ECOLE NATIONALE DE L'AVIATION CIVILE

TELECOM LAB - SIGNAL PROCESSING AND NAVIGATION RESEARCH GROUP

Using GNU Radio Companion to improve student understanding of signal processing theory through VHF Omni-Directional Range (VOR) signal demodulation

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Introduction

- Complex notions being taught in signal theory and signal processing courses need to find some practical realizations.
- Some practicals are given to help the students understanding specific points in these courses.
- These practicals are completed by a long project which proposes, as a global case of application, to demodulate a VOR signal.
- This is realized by mean of a DVB-T USB dongle (one per pair of students), operated through the GNU Radio Companion (GRC) software.
- The simultaneous learning of this powerful software is an interesting aside of this project, but if it is not its primary goal.
- This presentation provides insight into this long project.

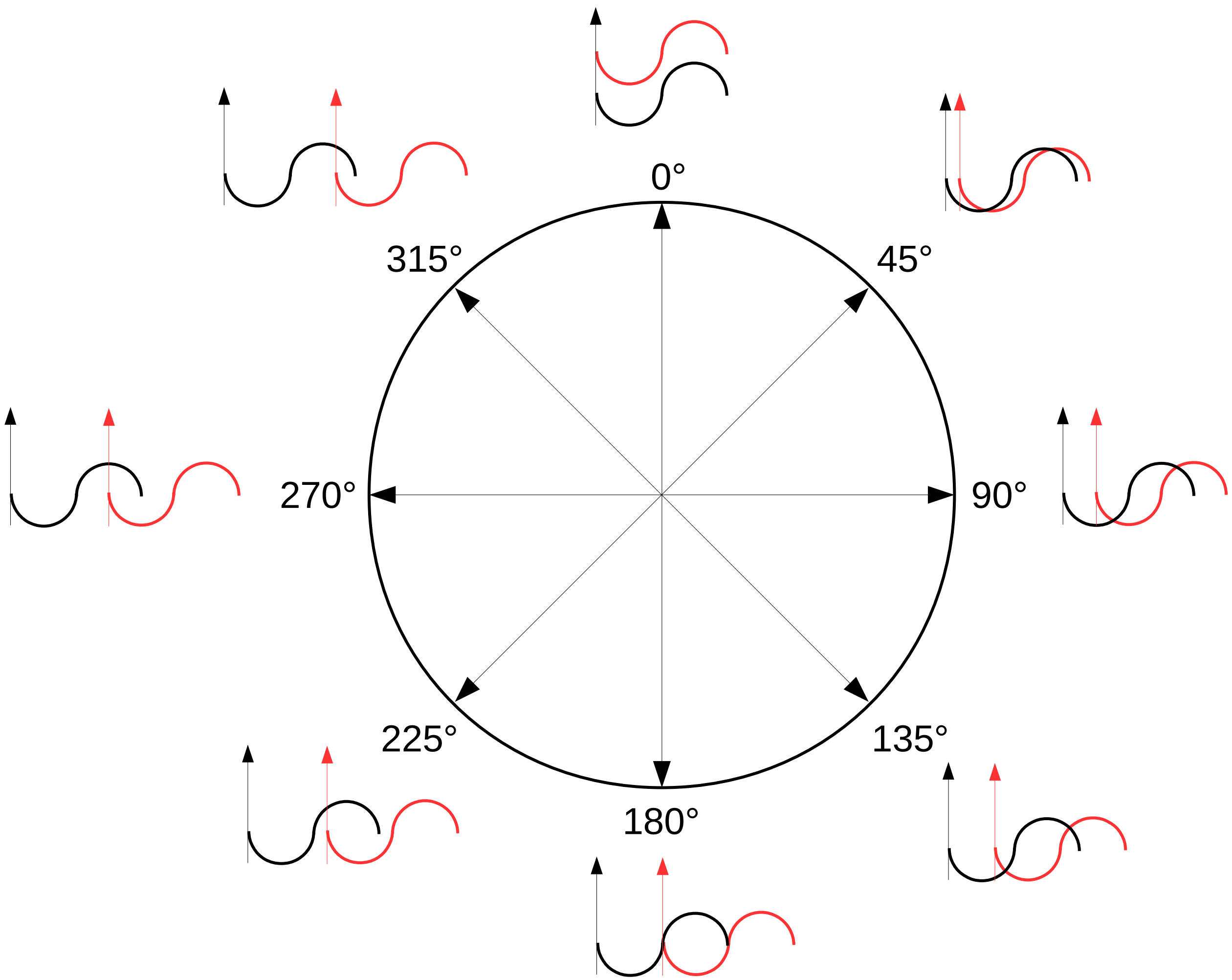
Outline of the presentation

1. A model of the VOR signal
2. The pedagogical approach
3. Two interesting technical points
4. Conclusions

1 A model of the VOR signal (1/2)

- The VOR system is a navigation aid designed to give the angle, in relation to the magnetic north, to the aircraft from a ground radio beacon of known position.
