ELB VOR and GNU GRC

Picture: ELB VOR, 117.2, SoCal

Overview

How to use GNU GRC and SDR dongles (e.g. HackRFOne, RTL-SDR, AirspyHF+...) in order to generate a VOR signal and to receive and how demodulate a VOR signal and find the relative location (TO/FROM) in relation to a VOR?

A brief overview how GNU Radio, esp. GNU Radio Companion (GRC) can be used.

What is a VOR?

A VOR stands for "*VHF Omni-directional Receiver*". It is used in airplanes to receive a ground based RNAV (Radio NAVigation) signal (instead of GPS). It tells the pilot, when receiving a VOR signal from a ground station in airplane, what the relative position of the airplane to this radio station is.

It works in this way (as a simplified explanation):

- The VOR acts like a lighthouse
- it has a flashing beacon – called *reference* signal
- it has a rotating beacon "light" which you get only when you are hit by the beam – called *variable* signal (the angle to the VOR is *variable*)
- the time difference between the reference signal (referencing *Magnetic North*) and the variable single (the *radial*) is displayed as relative bearing to the station

Technically it works this way:

- the *Magnetic North* signal is a 30 Hz signal – sent into all directions, permanently (omni-directional)

- the variable signal is the same 30 Hz signal – but now phase shifted: it “rotates” so that you get it when receiving a radial, with a phase difference
(BTW: the phase rotation is done via an antenna array, for the *radials*)
- The VOR has also an audio part (even voice could be transmitted): a 1020 Hz frequency is used to generate a pulsating and repeated Morce Code: the *station Identifier* (ID)

A pilot will tune to the VOR frequency (1)) and listen to (or verify on a display) the Morse Code (ID, IDENT). In case it is the right one and it is valid (VOR could be out of service) – the pilot will turn a knob, called OBS (Omni-Bearing Selector). Technically it adjust a Delay between the *reference* and the *variable* signal.
In case the phase difference between both 30 Hz is 0 (or 180) degree – the pilot can see the bearing (relative location) TO or FROM the station from his airplane.

FROM means: you receive the direct radial from the VOR station.
TO means: even you receive the radial, you convert it to the opposite, +180 degree, as it would be on the opposite site of the station pointing out from the station.

You receive only the radial you are FROM it (as it comes from the station). The TO indication is just a 180 degree inversion of a radial.

Airplane VOR receivers and displays have a flag for TO and FROM. When you fly right over the station or you cross the FROM/TO because of being perpendicular located to the station – the flag disappears and the VOR display is unreliable.

1) Find the VORs, their frequencies, morse codes... in flight charts (maps, for VFR or IFR) and Charts Supplements, e.g. via:https://skyvector.com/

How to generate a VOR signal?

The VOR signal is pretty easy to be generated.
It has these components:

- the signal is AM modulated
- it has the 30 Hz as AM
- plus the voice (limited to 4..5KHz bandwidth) or Morse Code, based on a 1020 Hz sound carrier (IDENT)
- the other 30 Hz signal is NBFM modulated, with a FM Deviation of 480: so, the FM frequency varies by 480 Hz around the FM sub-carrier of 9960 Hz (the FM fc) to encode this 30 Hz wave signal
- All is “mixed” together around the AM Carrier Frequency (as 0 Hz in base band).
Some parts, e.g. the Voice/Morse Code have a lower amplitude: if you do not hear the Morse Code – you do not have reliable reception (for navigation via the 30 Hz signals)
- The phase difference between both 30 Hz signals is the “information” (the bearing from the station)

