# OPTICAL-ELECTRONIC MODELING OF VOR AND DVOR SYSTEMS

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This paper deals with designing three dimensional didactic aid for visualization of creating course information of an airplane using an optical-electronic model of VOR and DVOR systems. The paper contains description of proposed model of the didactical aid which is using optical channel for information transmission. Design of optical-electronic VOR and DVOR systems is carried out in development environment Arduino and in electrotechnical design environment Eagle. Such a didactical model should serve as teaching tool for higher quality education and more effective explanation of VOR and DVOR systems operation principles.

Key words: didactical aid, optical system, platform, azimuth, navigation, VOR, DVOR

## 1 INTRODUCTION

Systems VOR and DVOR belong to the group of basic protractor, non-autonomous devices for short range navigation and keeping in mind that these system are irreplaceable in their current role, these will be operated for several more years. This is why problematic of these navigation systems is still actual.

Part of the curriculum compulsory syllabus “Navigation systems” included in the study program “Avionic systems” is teaching of problematic of radio navigation aids VOR and DVOR. For the quality and effectiveness of teaching these systems is appropriate to use three-dimensional education tool, serving to visually explain the operating principle. For this reason, a proposal to implement such a systems in the form of teaching aid has been raised.

Introductory section of this article contains brief description of the historical development of the VOR system and the subsequent description of the VOR and DVOR focused on the physical principle of directional information of both systems. Main part consists of a description of the proposal didactic aids and further processing of the proposal in the Arduino development environment and electronics design environment Eagle.

## 2 RADIO NAVIGATION SYSTEMS VOR AND DVOR

### 2.1 Historical development of radio navigation

VOR navigation system arose prior to World War II, when the designers realized that the anomaly of propagation occurring at low and medium frequency, navigation systems limit their use as standard systems for air traffic, which was becoming denser. In the 1930ies in the United States was widespread low frequency system, ground stations broadcasting on four courses "TO" or "FROM" from each ground station, which complemented the permanent air routes. Using 4-course system only two intersecting air routes could be used. From this perspective, the system seemed not sufficient. A new navigation system with the necessary amount of courses, which would also not be affected by the effects of low-frequency propagation, was required. Increasing flight altitude also related to the direct sight navigation led to the development of high frequency omnidirectional beacons VOR and their subsequent implementation as navigation standard in the U.S. in 1946. International usage of this systems started in year 1949. VOR system provided required number of courses which were easy to fly, and as VOR signals were spread in the VHF spectrum, also electrical interference was avoided. [2]

### 2.2 Display of VOR and DVOR navigation information.

The current ground beacons VOR and DVOR work in the radio band 108-118 MHz, these are compatible with each other, but way of creating course information in these systems is mutually exchanged [3]

**Fig. 1 Transmitter VOR**

System VOR, DVOR allows:

- flight directly from or to the station
- on route flight
- determine of the own position
- reception of ground station identifiers

Depending on the equipment, onboard aircraft indicators may show:

- pointer
- deviation from a given pointer
- indication of the direction of the movement of aircraft (TO-FROM)
- showing whether the aircraft is approaching the beacon or farther away
- information about usability of the system [4]


**Fig. 2 Omni-bearing indicator [7]**

## 2.3 Omnidirectional radio beacon VOR

In terms of operating principle there is a simple analogy when VOR signal uses light instead of radio waves. Imagine that a beacon that transmits omnidirectional light pulse every time the rotating beam of light heading north. If the rotation speed of light is known and the observer can record the time between the omnidirectional flash and beam, then observer can calculate the azimuth of the beacon. [2]

Receiver on board the aircraft thus measures the phase difference between two signals transmitted by VOR, phase reference signal and the signal with variable phase. The phase difference measured at another location can be used to determine magnetic pointer from VOR station. [3]

<u>Reference phase signal</u>

Reference signal consists of a carrier signal which is amplitude modulated by subcarrier modulation signal with frequency 9960 Hz, which is further frequency-modulated by harmonic 30 HZ signal 30 Hz with frequency sweep 480 Hz. Highest frequency is transmitted at the moment when radiation pattern of rotating antenna points to the magnetic north The carrier signal is further amplitude modulated by beacon identifier with frequency 1020 Hz. This signal is broadcasted omnidirectionally and has the same phase for all broadcasted radials [4]

<u>Variable phase signal</u>

Directional variable phase signal is transmitted by directional antenna system rotating at 30 revolutions per second. Due to antenna rotation there is a signal anywhere within transmitter range which appears to be amplitude modulated with suppressed carrier and modulation frequency 30 Hz from observer's point of view.

The resulting spectrum of the carrier contains two 30 Hz sidebands with amplitude modulation, which is caused by antenna rotation. [6]

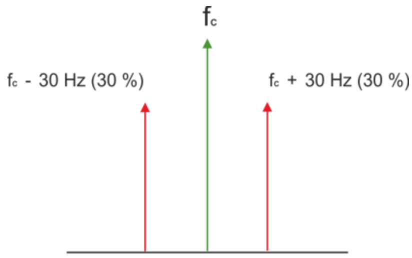


**Fig. 3 Carrier signal spectrum with two 30 Hz sidebands, according to [6]**

Second spectrum shows part of the same carrier without modulation signal, with suppressed carrier and double sideband with reference signal 9960 Hz. [6]