- The VOR beacon simultaneously transmits two 30 Hz signals:
  - A first one with a constant phase whatever the direction in which it is received.
  - A second one with a phase which consistently varies according to the direction in which it is received.
- The onboard receiver has to measure the phase between both 30 Hz signals.

1 A model of the VOR signal (2/2)



https://www.slideshare.net/btinus/vor-ppt

1.1 Time representation (1/2)

- A noise-free time model of this signal, as seen by the receiver, is presented to the students:

$$e(t) = (1 + M(t)) \cdot \cos(2\pi f_0 t + \theta_0), \text{ with } f_0 \in [108, 118] \text{ MHz}$$

- It is an Amplitude Modulation (AM) of a carrier signal at f_0. θ_0 is a random initial phase.
- M(t) is an hybrid signal carrying several components.

1.1 Time representation (2/2)

$$M(t)=\left[\begin{array}{l} 0{,}3\cdot\cos\left(2\pi 30 t-\mathrm{QDR}+\theta_{30}\right) \\ +0{,}05\cdot\mathrm{ident}(t)\cdot\cos\left(2\pi 1020 t+\theta_{1200}\right) \\ +0{,}3\cdot\cos\left(2\pi 9960 t+\theta(t)+\theta_{9960}\right)\end{array}\right.$$

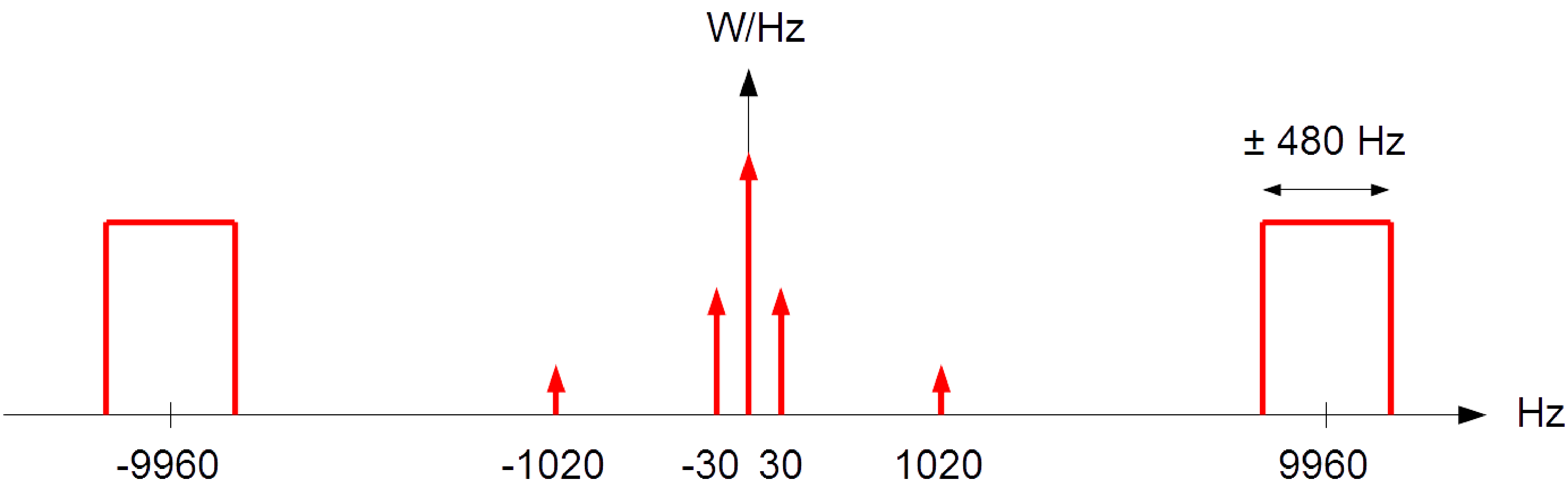
$$\theta(t)=16\cdot 30\cdot 2\pi\underbrace{\int_0^t \cos\left(2\pi 30 u+\theta_{30}\right)du}_{\text{Frequency Modulation (FM)}}=16\cdot\sin\left(2\pi 30 t+\theta_{30}\right)-16\cdot\sin\left(\theta_{30}\right)$$