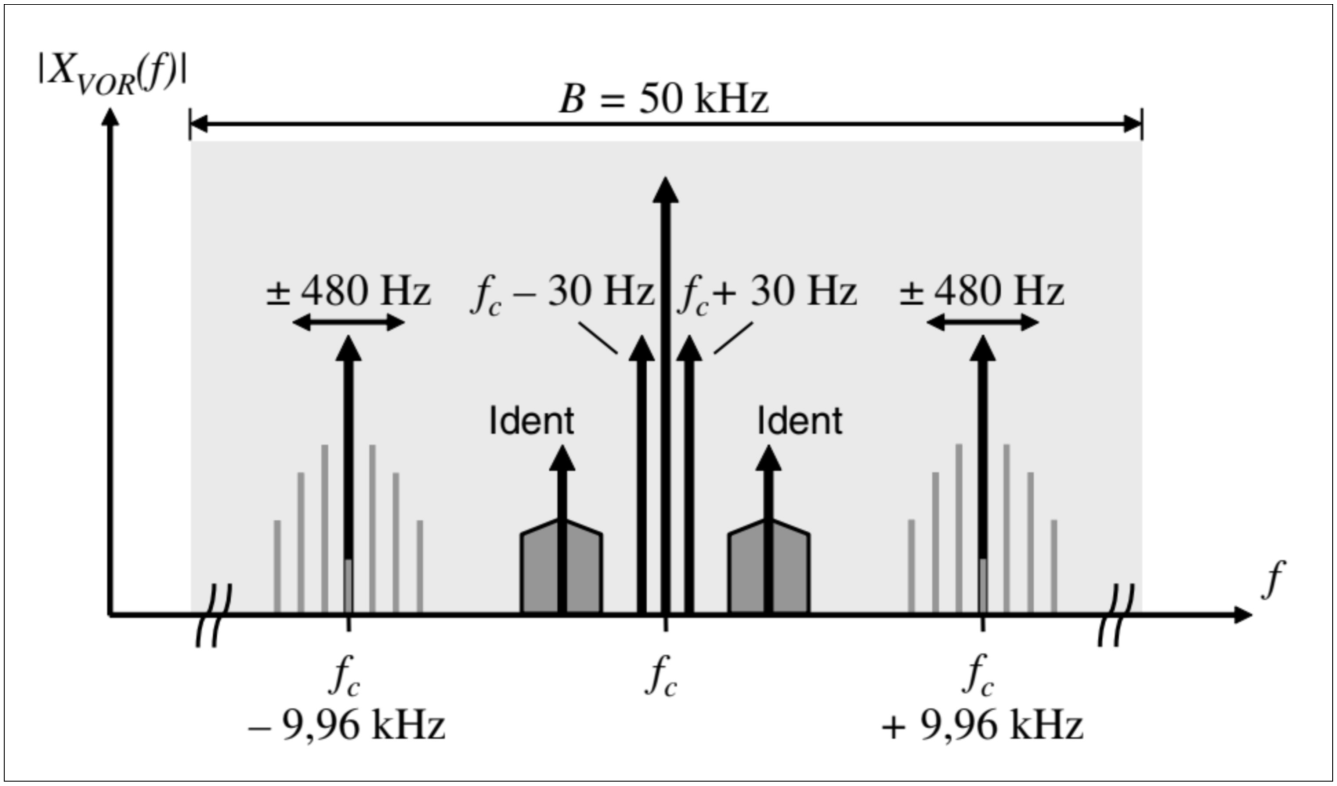

Figure 1: VOR signal spectrum

Remark

Which one the variable and the reference signal is – depends on which type of VOR is used:

CVOR vs. DVOR:
Conventional VOR vs. Doppler VOR – the *variable* and *reference* signals are just "flipped" (which one is AM and the other FM modulated).

For a VOR Receiver it does not matter because: at the end you will get two 30 Hz signals but you want to know the phase difference between both (for the bearing from the station). Which one is which does not matter for a receiver.

A Doppler (DVOR) as transmitter is less affected for ground reflections received in airplane (e.g. due to buildings, mountains, …).

GNU GRC Tx Graph

Here is a GRC graph how to generate a simple VOR signal:

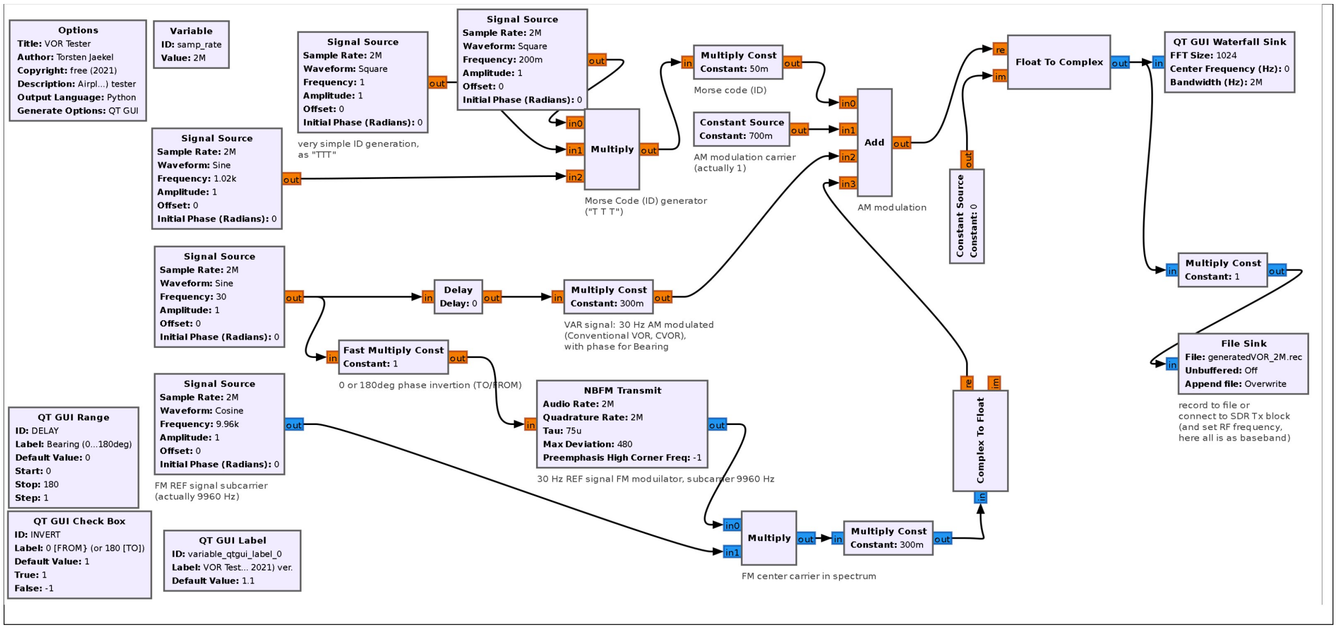

Figure 2: VOR Tx GRC

There is nothing special in this GRC graph: it has all the components needed in order to generate a VOR signal (to “mix” all the components together).

Remarks

Instead of the “File Sink” you would use your SDR dongle Tx Sink.

The final tansmission RF frequency, e.g. 117.2 MHz, is done by the SDR Tx Sink: this signal here is a “baseband signal”, centered around 0 Hz. The final RF carrier is done by the SDR Tx dongle.

There is a “Delay” block: this one is just there in order to “trim” the GRC graph, for a correct phase. It seems to happen, that the used filters and blocks modify the phase of the *variable* signal part in the final signal. This “Delay”block compensates for correct 0 degree (phase difference on the output).

It can also act to “simulate” a bearing: if you add more delays – it shifts the phase for the variable signal and therefore a receiver would see a different bearing FROM the station.

For some reason I had to tune down a bit the center carrier amplitude (see this 700m multiplication, instead of 1, potentially due to fact that the AM m=0.9 is required).

This graph follows the modulation math, as:

$$x_{VOR}(t)=\hat{x}\{1+m3[xLOP(t)+XRef(t)+XIdent(t)]\}*\cos(2\pi fct)$$

Please see here: https://www.skyradar.com/blog/navaids-a-technical-introduction-into-architecture-and-signals-of-ilsdme-and-vor

The Morse Code (IDENT) is very simplified generated:
it generates pulsed via muting a sound wave. It results in a morse code as “TTT” (3x dot).
The time interval when the IDENT is sent is much faster as in real life situations (e.g. every 10..20 seconds, here way more often).

VOR signal reception

The reception of a live signal with a SDR dongle Rx is much more complicated:

- receiving a VOR signal at the ground is quite impossible:
  VORs are intended to radiate into the air, to airplanes: the antenna radiation pattern is optimized for it. So, receiving a signal when on the ground, at the same elevation as the station, even when very closely located to a VOR station, results in a pretty weak signal (maybe also with a lot of reflections or spurious signals from other *radials*).
- A real life signal is not just weak, it will have also a lot of noise. If a large sample rate is used (and therefore a large bandwidth) you might get signals also from FM sound broadcast stations (which are right “under” the air traffic frequency band).
- The signal might have also amplitude variations (fading), so that the signal amplitude is not constant and varies also amplitude of the signal components inside the recorded signal.

I have done this:

Step out to a real VOR, try to get a close as possible (permitted) and try to record a signal with a tuned antenna. At best: use a directional antenna (Yagi) or at least a tuned dipole antenna.

Bear in mind that a VOR uses Horizontal Polarization: therefore your antenna has to be also twisted in the horizontal position.

A tiny whip antenna in any direction is not suitable!


Picture: you need direct “Line of Sight” with a VOR station!

Remarks

Depending on the type of VOR (high altitude, low altitude or terminal), the signal at the same ground elevation is weak.
The best is to look for a “Terminal VOR” (as ELB VOR is). But all VORs have a radiation characteristic like an inverted cone: the main power goes into the air (to airplanes) and at the ground level is just “parasitic” radiation.
Choose a location which is higher as the VOR elevation when trying to record a signal.

Remember also where you have recorded the signal:
It is important to figure out later your recording location in relation to the VOR station (bearing). Measure later the bearing and use this information in order to “trim” your receiver results (a “Delay” might be needed in order to get the correct result (bearing in degrees from the station).

