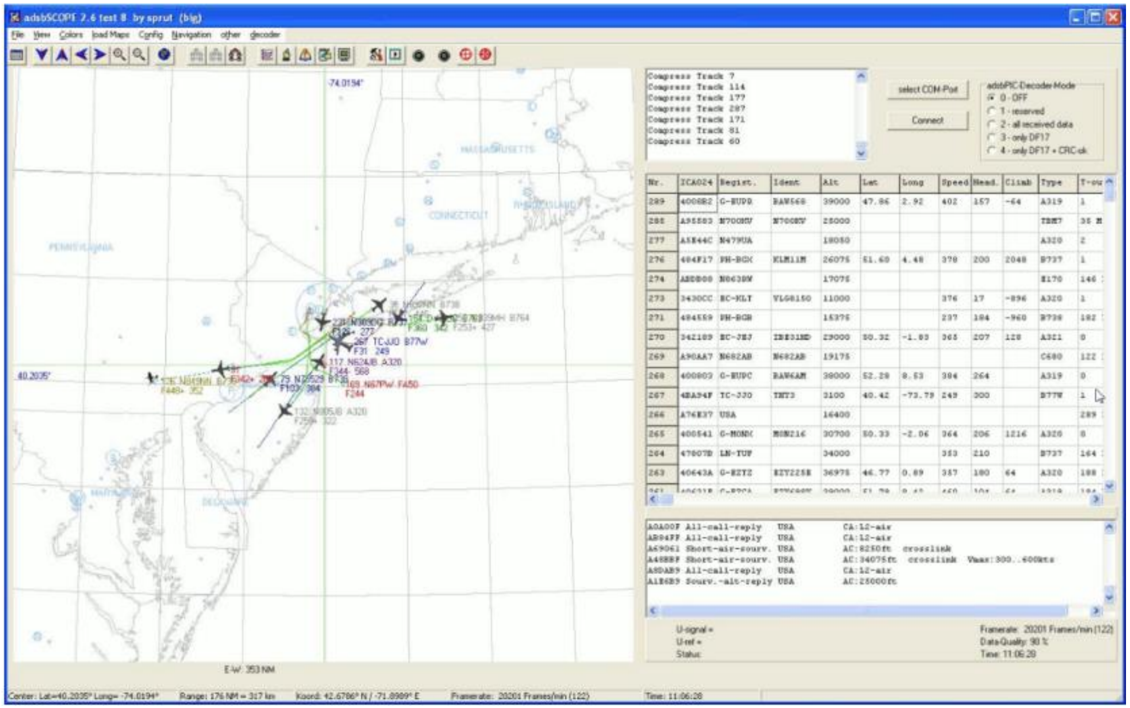
https://www.rtl-sdr.com/about-rtl-sdr/

Mini-Workshop on SDR using RTL-SDR

RTL-SDR, ADSB# software and an LNA for the reception of ADS-B aircraft flight identification for a later application.

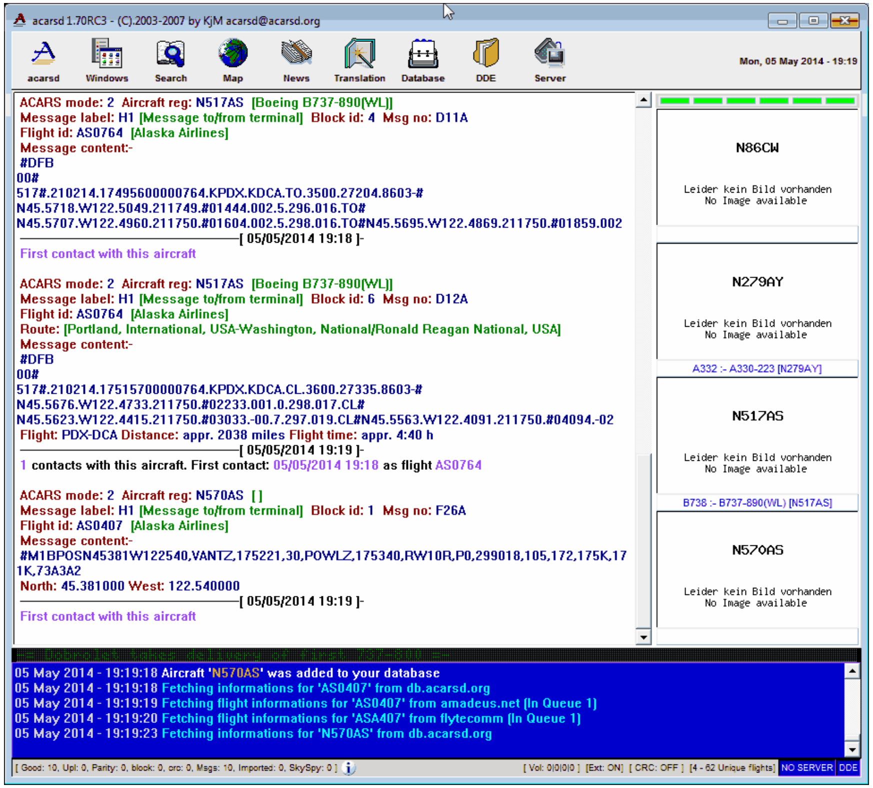
https://www.rtl-sdr.com/adsb-aircraft-radar-with-rtl-sdr/





Mini-Workshop on SDR using RTL-SDR

RTL-SDR, SDR# and ACARSD add-on for the reception of the Aircraft Communications Addressing and Reporting System (ACARS) for short messages to aircraft and from ground stations for a later application.

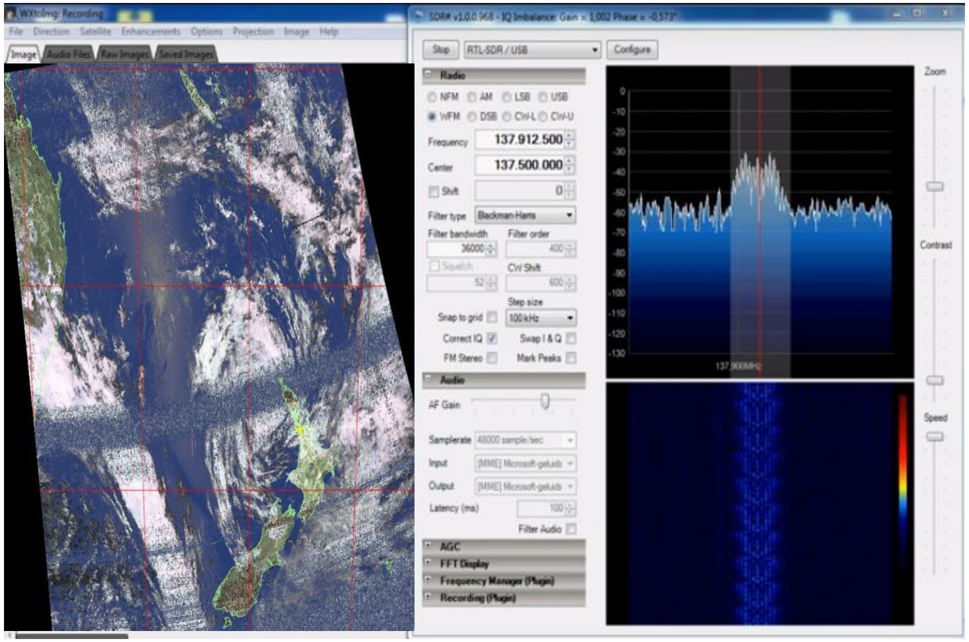


https://www.rtl-sdr.com/rtl-sdr-radio-scanner-tutorial-receiving-airplane-data-with-acars/

Mini-Workshop on SDR using RTL-SDR

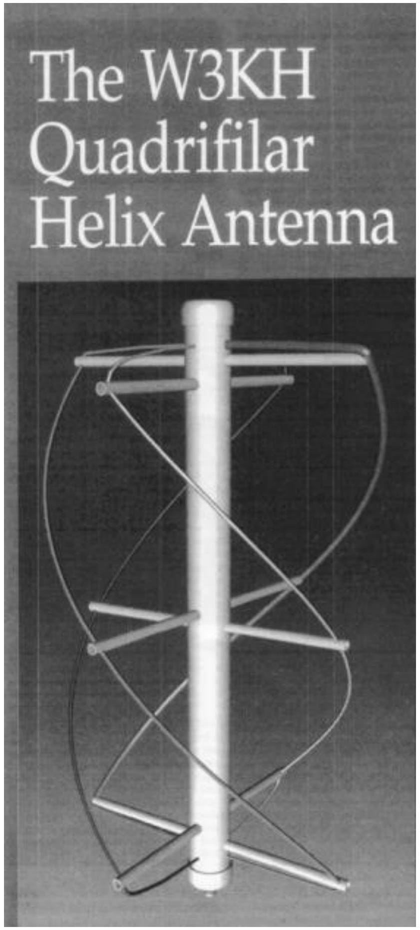
RTL-SDR, SDR#, quadrifilar antenna, LNA and WXtomg decoding software are used to receive NOAA weather satellite images at 137 MHz for a later application.

https://www.rtl-sdr.com/rtl-sdr-tutorial-receiving-noaa-weather-satellite-images/



Mini-Workshop on SDR using RTL-SDR

The quadrifilar antenna can be easily constructed.
http://jcoppens.com/ant/qfh/calc.en.php



Mini-Workshop on SDR using RTL-SDR

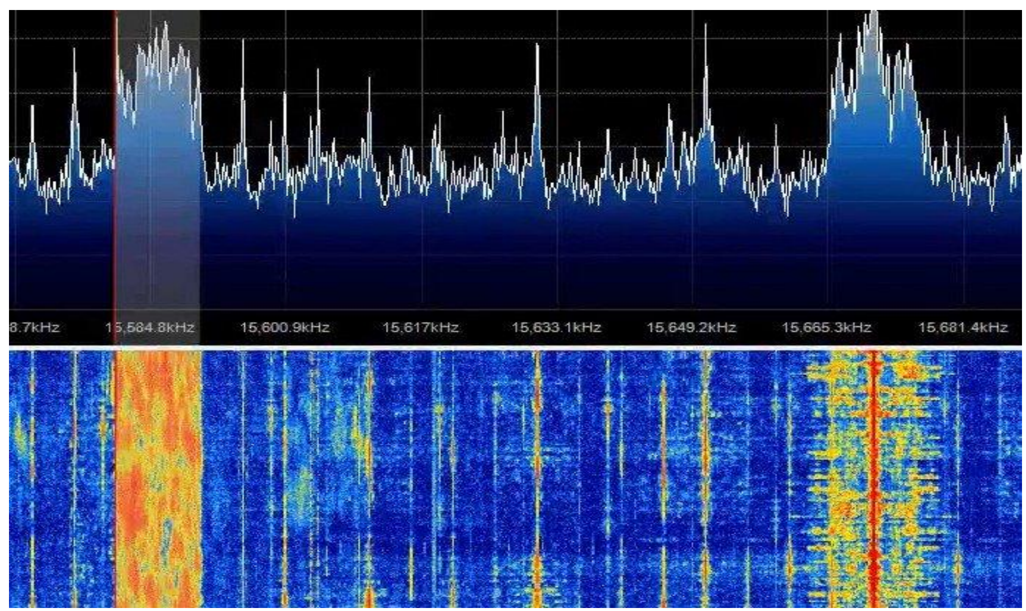
AM HF (3 to 30 MHz) shortwave broadcasting has been almost entirely replaced by Digital Radio Monodiale (DRM). RTL-SDR with a frequency downconverter and DREAM decoding software are used to receive DRM for a later application.

https://www.rtl-sdr.com/tutorial-drm-radio-using-rtl-sdr/

drm

drm

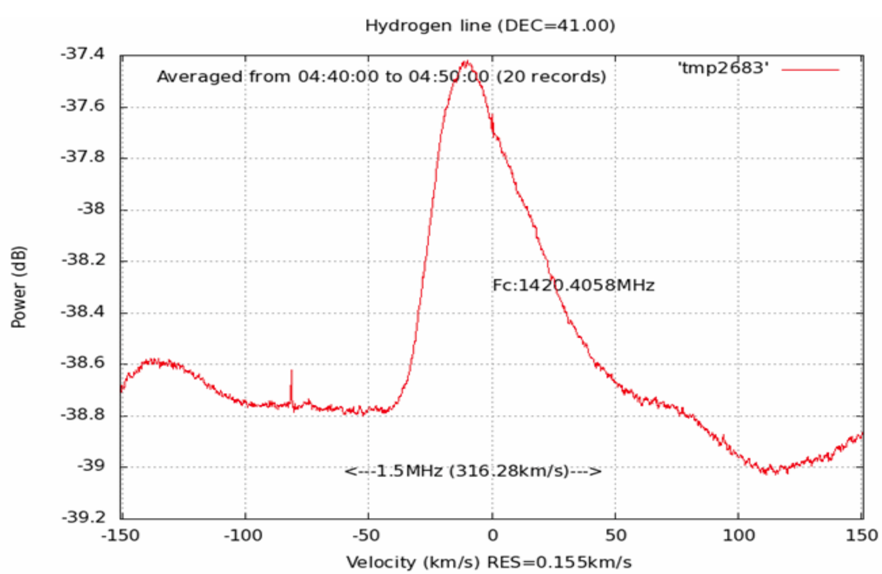
smart radio for all



Mini-Workshop on SDR using RTL-SDR

RTL-SDR with an LNA and external parabolic antenna can be used for radio astronomy experiments such as hydrogen line detection, meteor scatter and pulsar observations.

https://www.rtl-sdr.com/rtl-sdr-for-budget-radio-astronomy/



Mini-Workshop on SDR using RTL-SDR

The Rigol DG4202 Function/Arbitrary Waveform Generator is used for the real-time reception of analog and digital modulated signals by the RTL-SDR here.

The carrier frequency is 49.86 MHz as an *intentional radiator* under FCC Part 15 regulations (Sections 15.203 and 15.235) for a maximum power output of 1 mW (0 dBm) with a vertical antenna of less than 1 meter in length.

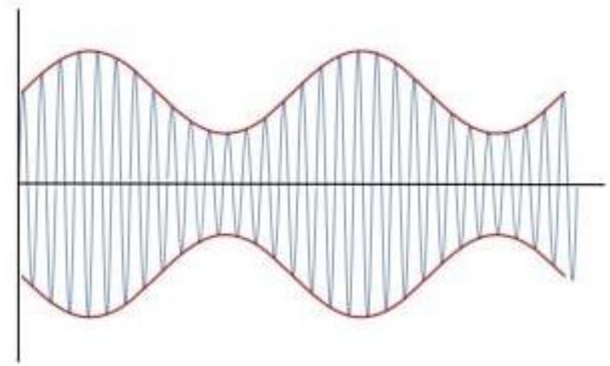
1 mW at $R_L = 50\ \Omega$ is an RMS amplitude of 0.223 V or a peak amplitude of 0.316 V = 316 mV.