with:

- QDR is the magnetic bearing from the station to the aircraft,
- ident(t) is the identification signal of the VOR beacon (Morse code),
- θ_{30}, θ_{1200} and θ_{9960} are random initial phases.

Note: the QDR may be in θ(t) (with a + sign) instead, then it is a VOR-D (Doppler) signal vs a VOR-C (Conventional) signal here.

1.2 Baseband spectrum



It is interesting to note that each component can be separated by filtering without difficulty.

The overall bandwidth can be safely set by excess to 12 kHz.

2 The pedagogical approach

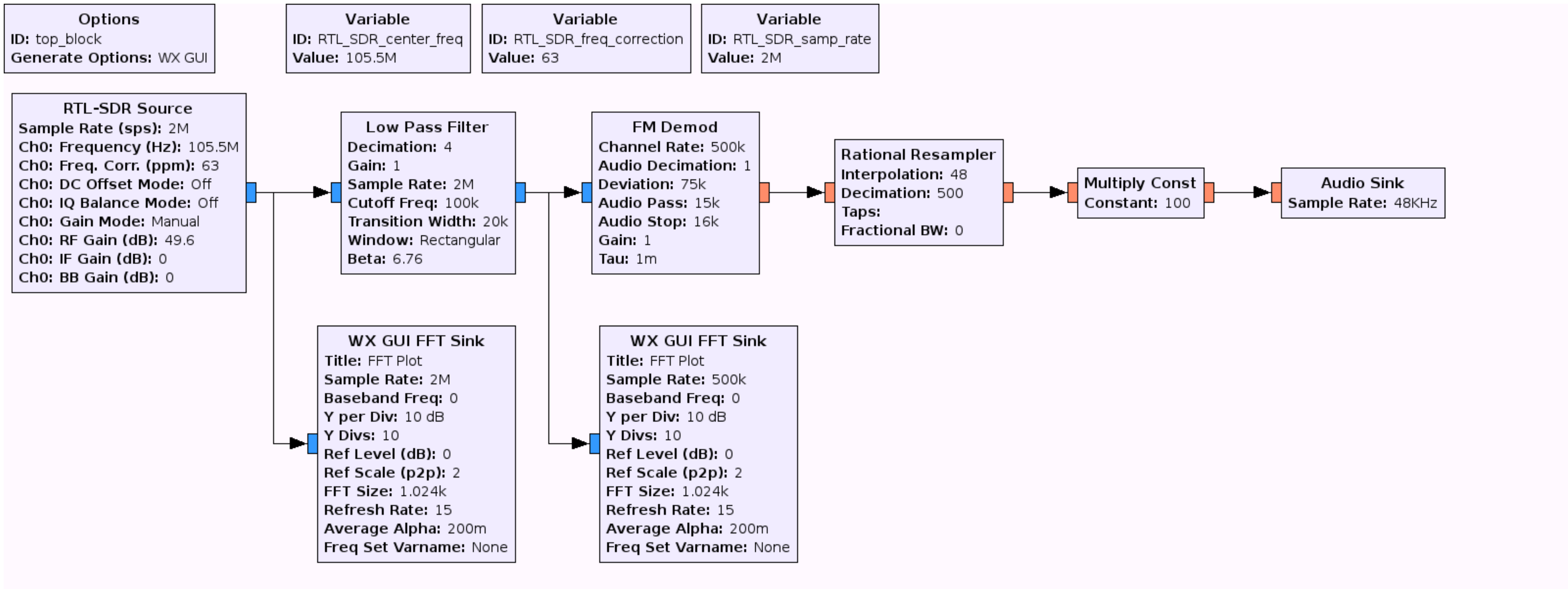
Strong guidelines are set to the students to support them toward the solution. Indeed, the project is split in four distinct and successive steps:

1. An interactive implementation of a simple FM radio-broadcast receiver.
2. The students have to produce flow diagrams which read, display and record to a file the I & Q samples.
3. A I & Q VOR signal generator has to be implemented, component after component.
4. The VOR receiver itself has to be developed. Again, a component by component method is suggested to the students, so they can safely move towards a proper final design.

2.1 The FM radio-broadcast receiver

This first SDR receiver serves as:

- a presentation of the GRC GUI capabilities,
- as a proof of the SDR concept for the students: it works!



2.2 The read, display and record flow diagrams

- The target of the second step is a more comprehensive handling of GRC and of the USB dongle.
- The students have to produce flow diagrams which read, display and record to a file the I & Q samples.

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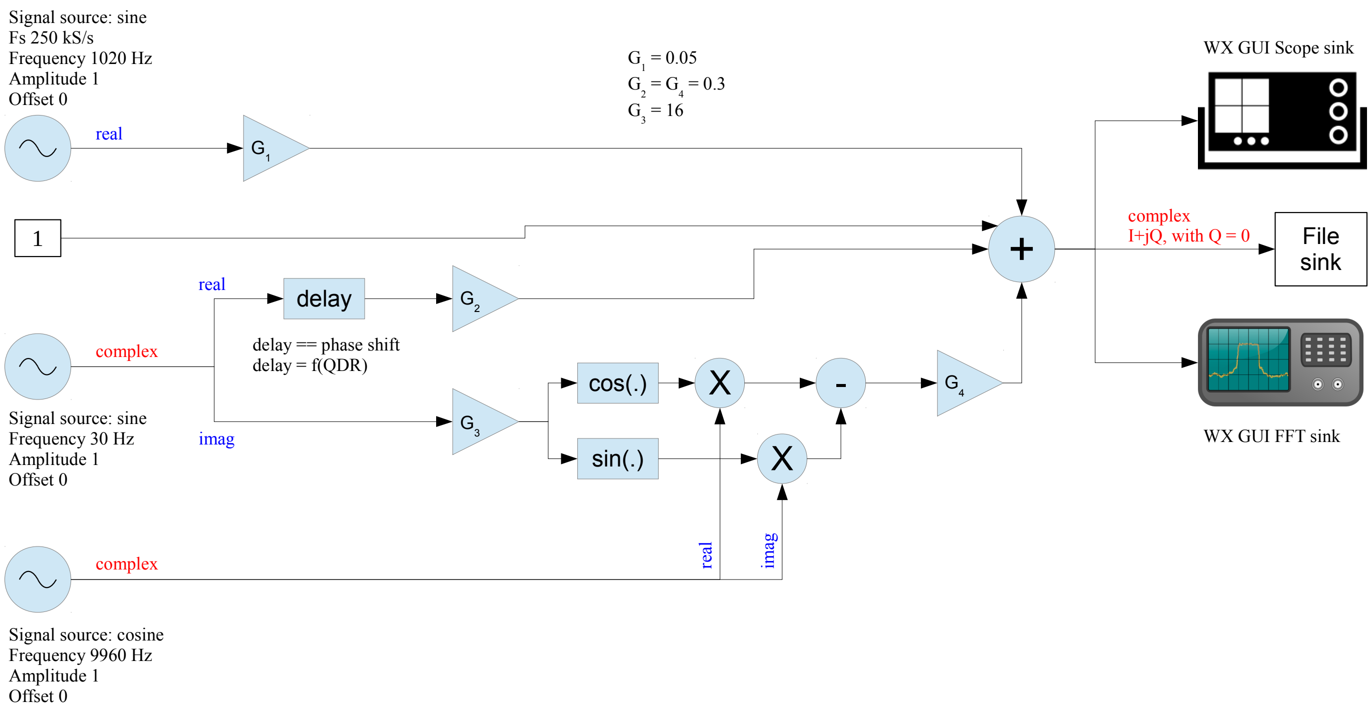
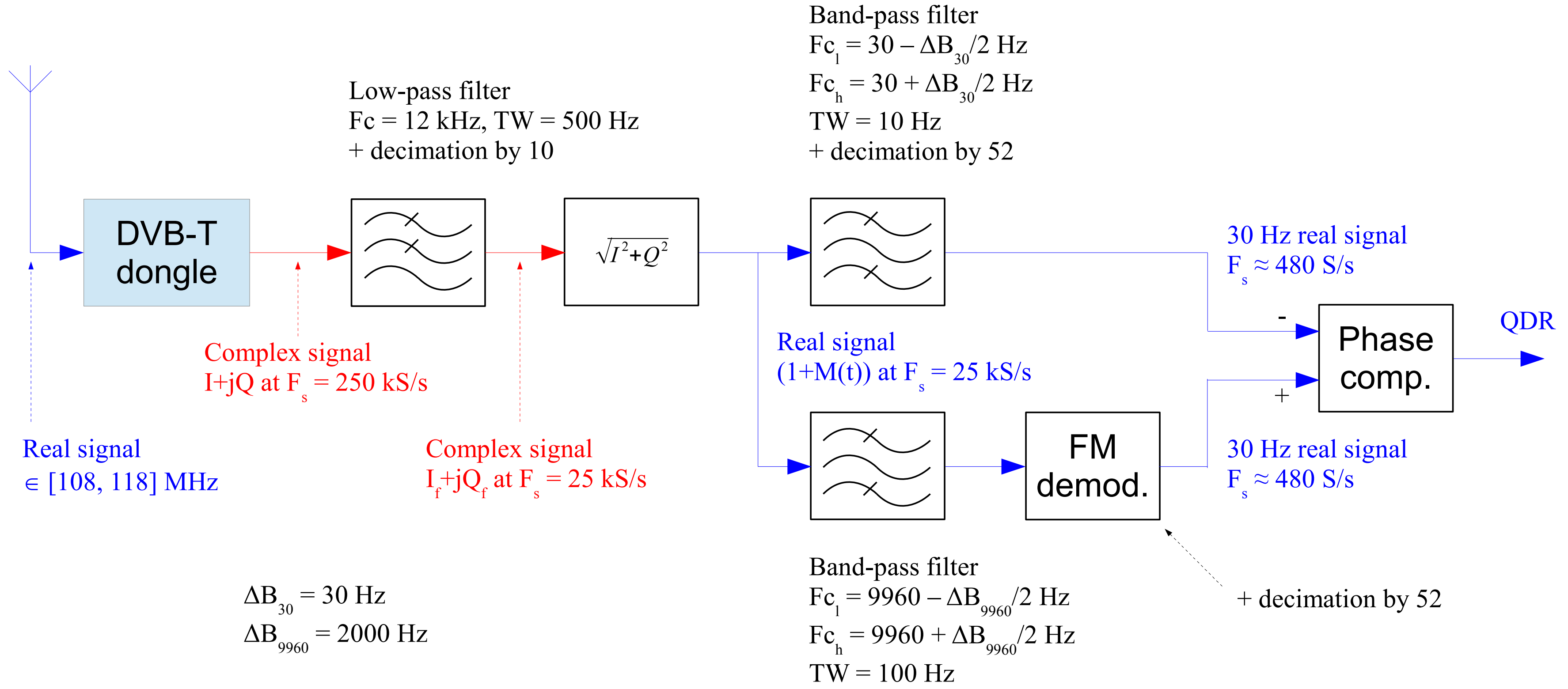
2.3 The I & Q VOR signal generator

- A detailed synoptic view is provided as a starting point.
- The aim of this step is to:
  - deepen the students understanding of the VOR signal structure.
  - provide the future receiver with synthetic test signals.