Picture: my post processing on Google Maps to find the bearing FROM the station when signal was recorded.

Bear also in mind the difference between “True North”, “Magnetic North” (used by VOR) and the “*Magnetic Variation*”. Every VOR has a variation setting and it is important to figure out and to know. The *magnetic variation* used by a VOR can be different from the real current variation (in relation to a real magnetic compass currently).

GNU GRC Rx Graph

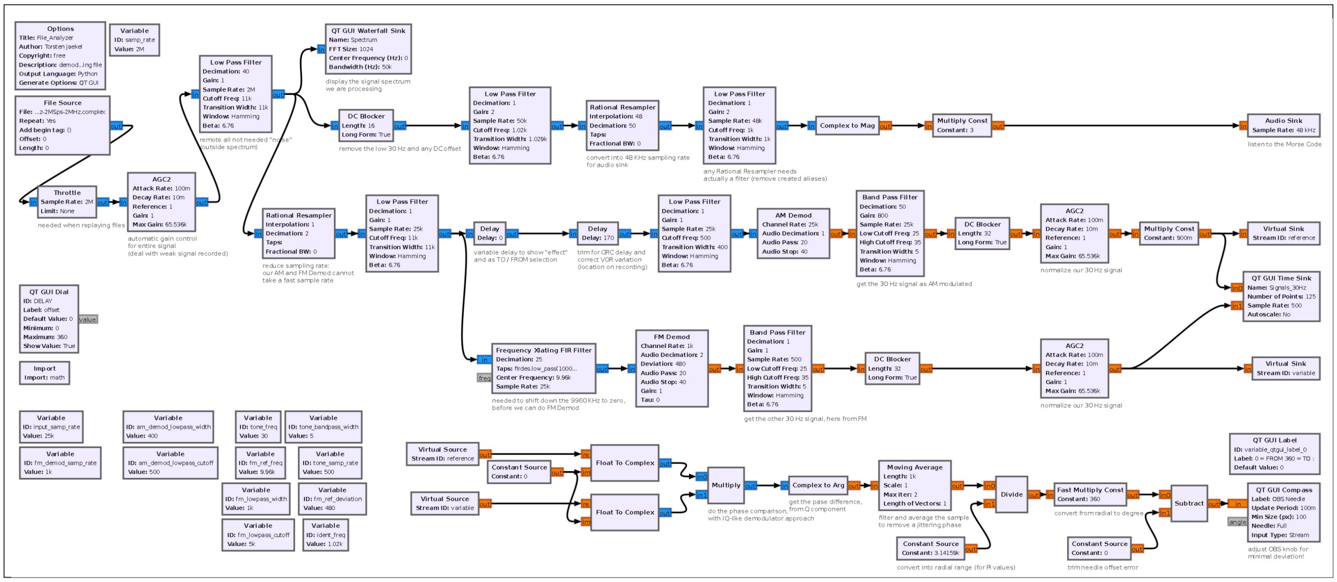

Figure 3: a possible VOR Rx GRC graph

The receiver does actually all the opposite:

- receive the entire spectrum (signal) and split it, into
- the 30 Hz *reference* signal
- and the 30 Hz *variable* signal
- one signal is AM demodulated, the other FM (actually NBFM) demodulated
- demodulate the voice, morse code signal (as AM, as audible signal for an “Audio Sink”)
- use AGCs (Automatic Gain Control) in order to deal with a weak signal, with variations in amplitudes (fading)
- do a Phase Difference measurement

The building blocks are the “opposite” to the transmitter graph, except to have additional blocks like AGCs, additional filters and the “Phase Difference” measurement.
The demodulation is “anti-symmetrical” to the generation of such a signal.

The Phase Difference measurement is the most tricky part (besides to use AGCs):

- it should work without to be dependent on the signal amplitudes!
- It should be quite accurate (small errors) and requires a “stable and accurate” signal processing: if GRC would add phase jitter or GRC is not “stable” on sampling rate (and performance) – all will result in a fluctuating result
- There are many different approaches to measure the phase difference, e.g.:
  via an FFT and using the imaginary part (Q, phase) Bin to do the comparison,
  to measure the time difference between the 0-value crossing of the two 30 Hz sine signals (not possible in GRC),
  to use the “complex plane”, as IQ, and the imaginary parts of the signal (done here),
  to use the “complex plane” and do multiplications, esp. with the conjugated signal involved

At the end, the internal result is a value as radian which has to be converted into a degree value (check the trigonometrical math needed for it).