Mini-Workshop on SDR using RTL-SDR

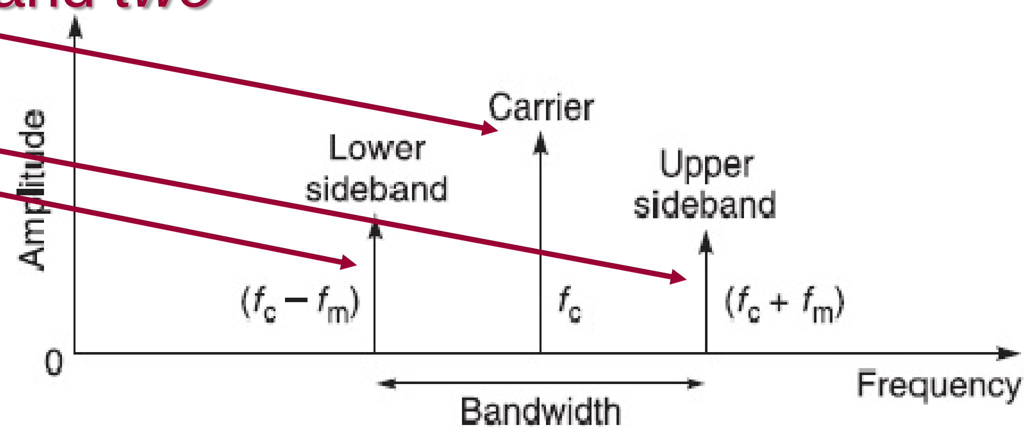
Single tone analog amplitude modulation (AM) is the multiplication of the tone signal (f_m) and a carrier frequency (f_c).

$$\sin(2\pi f_c t) \text{ x } \sin(2\pi f_m t) = [\cos(2\pi(f_c - f_m)t) - \cos(2\pi(f_c + f_m)t)]/2$$

analog AM temporal signal



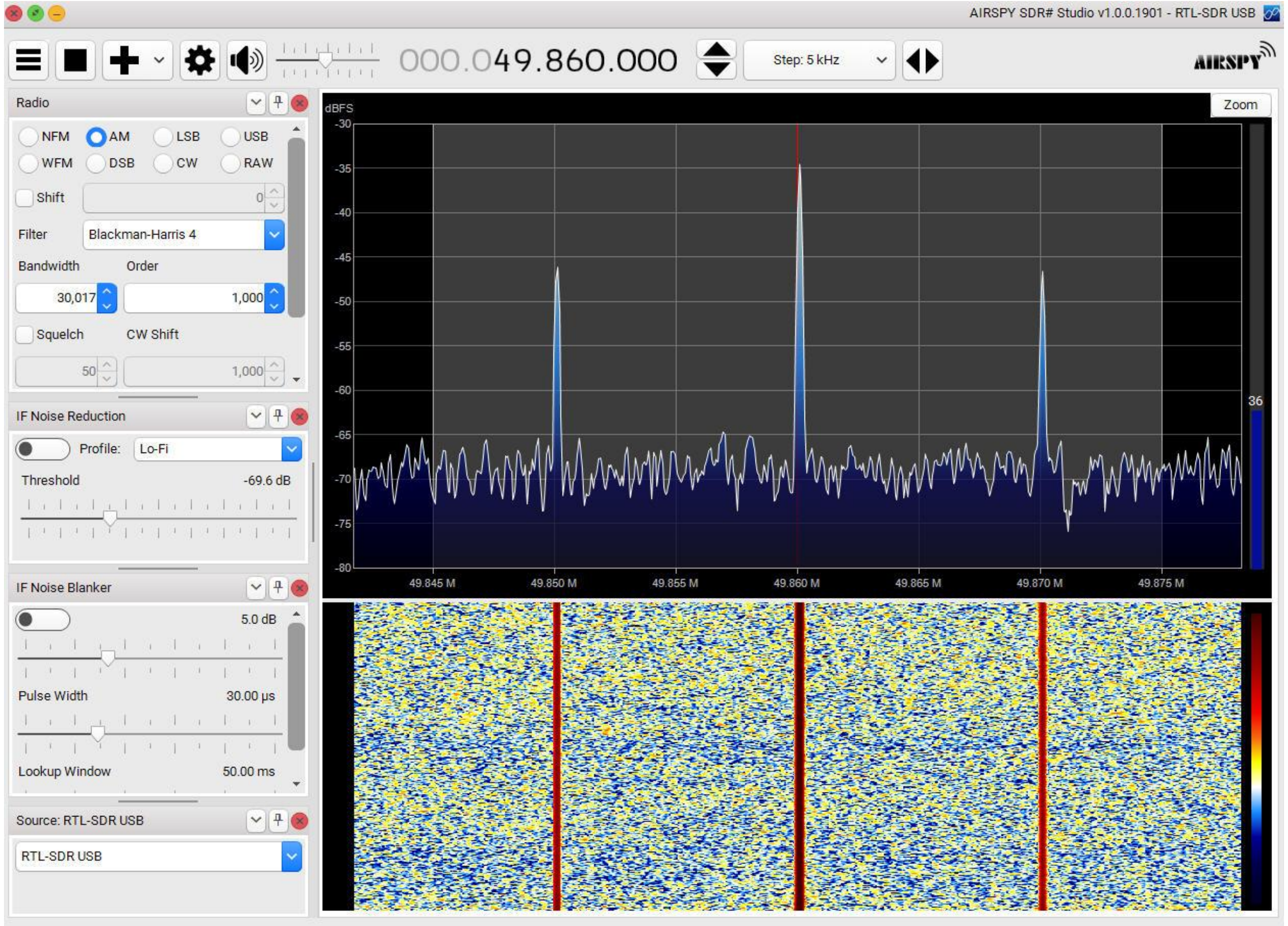
The AM signal spectrum has the *carrier component* and *two spectral peaks* at the sum and difference of f_c and f_m.



Mini-Workshop on SDR using RTL-SDR

Analog AM of the 49.86 MHz carrier at 50% (100% maximum) by a 10 kHz sinusoidal tone signal.

sdr1



Mini-Workshop on SDR using RTL-SDR

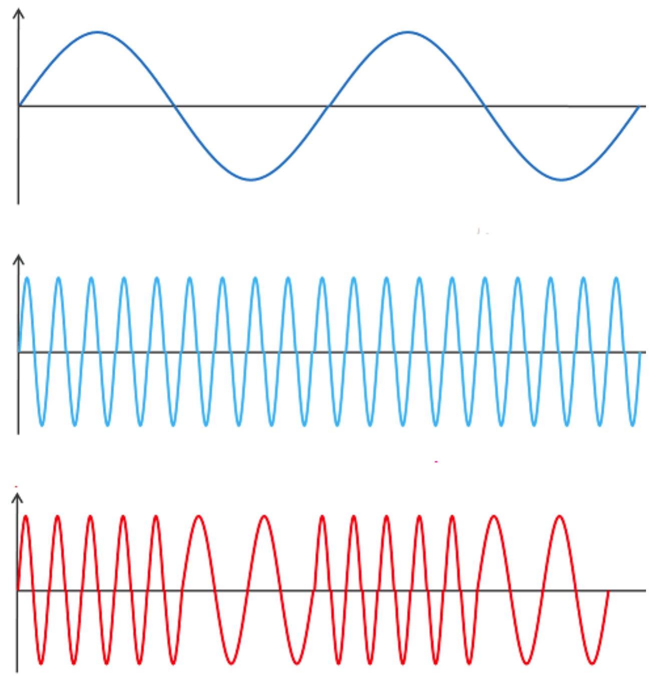
Single tone analog frequency modulation (FM) is more complex. A carrier frequency (f_c) is phase modulated by the tone signal (f_m).

$$\cos(2\pi f_c t + \beta \sin(2\pi f_m t)) = \sum_{k=-\infty}^{\infty} J_k(\beta)\cos(2\pi(f_c + k f_m)t)$$

where β is the modulation index:

$$\beta = \Delta f / f_m$$

and Δf is the frequency deviation from the carrier frequency.



analog FM temporal signal

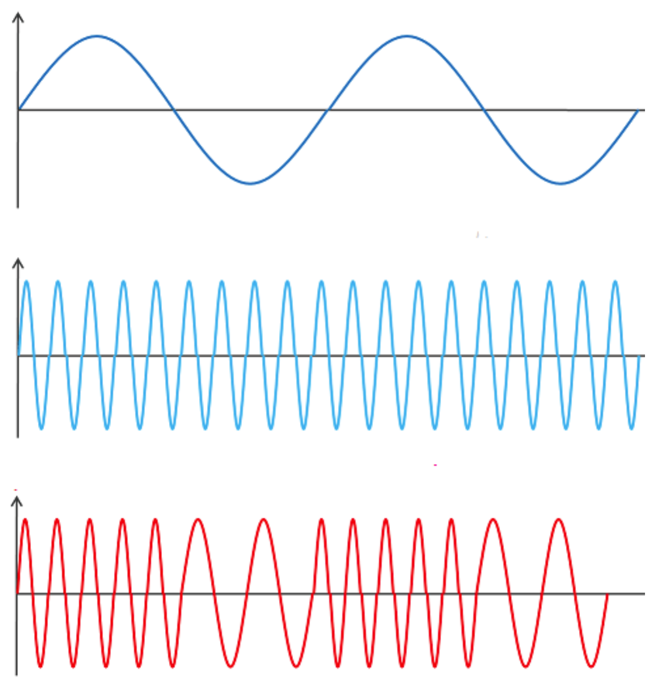
Mini-Workshop on SDR using RTL-SDR

The FM signal spectrum is a *sum* of components at an *infinite multiple* (*k*) of the sum and difference of f_c and f_m.

$$\cos(2\pi f_c t + \beta \sin(2\pi f_m t)) = \sum_{k=-\infty}^{\infty} J_k(\beta)\cos(2\pi(f_c + k f_m)t)$$

Although an *infinite sum*, the amplitudes are weighted by the *Bessel function* ($J_k(\beta)$) which decreases as *k* increases.

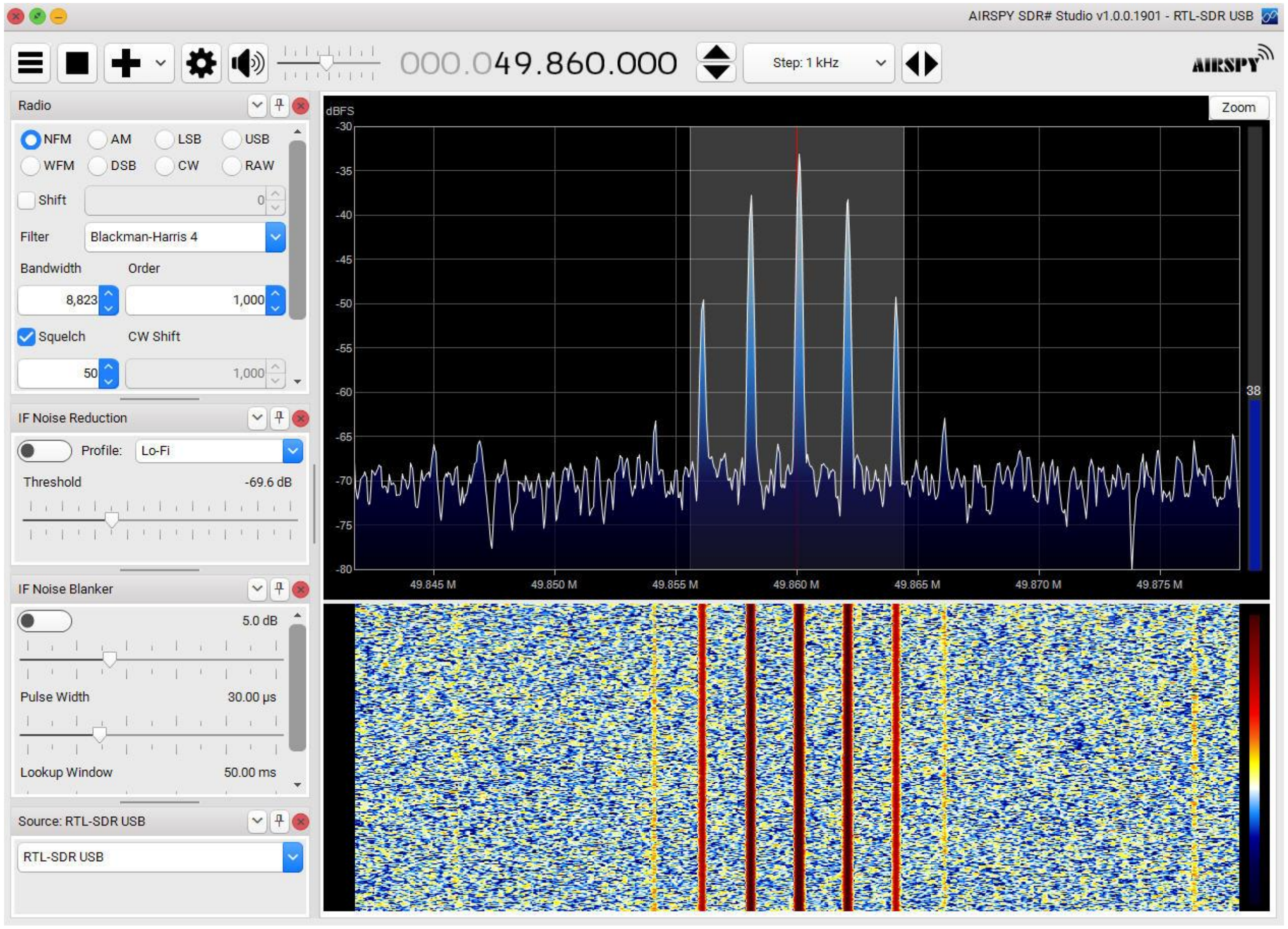
The infinite sum of the $J_k(\beta)$ terms equals unity, although the signal spectral bandwidth increases as β increases.



Mini-Workshop on SDR using RTL-SDR

Analog FM of the 49.86 MHz carrier at a frequency deviation *Δf* of 2 kHz by a 2 kHz sinusoidal tone signal f_m ($\beta = 1$).