2.4 The VOR receiver (1/2)

- A detailed synoptic view is provided as a starting point here also.
- Students have to validate their flow diagram with their own signals.



2.4 The VOR receiver (2/2)

A Software Course Deviation Indicator (CDI) is provided to the students to help them understanding the use of a VOR receiver onboard.

- Written in Python.
- Communicating through a ZeroMQ socket with GRC.

2 The pedagogical approach – evaluation

The project ends with a double evaluation:

- A one hour written examination, to check the understanding of various signal processing points.
- A test of reception of a real VOR signal with a QDR to decode.

This reception test is realized by radiating a low power VOR signal in the room, with the help of a Marconi 2030 signal generator.

The transmitted QDR is set according to the teaching team's wishes.

The students have to use their DVB-T USB dongle and their SDR VOR receiver to demodulate the signal.

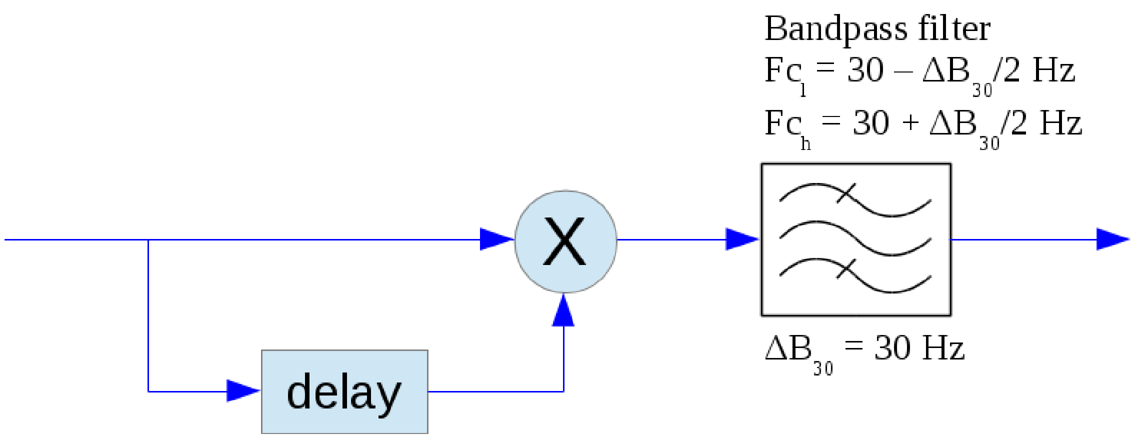
Then, they can announce the QDR they have demodulated.

3 Two interesting technical points

- The philosophy of this long project is to improve the understanding of the students in signal theory and signal processing
- Then, the use of high level blocks, like the FM Demod block, is forbidden.
- The students have to understand the different signal processing operations to be able to build them atomically.
- In this aspect, the two following ones are particularly interesting:
  - The frequency demodulation of the 9960 Hz signal.
  - The phase comparator.

3.1 The FM demodulation (1/2)

- The synoptic view of one specific demodulation method is given to the students.
- They not only have to implement it, but also to understand it.
- The calculation of the value of the delay is always an instructive brainstorm.



3.1 The FM demodulation (2/2)

- Let s(t) be the incoming signal:

$$s(t)=\cos\left(2\pi 9960\, t+\theta(t)+\theta_{9960}\right)$$

- A multiplication by s(t) delayed:

$$s(t).s(t-\tau)=\frac{1}{2}\Big[\cos\left(2\pi 9960\,\tau+\left(\theta(t)-\theta(t-\tau)\right)\right) \\ -\cos\left(2\pi 9960\,(2t-\tau)+\left(\theta(t)+\theta(t-\tau)+2\theta_{9960}\right)\right)\Big]$$