Remarks

Instead of displaying a bearing FROM the station in degree, it can also work as used in airplanes:

- rotate an "OBS Knob" until the phase difference is 0 (or 180) degree
- the (rotating) scale on the OBS Know shows you on which **radial** you are (compass rose)
- it means: try to get 0 (or 180) phase difference and read what you have dialed in order to get it (instead of showing a bearing withing a 360 degree compass rose, an airplane VOR receiver will act just in a range of +/- 10 degrees when you reach the correct bearing with OBS adjustment)

There is also a "Delay" block, mainly in order to trim the GRC graph:
When I know the bearing FROM the station when I have recorded the signal, I use it in order to "adjust" the GRC graph for the correct (expected) result displayed.
The GRC graph can have phase shifts due to filters used, how the signal is processed and I want to "eliminate" these phase errors (not coming from the signal, inserted by the graph itself).

Additionally, there can be a "Delay" acting like the OBS Knob (add a phase shift). When set to 0 or 360 (or should it be 180?) degree there should be a FROM vs. TO relation (it turns the result to the "opposite" direction).

Best Practice

The best approach to work on a VOR receiver is:

- record a live VOR signal (or find some recording files with known bearing, VOR and variation)
- have this file (with know sampling rate)
- replay this file via GRC and work on the receiver part (to demodulate the signal):
  you have to deal with all issues live in real life, e.g. weak signal, fading, noise, …
- When all is working with recorded file – than (!) you can try to receive a live signal:
  just substitute the "File Source" with your SDR Rx block (bear in mind to have the same sample rate)
- you can also try to generate (modulate) a signal and to decode (demodulate) it again: even this should work flawlessly (but you do not deal with weak and noisy signal here, except you would add noise on Tx or add a "RF channel simulation" between both graphs

Remarks and Experiences about GRC

1. Check all you sample rates:
   When you do "interpolation" or/and "decimation" - it changes the sample rates down the graph.
   Make sure all make sense, so that all blocks get the right amount of samples.
   Any mistake/mismatch results in an error free graph but it will not run properly (seems to stop or it spits out messages)
2. I do not know how accurate GRC is in terms of "phase accuracy", "phase stability" and "phase

jitter”.
At least, a GRC seems to insert a phase offset (hopefully constant), but without “compensation” (see the “Delay” blocks “needed”) - the result can be wrong.
A GRC has to be tuned and trimmed with a “Delay” for the correct results to get.
BUT: any change on parameters, like sample rate, decimation, interpolation, or adding/removing filters (and blocks) results in a new “adjustment” of this inserted “phase offset”

3. When it comes to the use of real SDR dongle Rx (and Tx) – their phase stability (even frequency stability) matters in addition: if the SDR Rx dongle is not accurate (stable) in frequency (and has a phase jitter) – it would be added to the even trimmed GRC graph.
This results in flaky results displayed.
Try to get a “perfect” GRC graph from file first. Deal with the SDR Rx dongle issues later (if possible).

4. The sample rate can be specified in “decimal” or as “binary”: the K (“kilo”) and M (“mega”) is different: in decimal: K and M are based on 1000, but in binary: it is based on a “power of two”.
Example: 1K can mean 1000 (decimal) or 1K is 1024 (binary 2**10).
Sometime, you need FFT (or other filters) which work best with a binary ratio on the sample rate (e.g. a 1.024K FFT size).
But a conversion from a decimal sample rate (via interpolation and decimation) to a binary based sample rate results in a Non-Integer ratio (not exactly an integer ratio).
Even the sample rates differ by just 0.01 – it can result in a phase drifting (besides sporadic messages on the GRC).
Best is: use everywhere and always integer ratios (without fractional results) for the sample rate. (See also 1.)
My experience: a drift on the phase is caused by a not correct sample rate setting all along the GRC graph!

Final Comments

It is possible to generate a VOR Tx signal (and even to transmit and receive via an antenna), also to have a live VOR Rx signal and decoded (and showing the bearing), but:

- the “correctness” will not satisfy the FAA requirements working as an aircraft test equipment
- the radiation of a wireless signal is not legal, esp. when such intent would interfere with real air traffic systems, esp. illegal to use close to or on an airport
- the handling of VOR signals at the ground (receiving, transmitting) to real airplanes can conflict with ATC and FCC regulations, it needs to consider other issues like “prop reflections”, “near field transmission” ...
- The only legal option to test VOR receivers in airplanes is to use real VORs, Test VORs (VOTs) or certified test equipment.

I think, a GNU GRC based Tx and/or Rx is not accurate enough to satisfy the FAA requirements for testing VOR receivers.

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