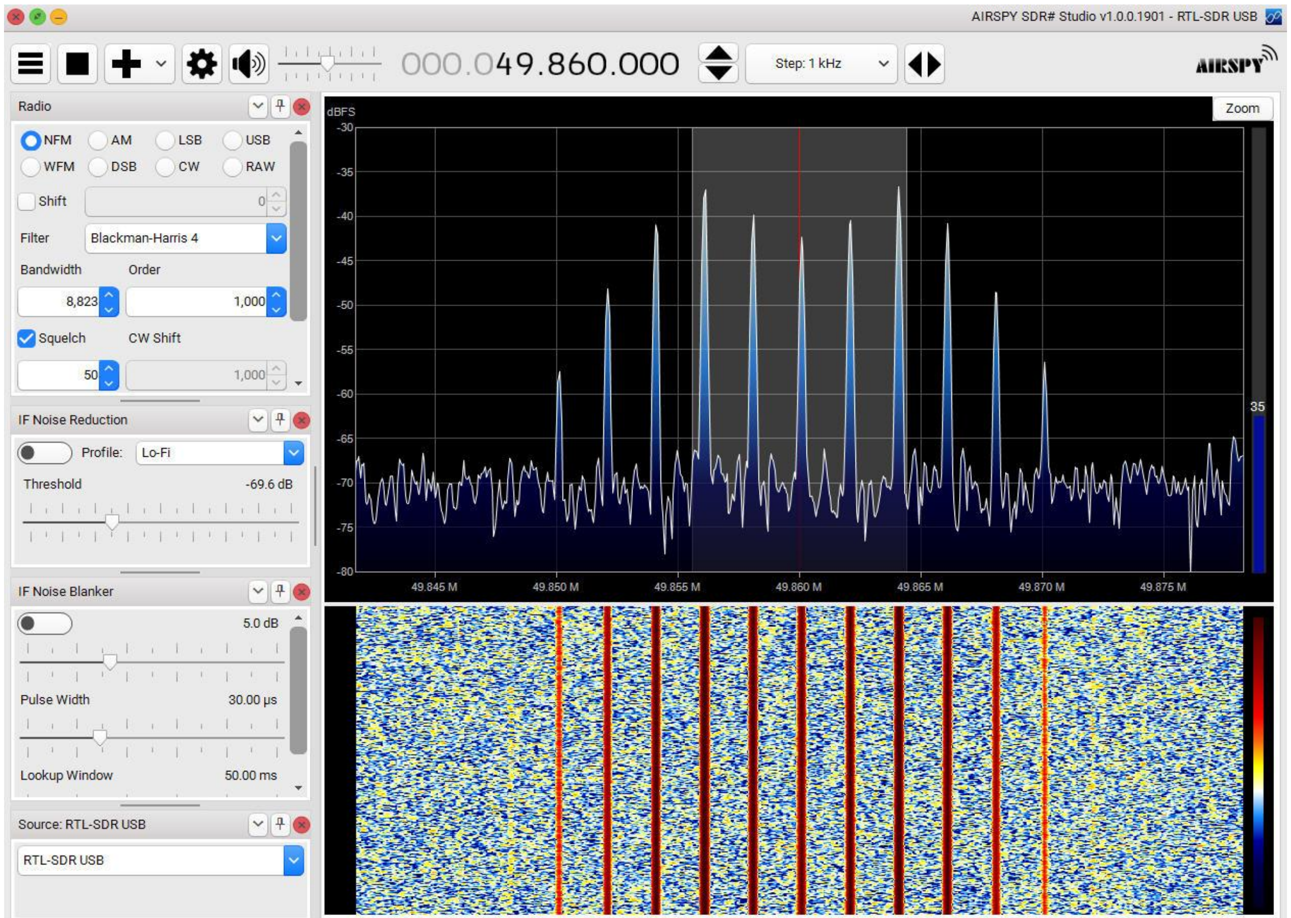
sdr2



Mini-Workshop on SDR using RTL-SDR

Analog FM of the 49.86 MHz carrier at a frequency deviation *Δf* of 6 kHz by a 2 kHz sinusoidal tone signal f_m ($\beta = 3$).

sdr3

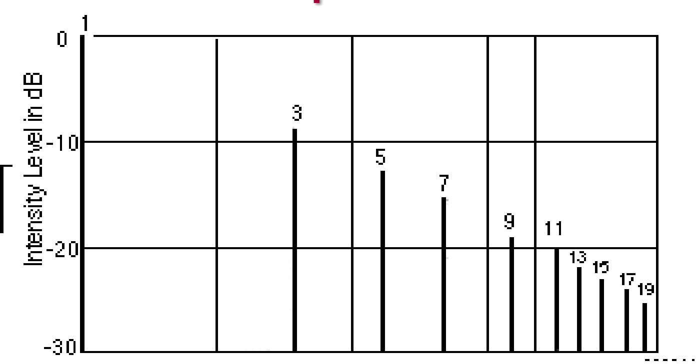


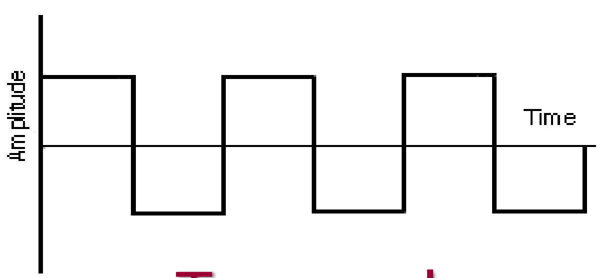
Mini-Workshop on SDR using RTL-SDR

The Rigol DG4202 Function/Arbitrary Waveform Generator can generate data signals at various bit rates for digital modulation but only as a periodic pattern.

This is not *random* binary data and the result is a line spectral at the period of the data. With a 50% *duty cycle* the even harmonics are zero and the odd harmonics decrease in amplitude.

Spectrum





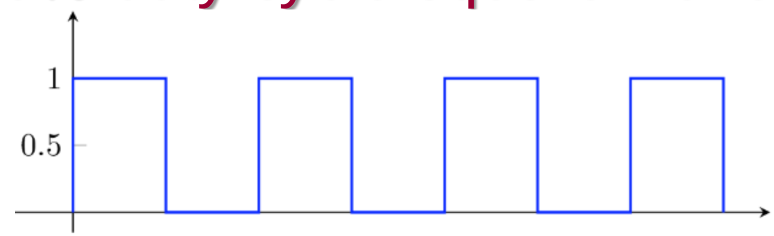
Temporal

Mini-Workshop on SDR using RTL-SDR

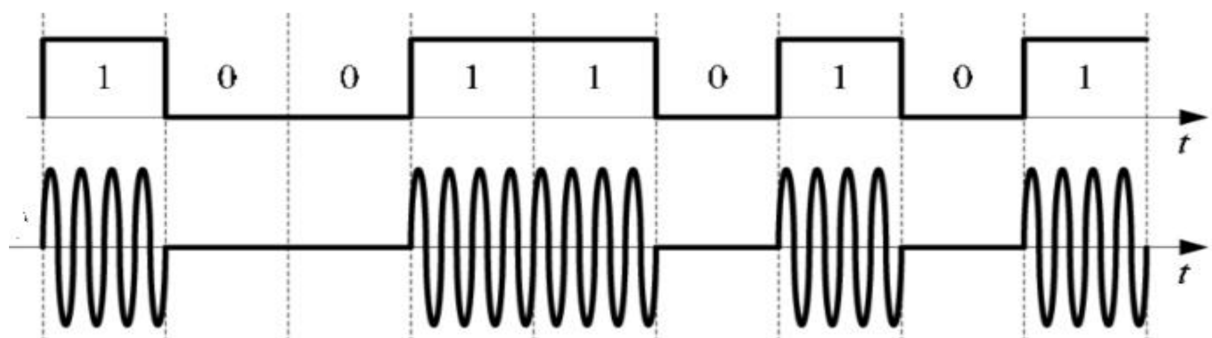
A digital Binary Amplitude Shift Keying-On/Off Keying (BASK-OOK) changes the amplitude of a carrier frequency (f_c) with the modulation signal $m_j(t)$.

$$s_j(t) = A\, m_j(t) \sin(2\pi\, f_c t) \quad (i-1)T_b \le t \le i\,T_b \quad j = 0, 1$$

Here $m_j(t)$ = 0 or 1 and is a 50% duty cycle square wave and A is the unmodulated carrier amplitude.



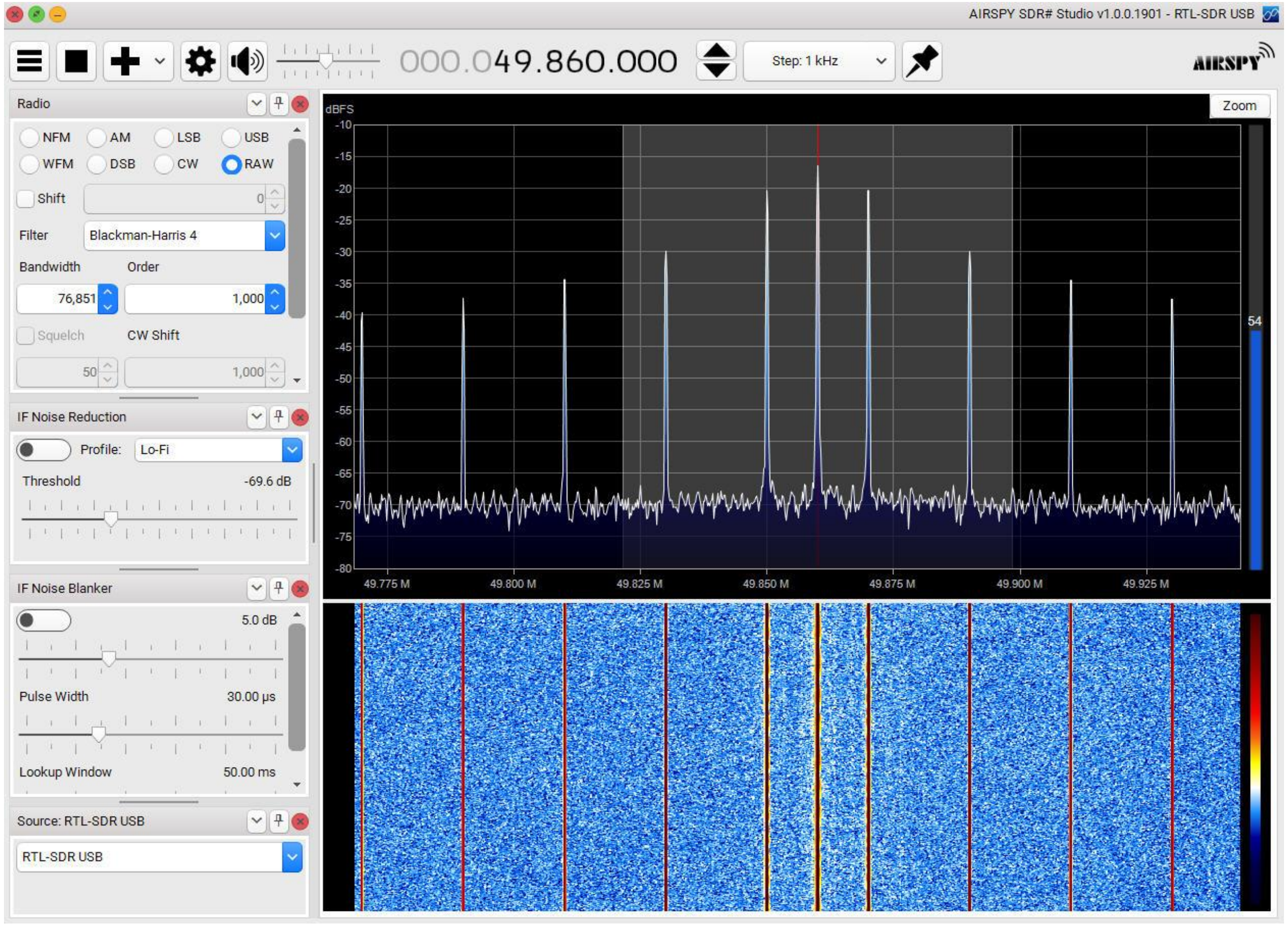
For *random binary data* a BASK-OOK modulated signal is:



Mini-Workshop on SDR using RTL-SDR

BASK-OOK of the 49.86 MHz carrier by a 50% duty cycle square wave at 10 kHz (20 kb/sec).

sdr4



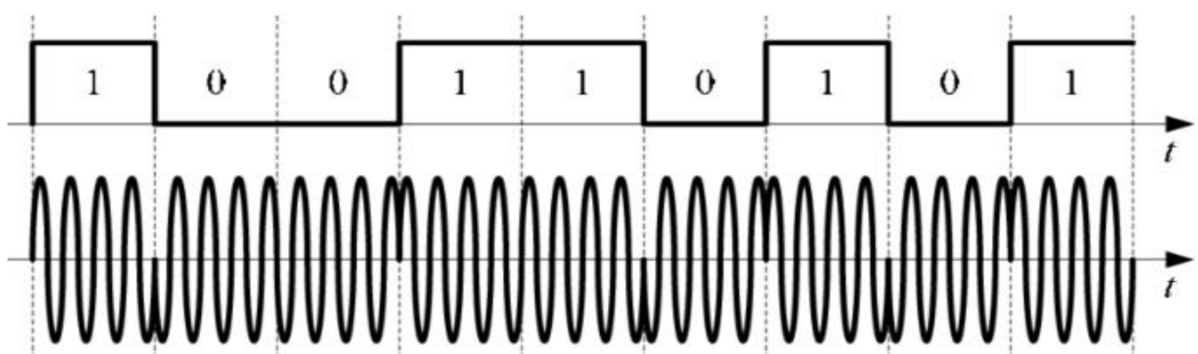
Mini-Workshop on SDR using RTL-SDR

A digital Binary Phase Shift Keying (BPSK) changes the phase of a carrier frequency (f_c) with the modulation signal $m_j(t)$.

$$s_j(t) = A\sin(2\pi f_c t + k_p m_j(t)) \quad (i-1)T_b \le t \le iT_b \quad j = 0, 1$$

Here k_p is the *phase deviation factor*, $m_j(t)$ = 0 or 1 and is a 50% duty cycle square wave and A is the unmodulated carrier amplitude. If $k_p = \pi$ radians, then the phase deviation is 0 or 180 degrees.