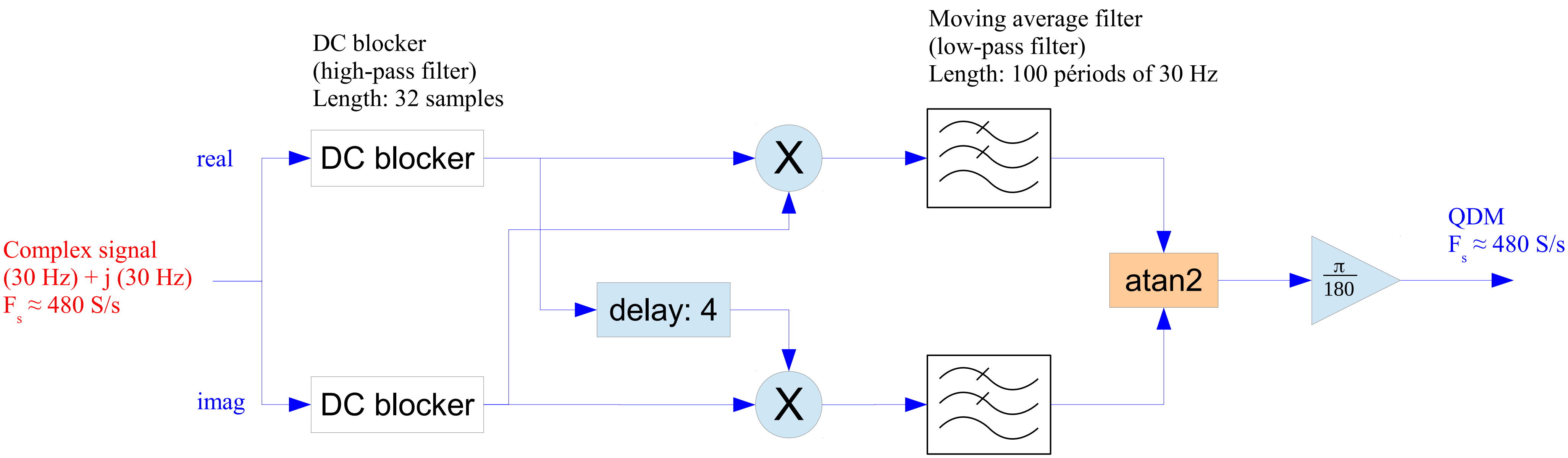
- The second term is suppressed by the 30 Hz band-pass filter.
- If τ (has to be a multiple of T_s) is set so that 2π9960τ = π/2 [π], then:

$$s(t).s(t-\tau)\big|_{\text{filtered}}=\pm\frac{1}{2}\sin\left(\theta(t)-\theta(t-\tau)\right)$$

- If what is more τ << 1/30: $s(t).s(t-\tau)\big|_{\text{filtered}}\approx\pm\frac{1}{2}\left(\theta(t)-\theta(t-\tau)\right)\approx\pm\frac{\tau}{2}\dot{\theta}(t)$

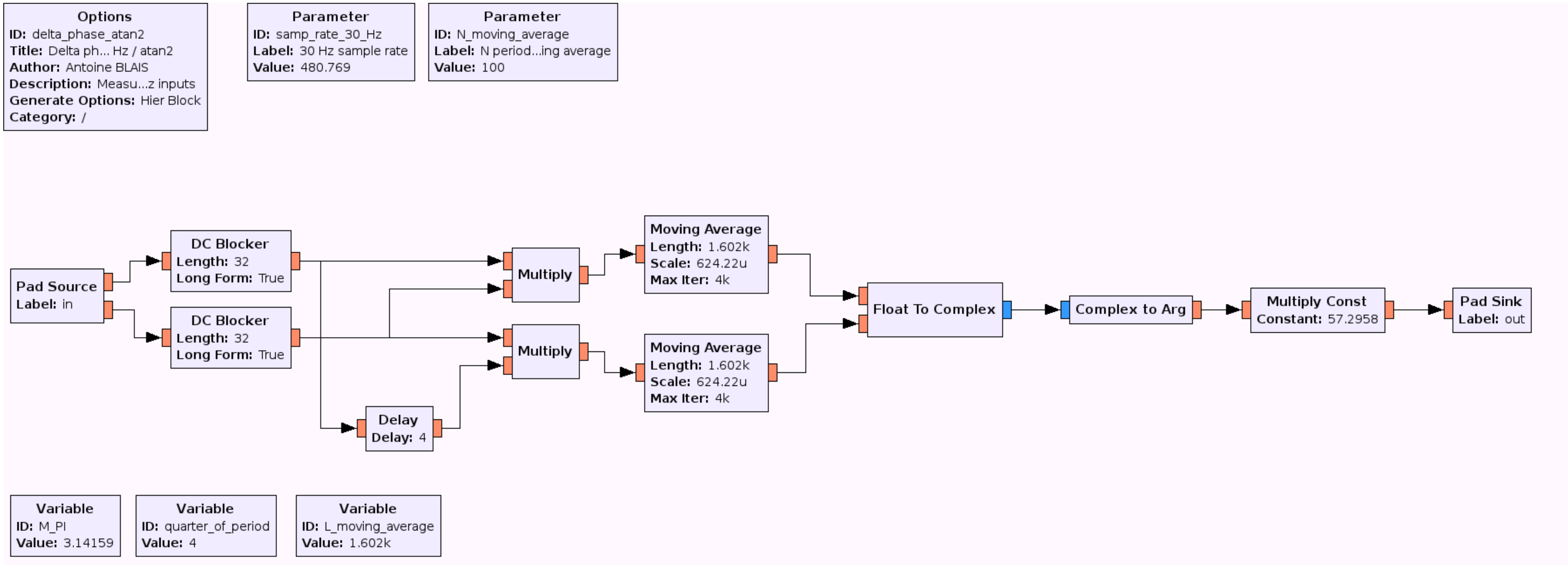
3.2 The phase comparator (1/4)