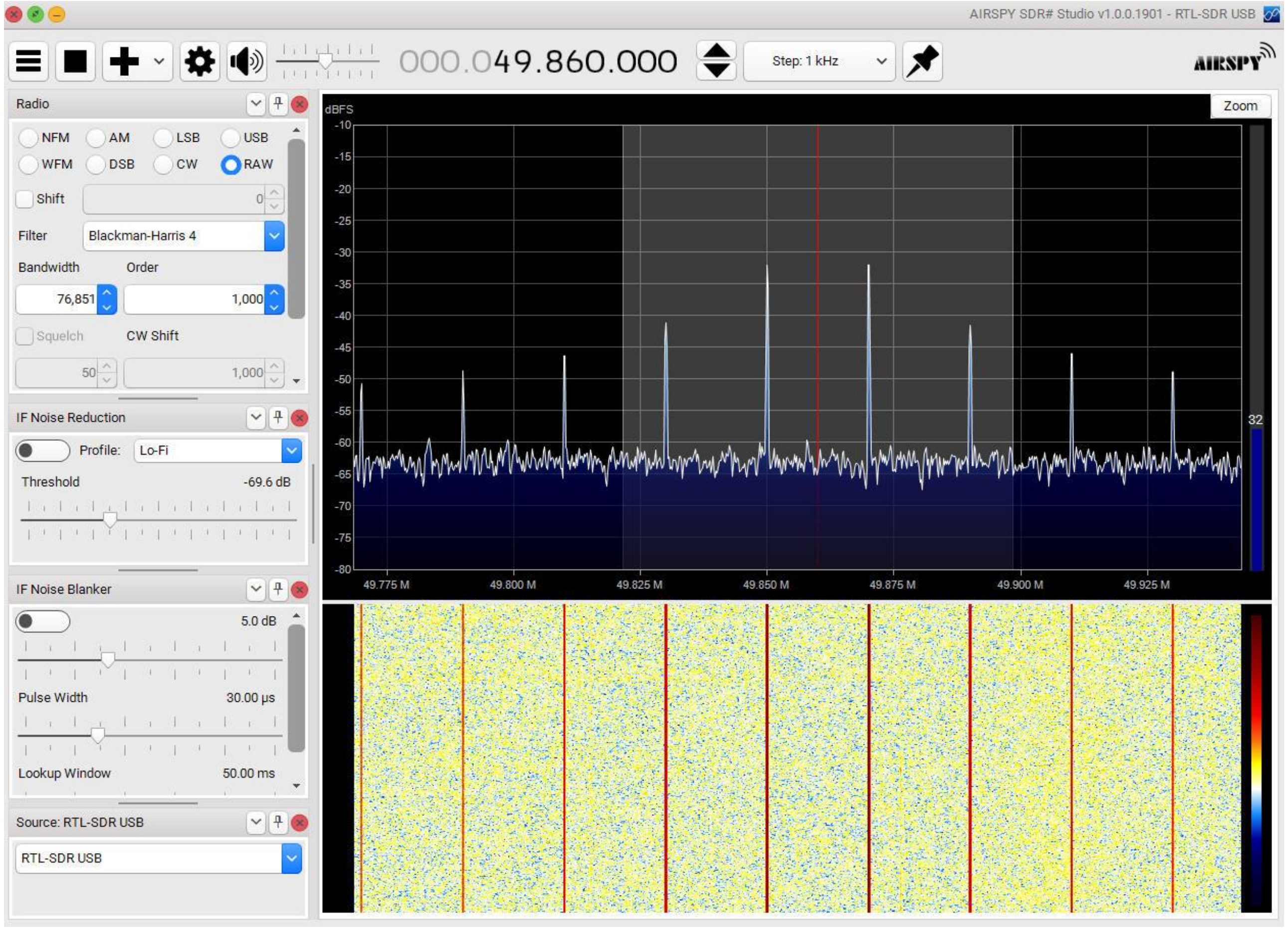
For *random binary data* a BPSK modulated signal is:



Mini-Workshop on SDR using RTL-SDR

BPSK of the 49.86 MHz carrier by a 50% duty cycle square wave at 10 kHz (20 kb/sec).

sdr5



Mini-Workshop on Software Defined Radio using the RTL-SDR

Additional Topics

- Antenna Construction
- RTL-SDR and GNU Radio
- Resources and References
- Advanced SDR Applications

Mini-Workshop on Software Defined Radio using the RTL-SDR

Additional Topics

- Antenna Construction
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Mini-Workshop on SDR using RTL-SDR

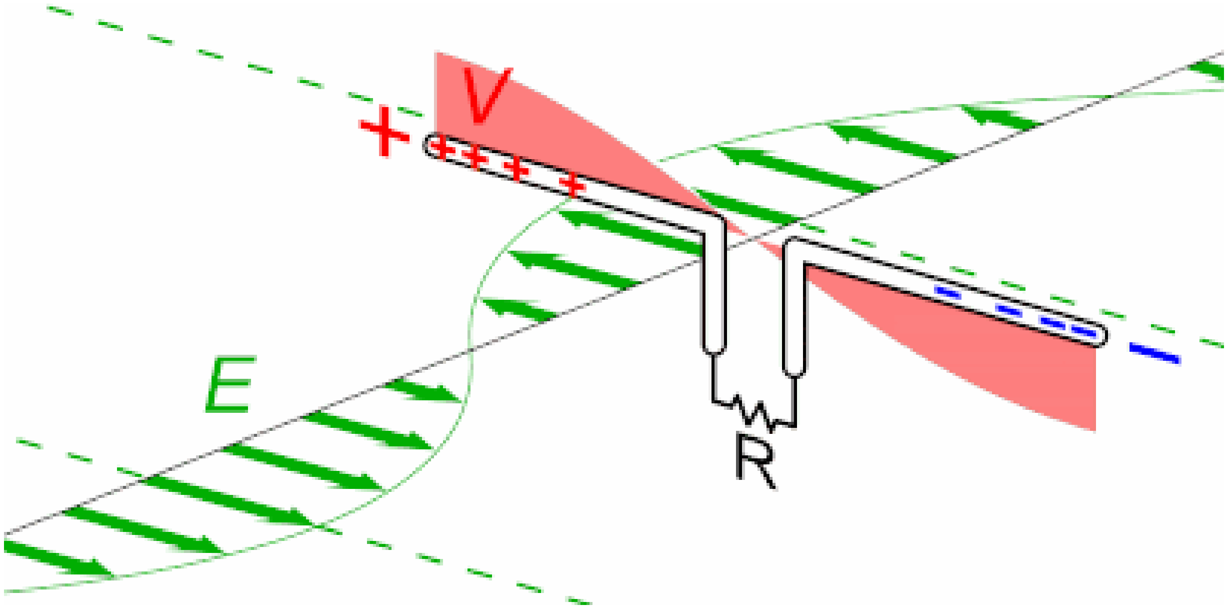
An external antenna is key for quality reception using the RTL-SDR and is an interesting additional activity.

The simple *dipole* or *monopole* antenna provided with the RTL-SDR is not optimum because it exhibits little gain and, if inside, is not *in the clear*.

However, a variety of gain antennas for specific frequencies can be easily constructed.

Mini-Workshop on SDR using RTL-SDR

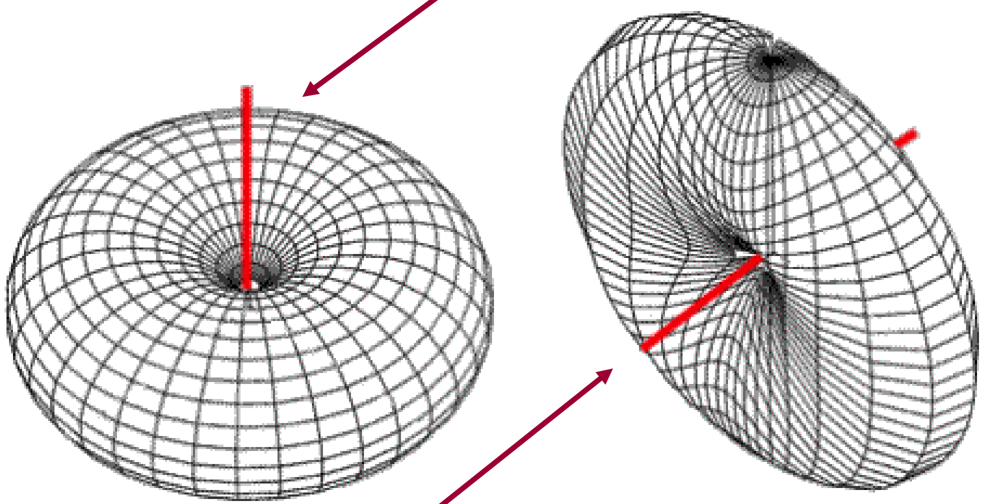
Antenna theory for reception begins with oscillating currents being induced on the resonant length of the dipole.



Antennas are symmetrical and a transmitter current on the resonant length of the dipole induce a propagating ***E*** and ***H*** field also (only the ***E*** field is shown).

Mini-Workshop on SDR using RTL-SDR

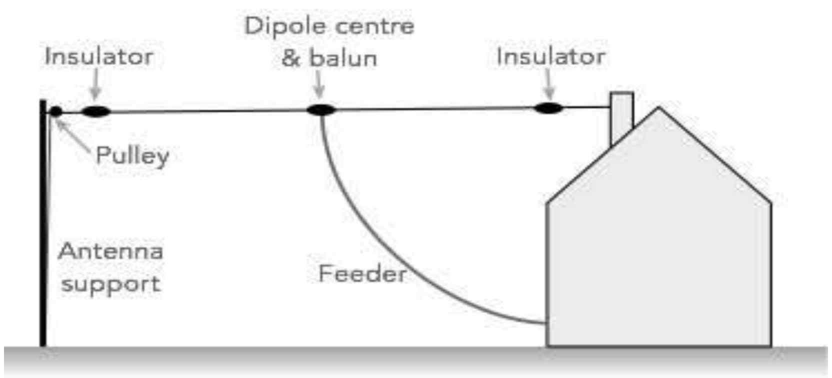
The *dipole antenna* is two ¼ wavelength rods but must be in the clear. If mounted vertically the dipole has an *omnidirectional* pattern.



If mounted horizontally (often used when the antenna is large) the dipole has a *bidirectional* pattern.

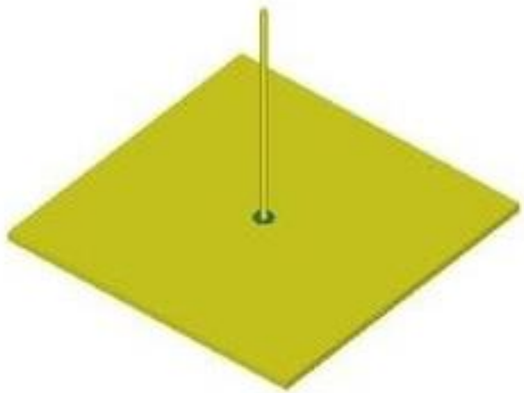
Mini-Workshop on SDR using RTL-SDR

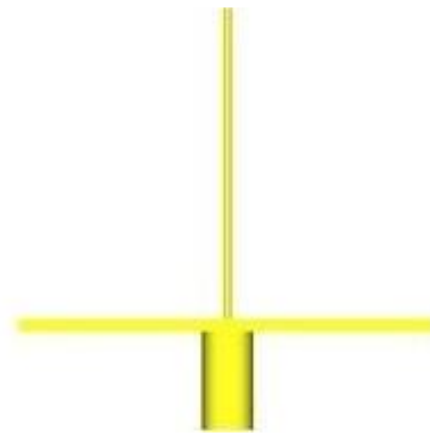
The *vertical dipole* is constructed of copper tubing and no ground plane is used. Large *horizontal dipole* antennas for HF (3 - 30 MHz) are constructed of copper wire and mounted between supports. The coaxial cable is 75 Ω.



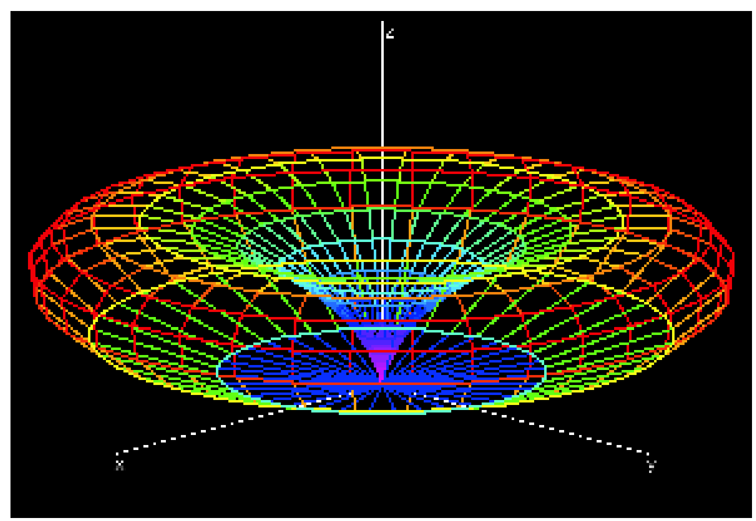
Mini-Workshop on SDR using RTL-SDR

The *omnidirectional monopole* antenna is a ¼ wavelength rod above a ground plane.



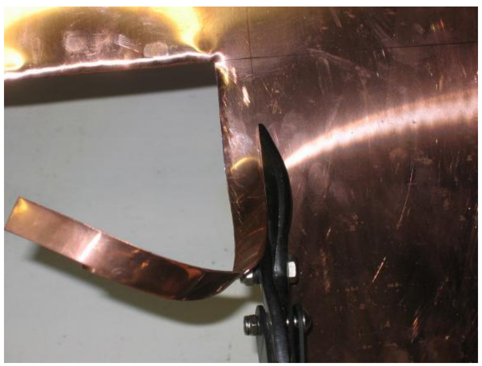


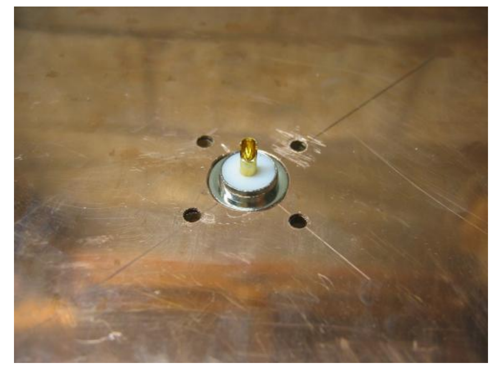
Antenna modeling software can display the far ***E*** field pattern.

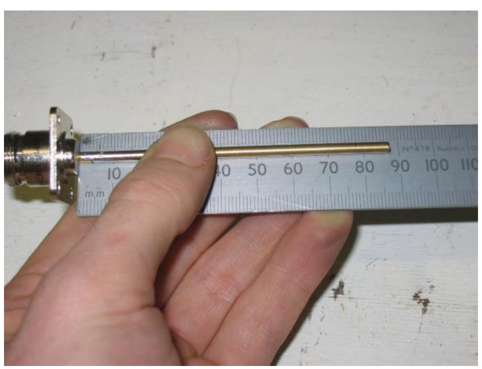


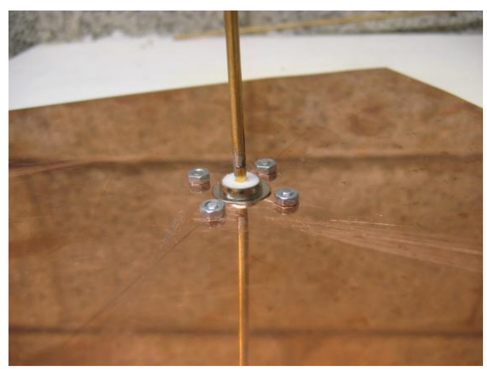
Mini-Workshop on SDR using RTL-SDR

Construction of a monopole antenna with ground plane is shown. The antenna rod is ¼ wavelength (λ), equal to the speed of light *c* divided by the frequency *f* or $\lambda = c / f$ in a vacuum but reduced by 0.93 in air.







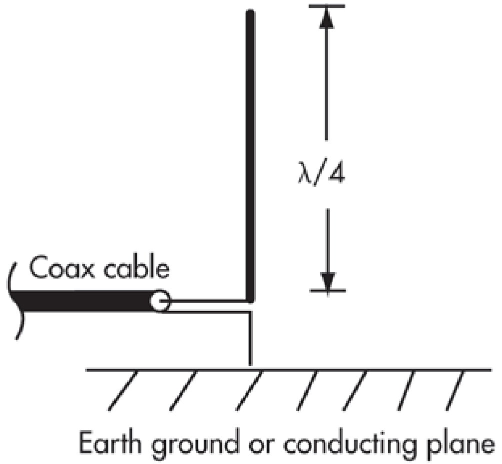


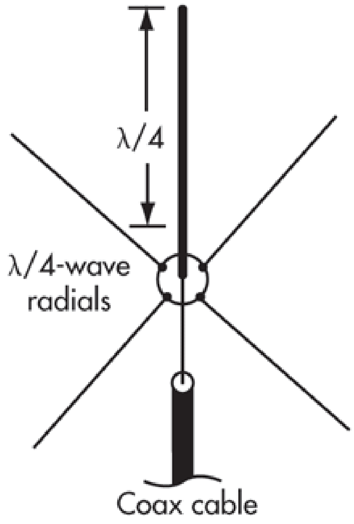
Mini-Workshop on SDR using RTL-SDR

The *ground plane* is ¼ wavelength in size. A series of ¼ wavelength radial wires can be used instead of a large metal plate with a 50 Ω coaxial cable.

$\lambda_{vacuum} = c\ /\ f\ \approx 2.998 \times 10^8\ f \quad \text{m}$

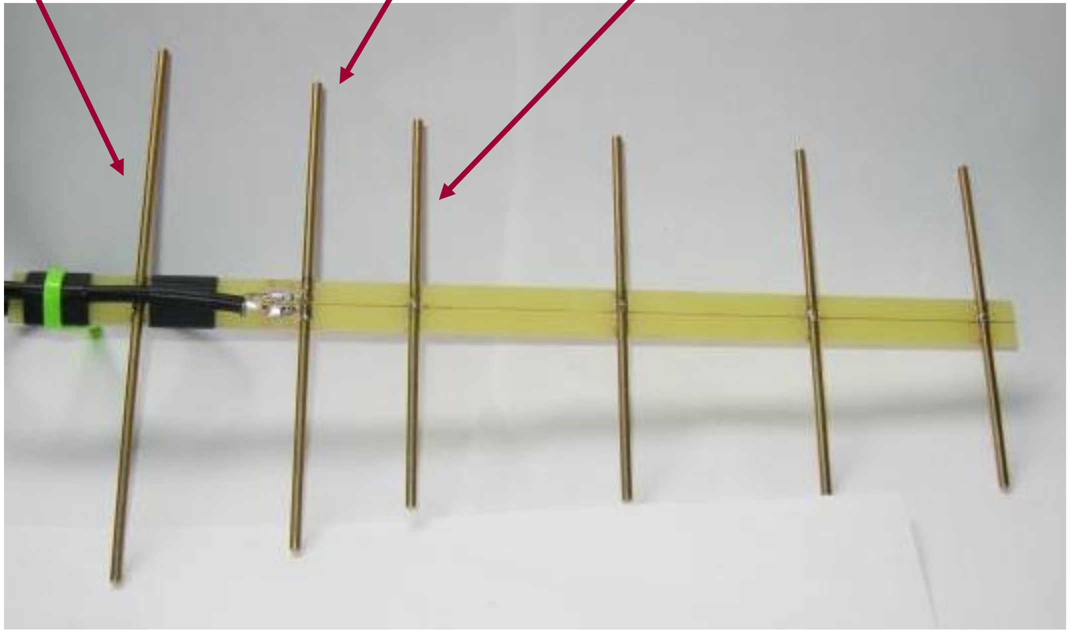
$\lambda_{air} = 0.93\ c\ /\ f\ \approx 2.788 \times 10^8\ f \quad \text{m}$





Mini-Workshop on SDR using RTL-SDR

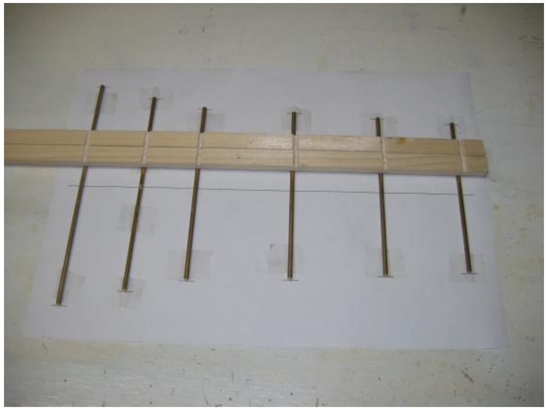
The *Yagi* antenna is an active dipole with a set of passive reflector and director elements.

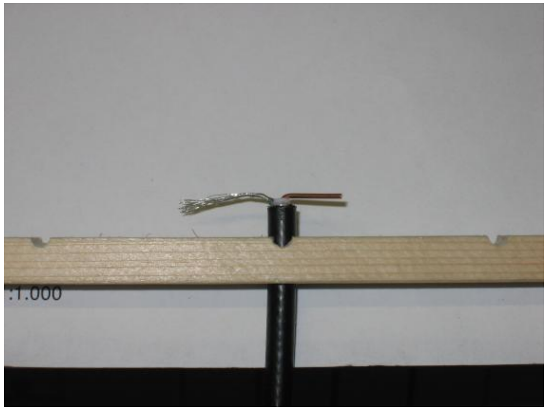
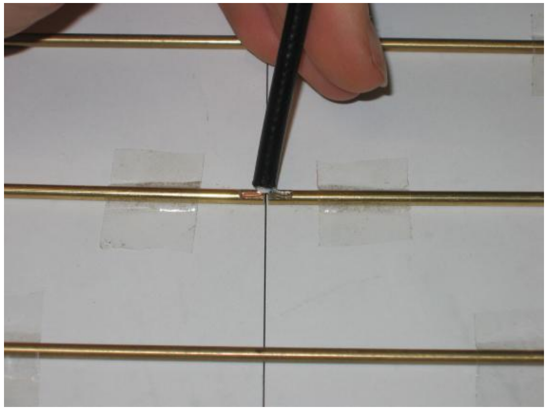
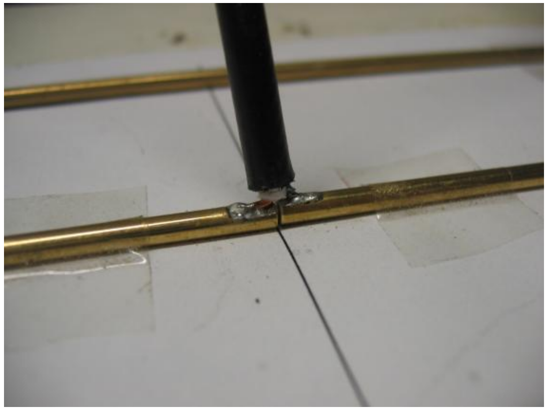
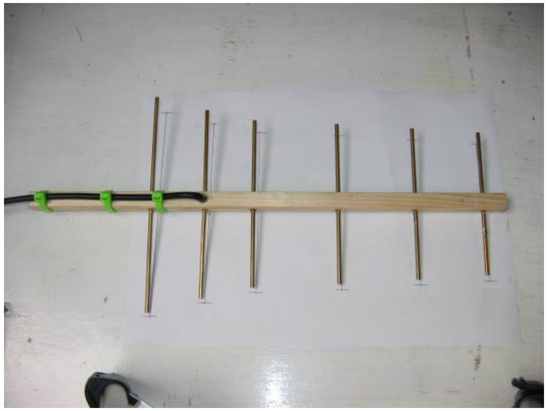


The Yagi antenna is highly directional but exhibits large forward gain and attenuation in the reverse direction.

Mini-Workshop on SDR using RTL-SDR

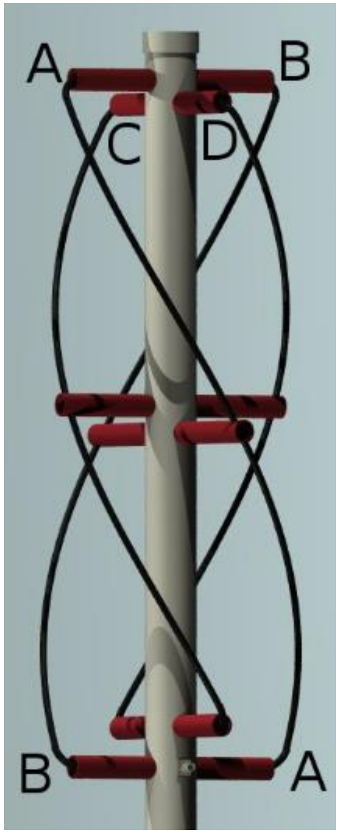
Construction of the Yagi antenna using brass rods and a wooden boom is shown. The elements are tapered and non-uniformly spaced with a 50 Ω coaxial cable.

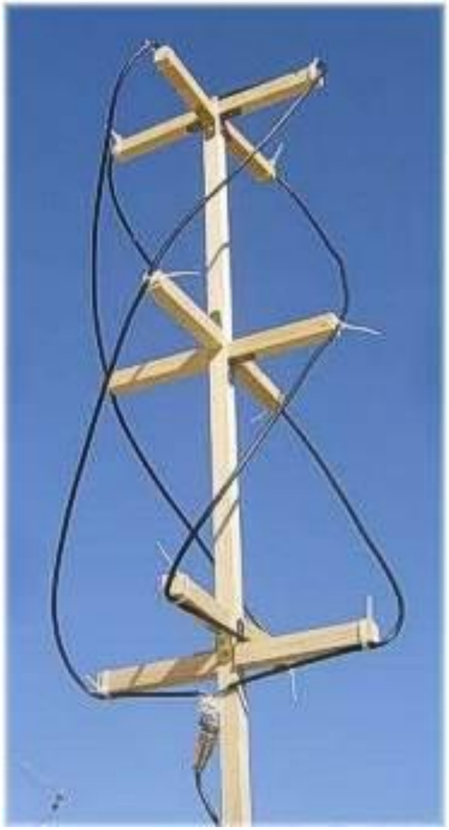


Mini-Workshop on SDR using RTL-SDR

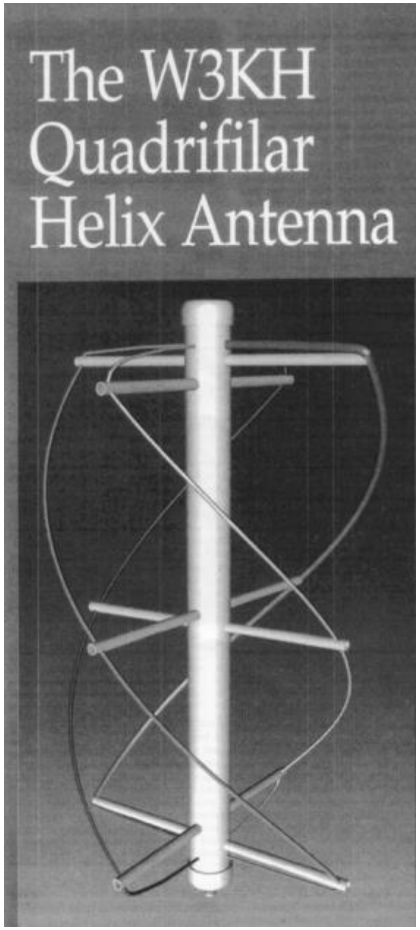
A *quadrifilar* antenna is designed for LEO satellite telemetry that present time varying (circular or elliptical) antenna polarization.





Mini-Workshop on SDR using RTL-SDR

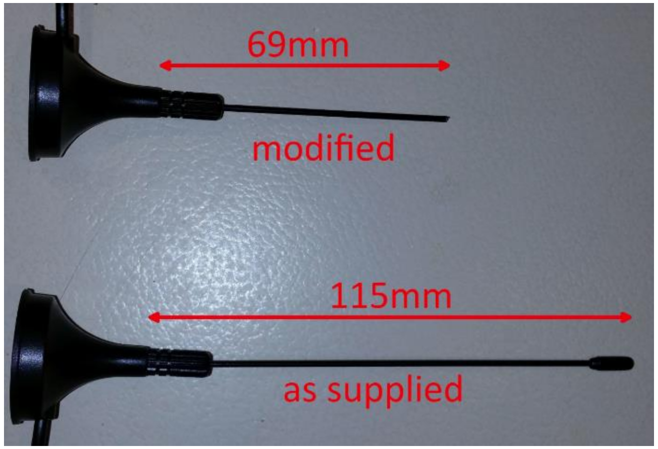
The quadrifilar antenna can be easily constructed.
http://jcoppens.com/ant/qfh/calc.en.php

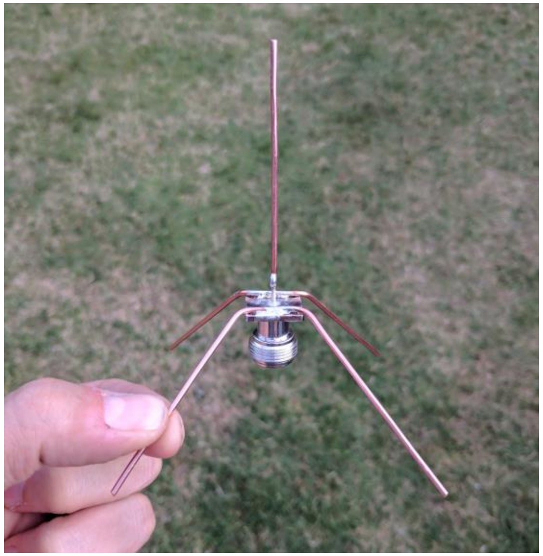


Mini-Workshop on SDR using RTL-SDR

An antenna for the *Automatic Dependent Surveillance-Broadcast* (ADS-B) Mode-S transponder broadcasting location and altitude information to air traffic controllers at 1.09 GHz can be constructed.