- The phase comparator, needed to extract the QDR is an opportunity to introduce the students with the principle of the Hier block.
- They are asked to embedded this phase comparator in a dedicated Hier block.
- A possible implementation for this phase comparator Hier block:



3.2 The phase comparator (2/4)

- The dedicated Hier block has to be tested and validated independently from the main flow diagram.



3.2 The phase comparator – detail of the calculation (3/4)

- Let $s_1(t)$ and $s_2(t)$ be the inputs of the block, with f_c = 30 Hz:

$$s_1(t)=A_1\cos(2\pi f_c t+\phi_1) \qquad s_2(t)=A_2\cos(2\pi f_c t+\phi_2)$$

- Let $s_1(t)$ be a delayed version of $s_1(t)$:

$$s_3(t)=s_1(t-\tau)=A_1\cos(2\pi f_c t-2\pi f_c \tau+\phi_1)$$

- If $\tau=1/(4f_c)$

$$s_3(t)=A_1\cos(2\pi f_c t-\pi/2+\phi_1)=A_1\sin(2\pi f_c t+\phi_1)$$

- The two cross-products give:

$$p_a(t)=s_1(t)\times s_2(t)=A_1 A_2\cos(2\pi f_c t+\phi_1)\times\cos(2\pi f_c t+\phi_2)$$

$$p_b(t)=s_3(t)\times s_2(t)=A_1 A_2\sin(2\pi f_c t+\phi_1)\times\cos(2\pi f_c t+\phi_2)$$

3.2 The phase comparator – detail of the calculation (4/4)

$$p_a(t)=\frac{A_1 A_2}{2}\left\{\cos\left(4\pi f_c t+\phi_1+\phi_2\right)+\cos\left(\phi_1-\phi_2\right)\right\}$$

$$p_b(t)=\frac{A_1 A_2}{2}\left\{\sin\left(4\pi f_c t+\phi_1+\phi_2\right)+\sin\left(\phi_1-\phi_2\right)\right\}$$

- The low-pass filters suppress the first terms:

$$p_a^f(t)=\frac{A_1 A_2}{2}\cos\left(\phi_1-\phi_2\right)$$

$$p_b^f(t)=\frac{A_1 A_2}{2}\sin\left(\phi_1-\phi_2\right)$$

- The atan2 function (a `complex to arg` block) is then used to recover the value of Φ_1 - Φ_2.

Conclusions

- It is the third year this long project is given.
- The teaching team has observed each time the benefits of this materialization of the theoretical notions taught during the related courses.
- The knowledge and skill of the students are clearly improved as well as their hindsight on the covered topics.

Thank you for your attention

Any question ?