A standard monopole can be shortened or a small ground plane can be built.





Mini-Workshop on SDR using RTL-SDR

A reasonable and wide bandwidth (25-1300 MHz) antenna is the *discone* which can be bought commercially or built.

Discone antenna at TUARC K3TU

Homebrew Discone

Mini-Workshop on SDR using RTL-SDR

Antenna construction reference links:

Dipole antenna:
http://www.westmountainradio.com/antenna_calculator.php

Monopole antenna:
https://273k.net/gsm/designing-and-building-a-gsm-antenna/monopole/

Yagi antenna:
https://273k.net/gsm/designing-and-building-a-gsm-antenna/yagi/

Discone antenna:
https://www.rtl-sdr.com/?s=discone+antenna

Mini-Workshop on Software Defined Radio using the RTL-SDR

Additional Topics

- Antenna Construction
- RTL-SDR and GNU Radio
- Resources and References
- Advanced SDR Applications

Mini-Workshop on SDR using RTL-SDR

The RTL-SDR can be used for advanced applications with GNU Radio. GNU Radio is available for Windows 10:
http://www.gcndevelopment.com/gnuradio/downloads.htm

GNU Radio
THE FREE & OPEN SOFTWARE RADIO ECOSYSTEM

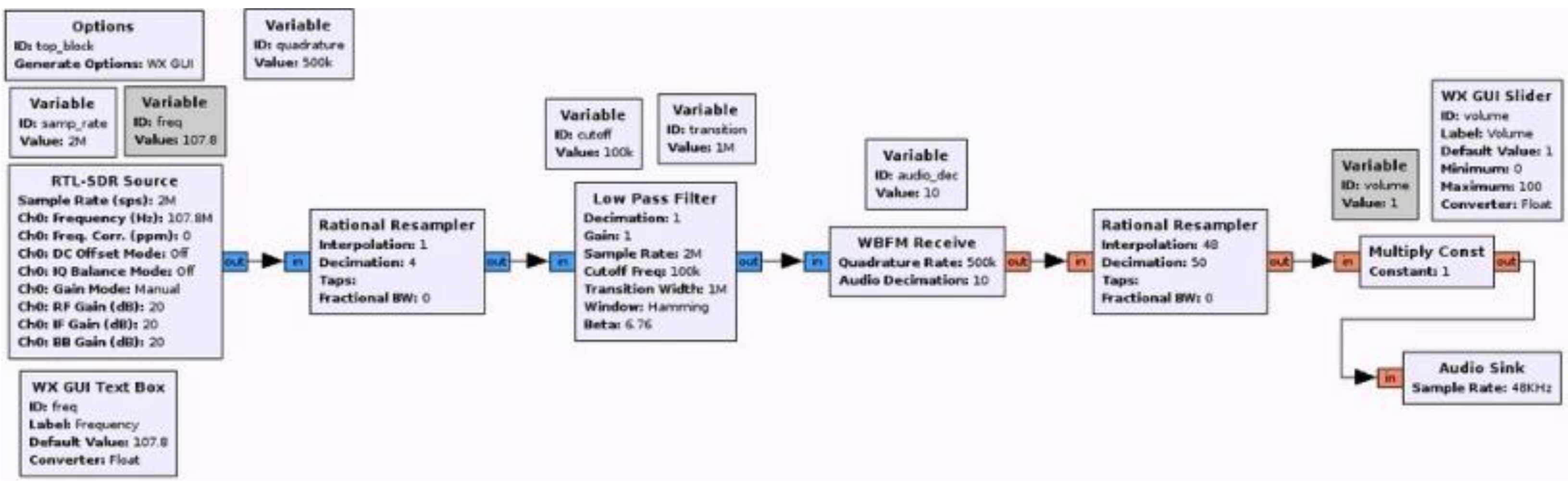
However, the *learning curve* for GNU radio is substantial. Python, pip and other dependencies like numpy and pyqt are required to be installed and the system PATH must be set correctly.

A video tutorial is available:
https://www.rtl-sdr.com/video-tutorial-installing-gnu-radio-on-windows-10/

Mini-Workshop on SDR using RTL-SDR

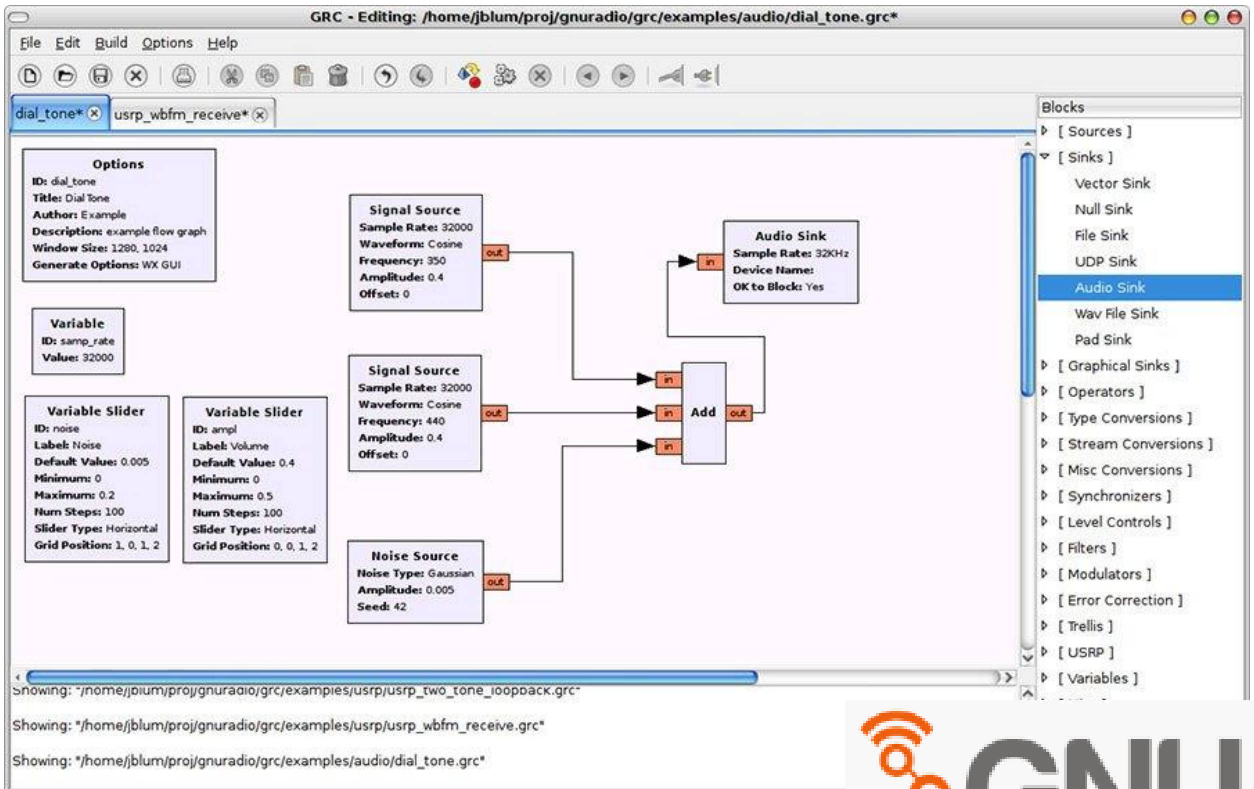
A reasonable first project with the RTL-SDR and GNU radio is the creation of an FM broadcast receiver.

After installation of GNU Radio, the FM broadcast receiver (wide band FM, WBFM) is described: https://www.instructables.com/id/RTL-SDR-FM-radio-receiver-with-GNU-Radio-Companion/



Mini-Workshop on SDR using RTL-SDR

A recent compendium of information about GNU Radio is available on the wiki:
https://wiki.gnuradio.org/index.php/Main_Page



Mini-Workshop on SDR using RTL-SDR

There is also a Wiki page with GNU Radio tutorials: https://wiki.gnuradio.org/index.php?title=Tutorials

Beginner Tutorials

Introducing GNU Radio

1. What is GNU Radio?
2. Installing GNU Radio
3. Your First Flowgraph

Flowgraph Fundamentals

1. Python Variables in GRC
2. Variables in Flowgraphs
3. Runtime Updating Variables
4. Signal Data Types
5. Converting Data Types
6. Packing Bits
7. Streams and Vectors
8. Hier Blocks and Parameters

Creating and Modifying Python Blocks

1. Creating Your First Block
2. Python Block With Vectors
3. Python Block Message Passing
4. Python Block Tags

DSP Blocks

1. Low Pass Filter Example
2. Designing Filter Taps
3. Sample Rate Change

Intermediate/Advanced Tutorials

Core GNU Radio Mechanics

1. Stream Tags
2. Polymorphic Types (PMTs)
3. Message Passing

Modulation and Demodulation

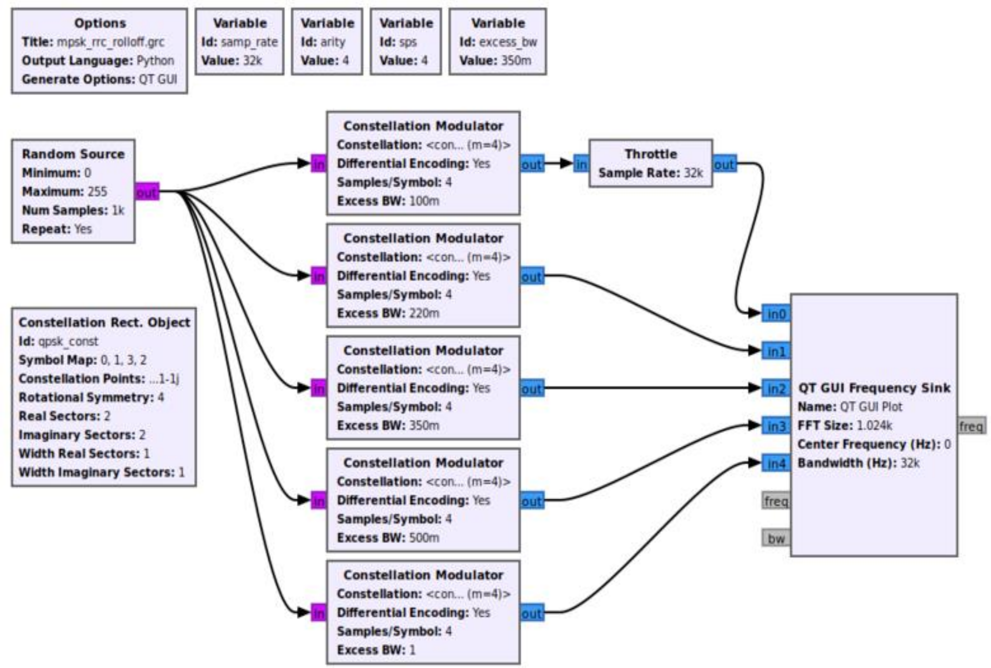
1. Narrowband FM
2. Single Sideband (SSB)
3. BPSK Demodulation
4. QPSK Mod and Demod
5. Frequency Shift Keying (FSK)
6. OFDM Basics
7. Packet Communications

C++ Blocks and OOTs

1. Out of Tree Modules (OOTs)
2. Writing blocks in C++
3. Writing the YAML file for a bloc

Miscellaneous

1. Understanding a Flowgraph's Python Code
2. Using GNU Radio With SDRs
3. IQ and Complex Signals
4. Understanding Sample Rate
5. Understanding ZMQ Blocks



GNU Radio

THE FREE & OPEN SOFTWARE RADIO ECOSYSTEM

Mini-Workshop on Software Defined Radio using the RTL-SDR

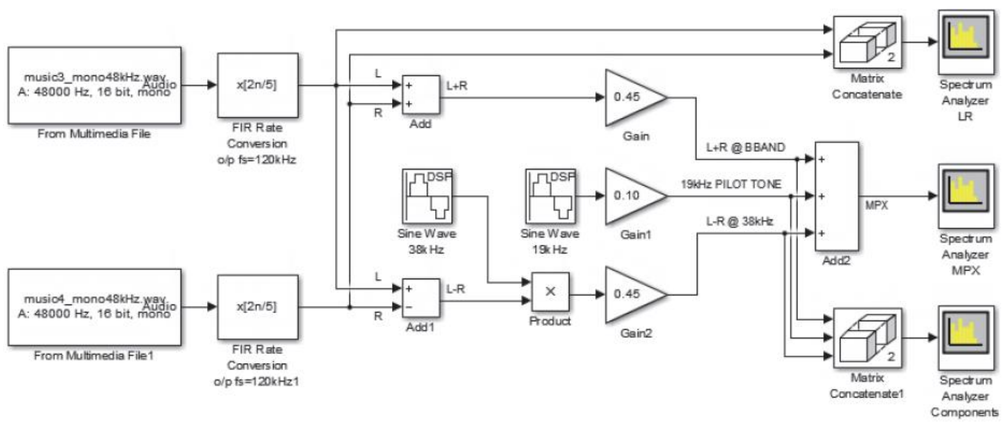
Additional Topics

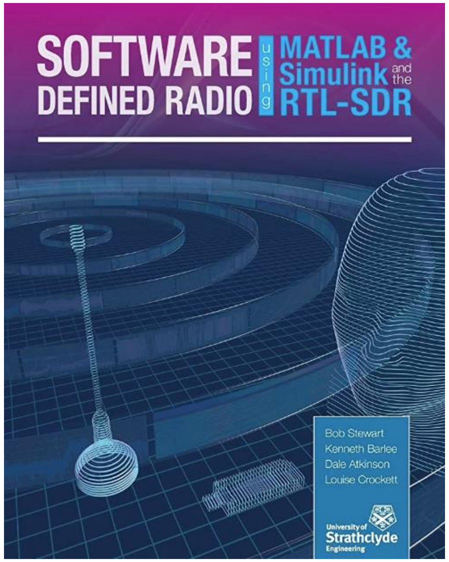
- Antenna Construction
- RTL-SDR and GNU Radio
- Resources and References
- Advanced SDR Applications

Mini-Workshop on SDR using RTL-SDR

Software Defined Radio using MATLAB & Simulink with the RTL-SDR is a freeware text available as a pdf from The Mathworks.

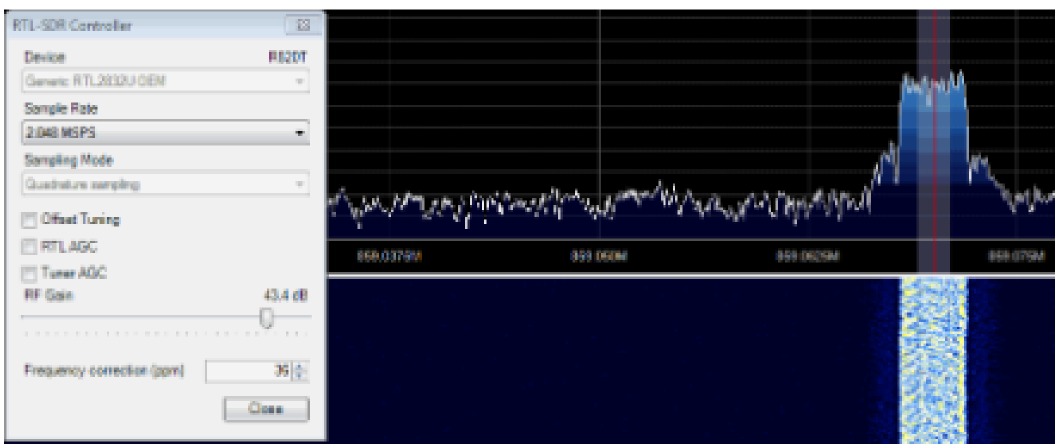
https://www.mathworks.com/academia/books/software-defined-radio-using-matlab-simulink-and-the-rtl-sdr-barlee.html

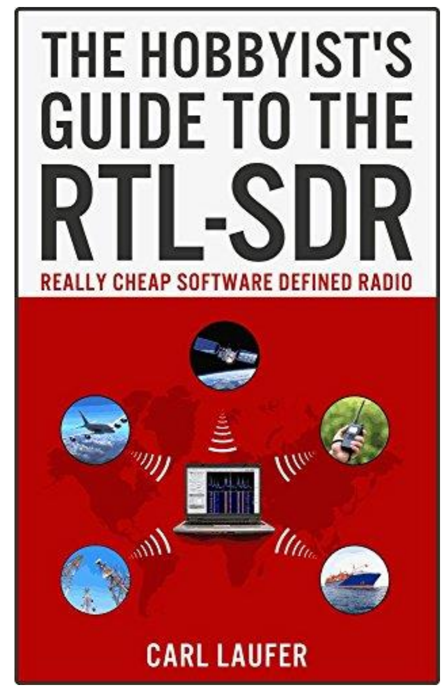




Mini-Workshop on SDR using RTL-SDR

The Hobbyist's Guide to the RTL-SDR is available in hardcopy from booksellers but has a Kindle Edition. The text describes SDR# and various enhancements (*plug-ins*).

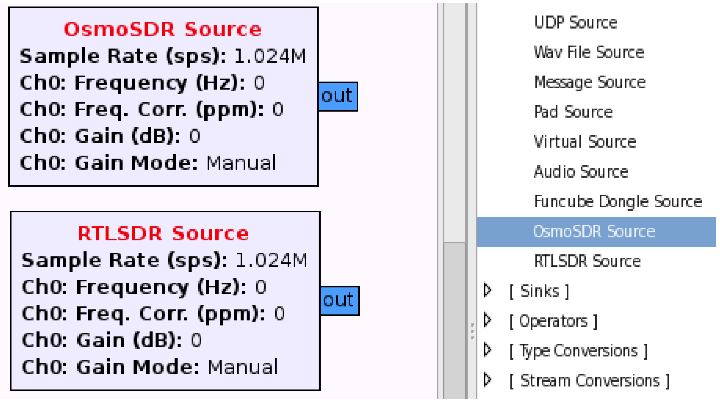




Mini-Workshop on SDR using RTL-SDR

The RTL-SDR community has a Wiki page:

https://osmocom.org/projects/rtl-sdr/wiki/Rtl-sdr



The hobbyist website *Hackaday* has RTL-SDR projects posted:

https://hackaday.com/blog/?s=RTL-SDR

Mini-Workshop on Software Defined Radio using the RTL-SDR

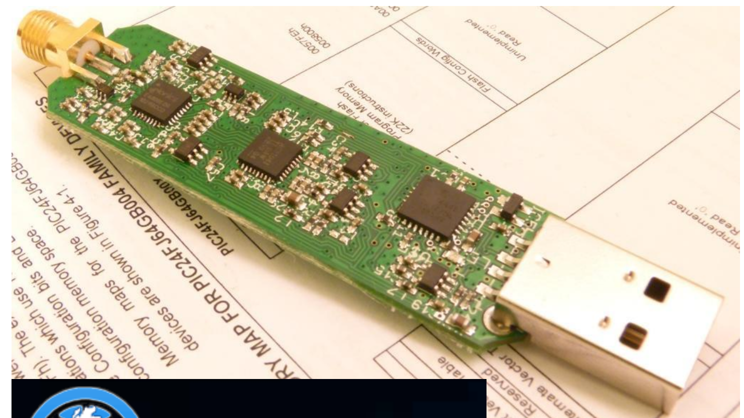
Additional Topics

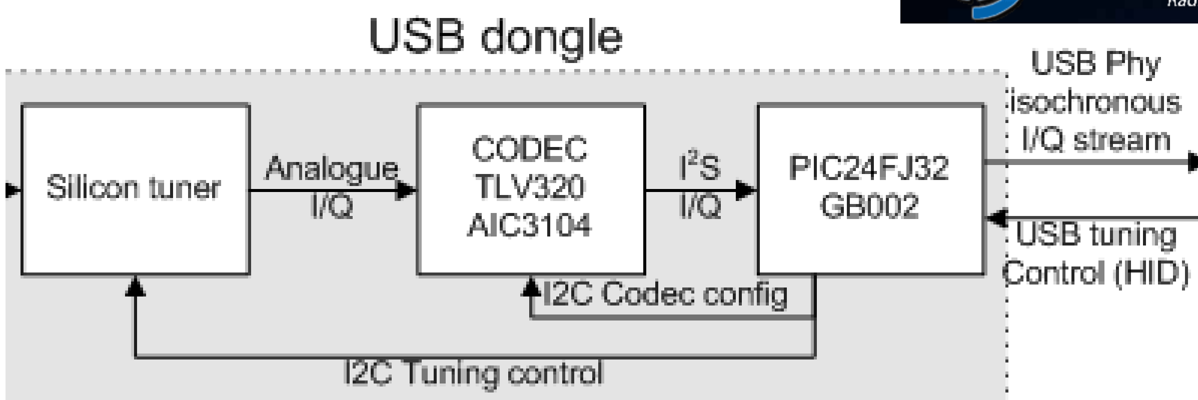
- Antenna Construction
- RTL-SDR and GNU Radio
- Resources and References
- Advanced SDR Applications

Mini-Workshop on SDR using RTL-SDR

The next level of the receive only SDR is the FUNcube project of AMSAT-UK. AMSAT is the global Amateur Radio satellite organization with over 80 LEO satellites.

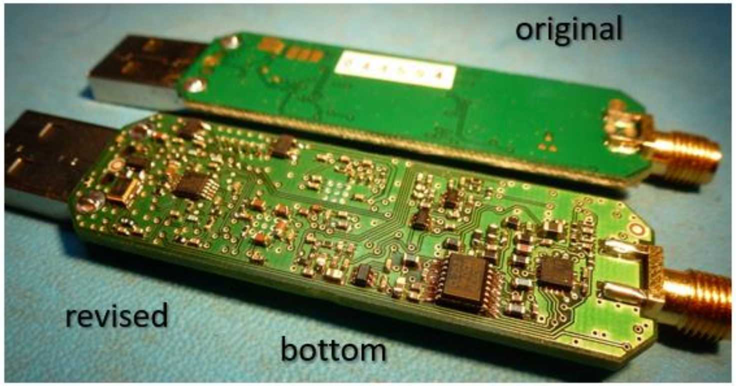
The FUNcube SDR dongle is more sophisticated and sensitive than the RTL-SDR.

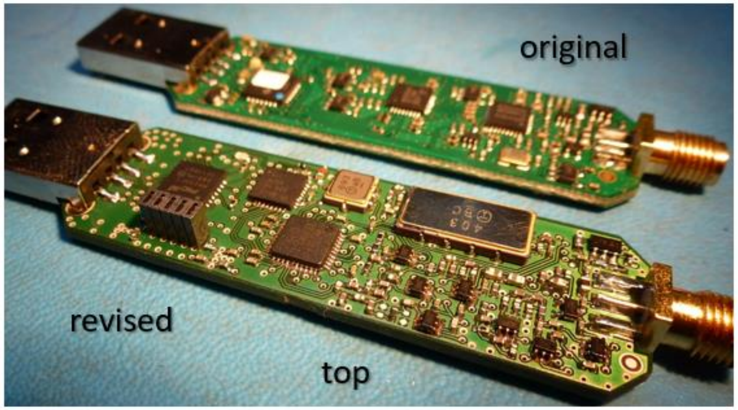




Mini-Workshop on SDR using RTL-SDR

With continuous improvement there were two models of the FUNcube SDR dongle.





Frequency range:
- 150 kHz-240 MHz
- 420-1.9 GHz

Bandwidth: 160 kHz

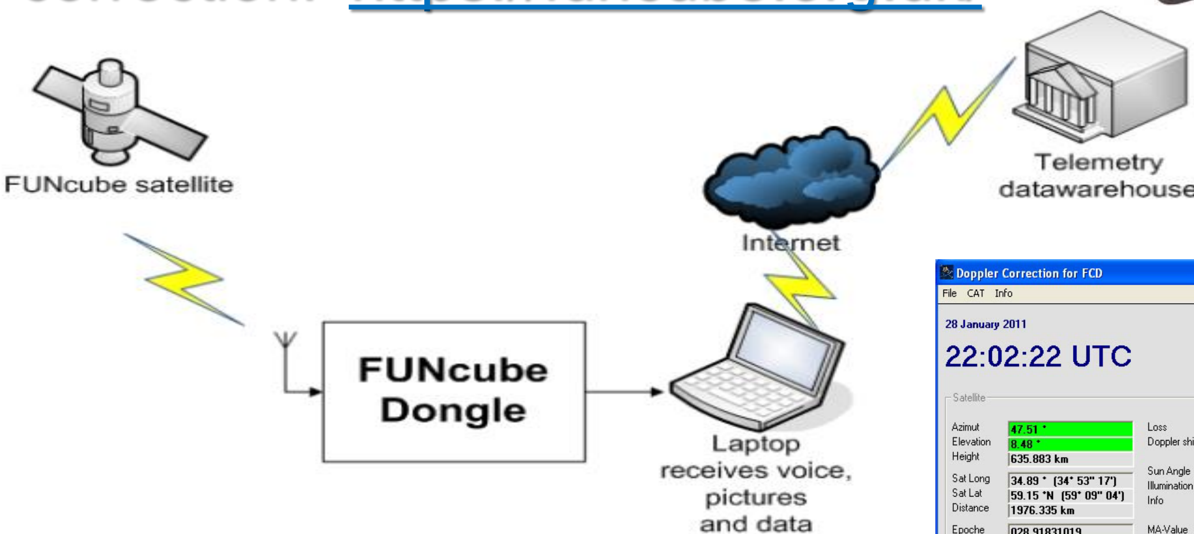
Sensitivity:
- 0.15 μV 12 dB SINAD

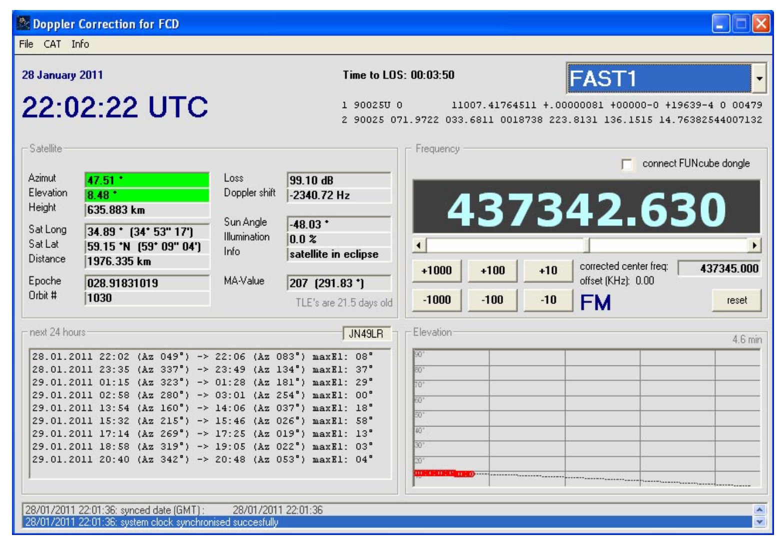
Noise figure: 3 to 5 dB

http://www.funcubedongle.com/

Mini-Workshop on SDR using RTL-SDR

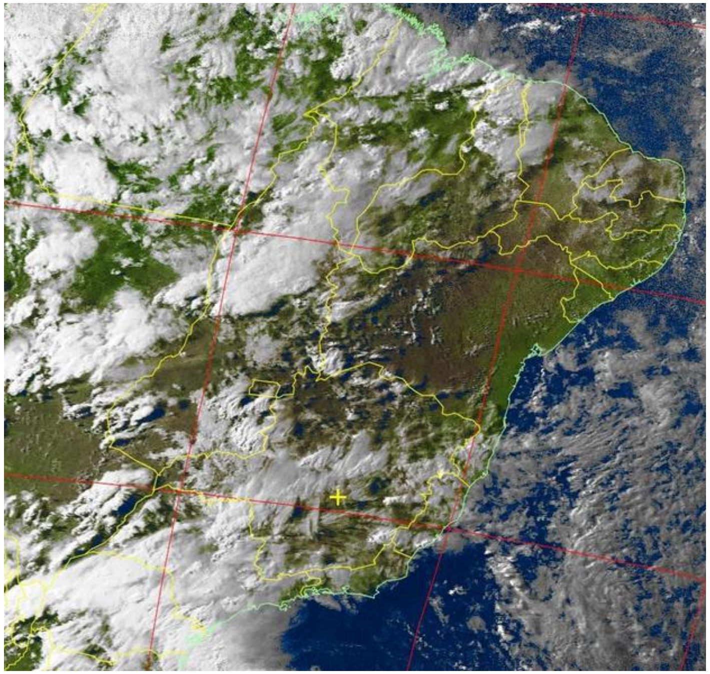
The FUNcube dongle is intended for STEM outreach with Amateur Radio LEO satellites for signal acquisition and doppler shift correction. https://funcube.org.uk/





Mini-Workshop on SDR using RTL-SDR

The high performance FUNcube SDR dongle capturing NOAA-15 weather images in color at TUARC K3TU with a wideband discone antenna.



Mini-Workshop on SDR using RTL-SDR

All *transmit and receive* (TX/RX) SDRs in transmit must have restricted spurious emissions (*distortion* and *harmonics*) as set by FCC *Part 15* regulations (Section 209).

Frequency MHz	*EIRP dBm*	*EIRP µW*
30-88	–55.2	0.0030
88-216	–51.7	0.0067
216-960	–49.2	0.0120
> 960	–41.2	0.0759

EIRP is *E*ffective *I*sotropic *R*adiated Power

Mini-Workshop on SDR using RTL-SDR

An example of a TX/RX) SDR is the Analog Devices ADALM-Pluto SDR.

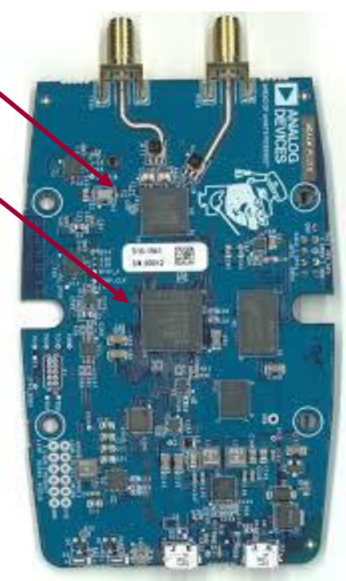
The transmitter is a *low power* (less than 10 dBm or 10 milliwatts) device under FCC Part 15 regulations (Sections 15.207, 15.209 and 15.221).

However, it can only transmit with restricted spurious emissions and on allowed frequencies in the 900 MHz and 2.4 GHz band.

Mini-Workshop on SDR using RTL-SDR

The ADALM-Pluto has a maximum power output of 7 mW (5 dBm).

The ADALM-Pluto is a TX/RX SDR which uses the AD9363 RF Agile Transceiver and the Xilinx Zynq Z-7010system-on chip (SoC) devices.

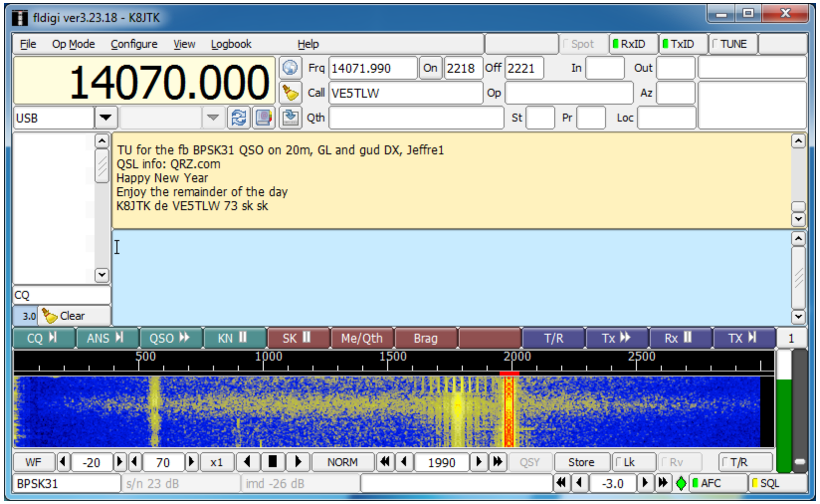


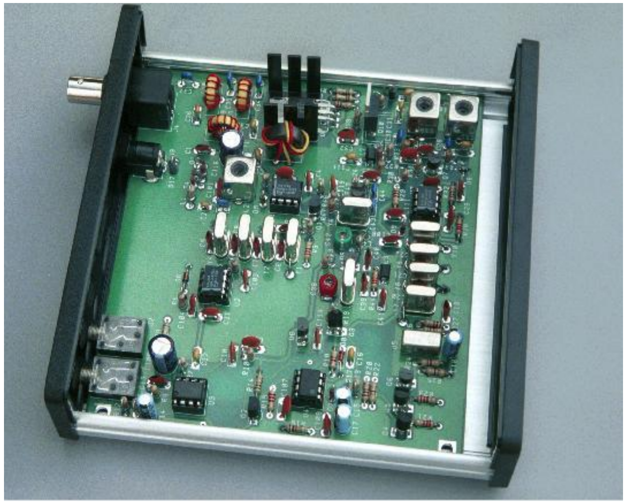
The nominal RF bandwidth of the AD9363 device is 325 MHz to 3.8 GHz but can be modified for a 70 MHz to 6 GHz range by modification of the ADALM-Pluto firmware.

Mini-Workshop on SDR using RTL-SDR

However, a TX/RX SDR when used on Amateur Radio frequencies with an FCC license is a *Part 97* device and not subjected to the EIRP and low power restrictions.

One of the earliest TX/RX SDR was the PSK-20 which operated on the 14 MHz (20 meter) Amateur Radio band for digital keyboard transmission. It used the PC sound card and was essentially an RF *front end*.

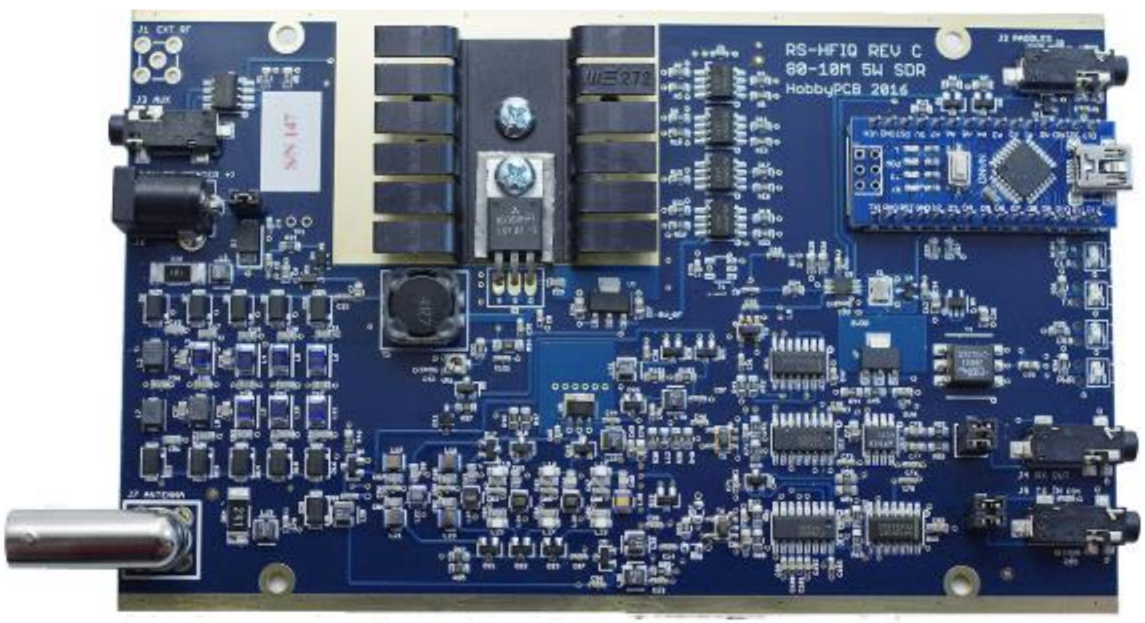




Mini-Workshop on SDR using RTL-SDR

The RS-HFIQ is an 5 W HF TX/RX SDR designed to translate I/Q baseband signals to RF on the 3.5, 7, 10.1, 14, 18, 21 and 28 MHz Amateur Radio bands.

The I/Q signals are provided and processed by an external DSP executing on a PC.

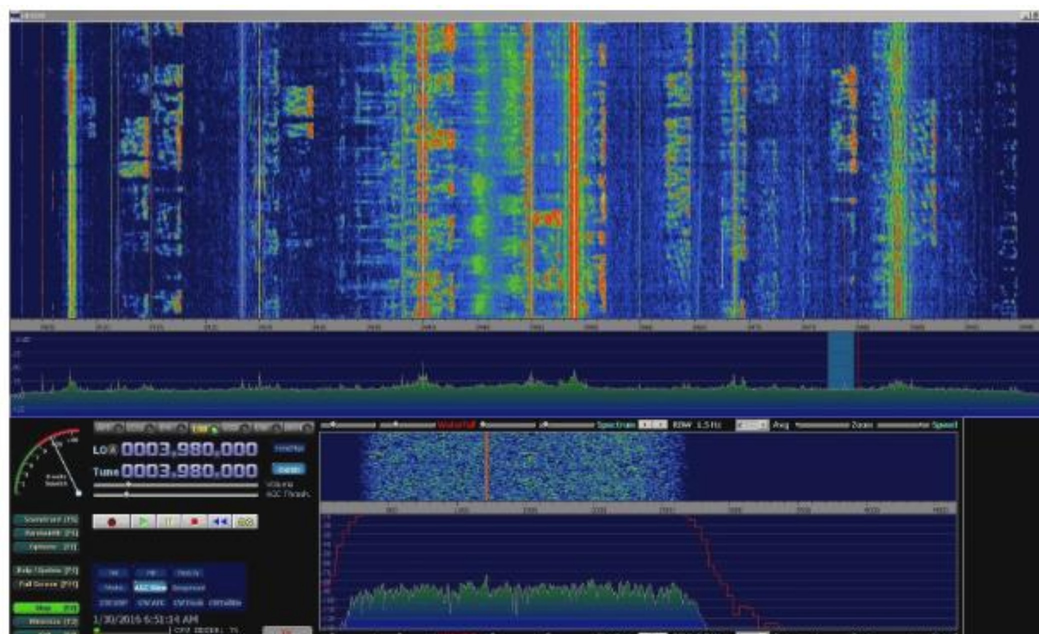


Mini-Workshop on SDR using RTL-SDR

The RS-HFIQ has reasonable RX SDR specifications with the crucial LO leakage < −50 dBc at 5 W (dBc is dB referenced to the carrier power) and a minimum detectable signal (MDS) of ≈ −130 dB.

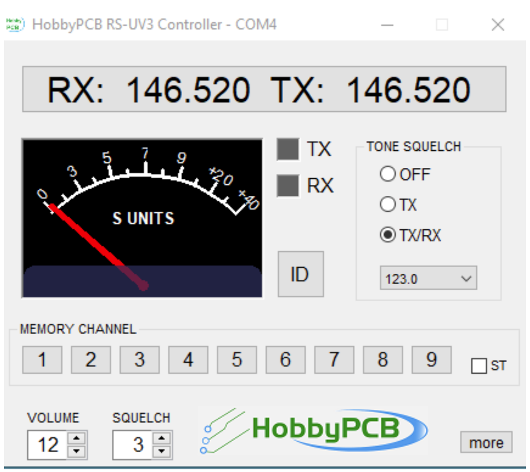
Spurious and harmonic emission are < −55 dBc

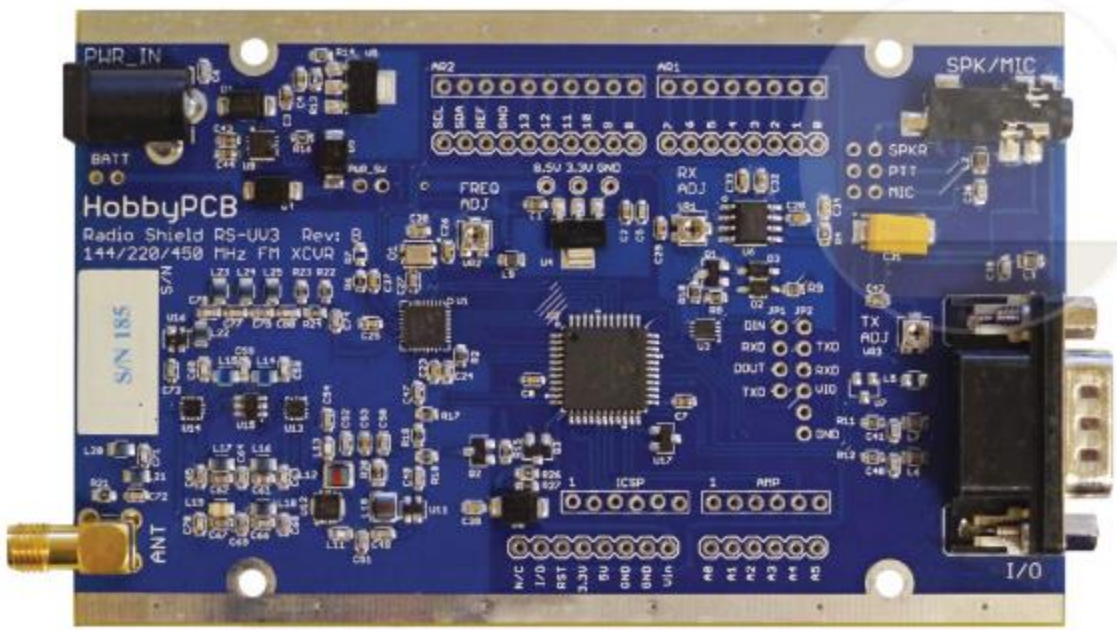
HSSDR with the RS-HFIQ on the 3.5 MHz (80 meter) Amateur Radio band



Mini-Workshop on SDR using RTL-SDR

The RS-UV3 is a 0.2 W FM TX/RX SDR for the 144/222/440 MHz Amateur Radio bands . The receiver sensitivity is −120 dBm (10^{-15} W or ≈ 2.2 μV at 50 Ω) for 12 dB SINAD (the ratio in dB of signal+noise+distortion to noise+distortion). Spurious and harmonic emissions are < −60 dBc.





Mini-Workshop on SDR using RTL-SDR

The most advanced TX/RX SDRs on the HF Amateur Radio frequencies are now available (at some cost, up to $5000).

The FlexRadio 6600 does not require an external PC, has four independent receivers, but crucial to SDR performance is the 16-bit ADC operating at 245.76 Msamples/sec (the RTL-SDR uses an 8-bit ADC at 28.8 Msamples/sec).

Mini-Workshop on Software Defined Radio using the RTL-SDR

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IEEE USA

IEEE Student Branch

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