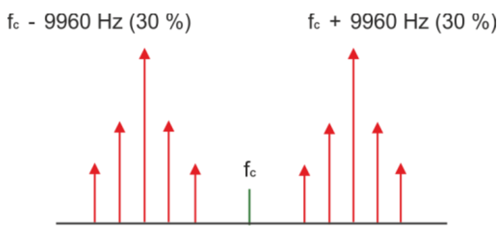


**Fig. 4 Double sideband with reference signal, according to [6]**

Signal which is received by the receiver is sum of these two signals. Voice signal and Morse code identifier is also contained in this signal. The result is amplitude modulated signal with 30% modulation depth same as by 9960 Hz subcarrier. [6]

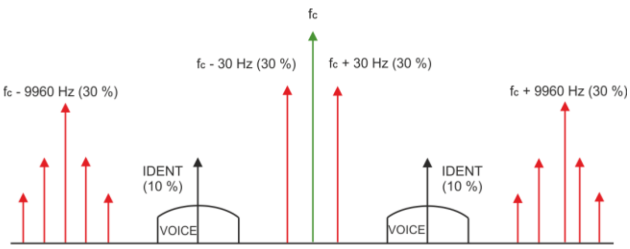


**Fig. 5 The sum of signal spectrums of reference and variable signals with voice modulation and Morse code identifier, according to [6]**

VOR ground station uses four Alford loops arranged in a square which four corners are oriented to the northeast, southeast, northwest, southwest. Alford loops are spaced one quarter of a wavelength and are deployed on a large area which emits energy field in a slightly upward angle preventing interaction with related structures. [6]

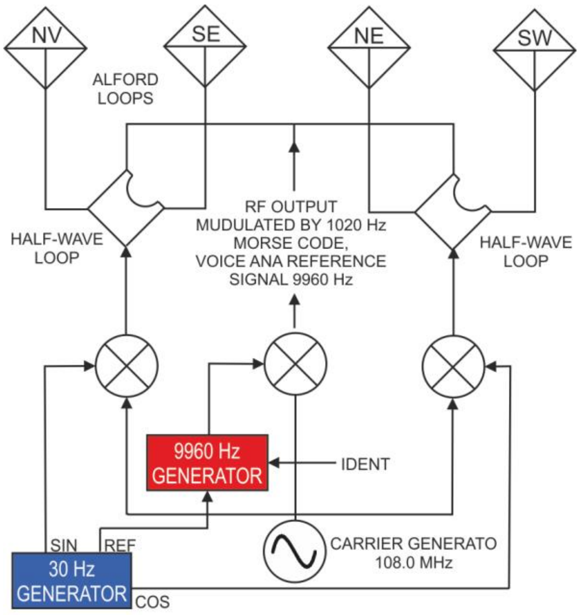


**Fig. 6 Block diagram of the antenna emitter of VOR transmitter, according to [6]**

Northwest and southeast pair of loops is fed by carrier modulated by identifier tone and reference frequency modulated 9960 Hz signal. Between these two antennas there is approximately half wavelength delay. The actual delay depends on the distance of the antennas from each other. The result of such arrangement is octal radiation pattern. The same is true for northeast / southwest pair, which has also octal radiation pattern. If these two characteristics are combined, the result is omnidirectional radiation pattern. [6]

Northwest / southeast pair is fed by same carrier but modulated by 30 Hz and in phase. Northeast / southwest pair is fed by similar signal only 30 Hz modulation signal phase is shifted by 90° compared to northwest / southeast pair. The result is rotating cardioid characteristic, which rotates at 30 revolutions per second. [6]

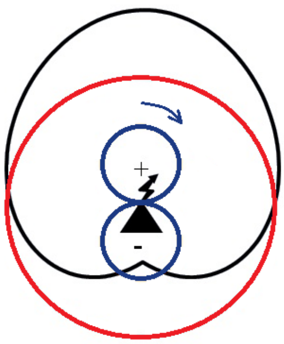


**Fig. 7 Rotating cardioid VOR transmitter pattern, according to [4]**

### 2.4 Omnidirectional DVOR beacon

DVOR beacon is completely compatible with VOR nut is much more accurate from transmitted information point of view, it is more stable and less dependent on the surrounding terrain and terrain obstacles. This improved station name is derived from the method for generating a signal, which is generated due to the Doppler shift. Methods of producing reference and variable signals are swapped at this beacon.

DVOR station has one fixed omnidirectional antenna and pairs of seemingly moving omnidirectional antennas. DVOR generates signals without the use of directional antennas.

In the middle of DVOR station is located horizontally polarized omnidirectional antenna, which transmits a carrier frequency signal which is 30Hz amplitude modulated with 30% modulation depth. It also transmits identifier in a Morse code and voice modulation form.

Around the central horizontal omnidirectional antenna, there is an omnidirectional ring of 56 antennas. These antennas are always fed in opposing pair in a moment and sequentially switched to create apparent antenna motion. One antenna is fed by source of carrier frequency +9960 Hz and the other one by carrier frequency -9960 Hz. These two frequencies must be accurate and are generated by mixing 9660 Hz sine function and the center frequency oscillator. Two mixers with suppression of mirror frequency are generating the upper and lower sideband, which are filtered, amplified and provided as carrier source for rotating antennas.

The upper and lower 9960 Hz sideband are fed into the omnidirectional antennas. These two sidebands are switched anti-clockwise from one antenna to neighbor one and so form complete ring of antennas in 1/30 of a second. [6]

## 3 OPTICAL-ELECTRONIC MODELING OF VOR AND DVOR SYSTEMS

### 3.1 Description of the system

To determine the position of the aircraft to ground station, as a source of course information, two separate optical signals in the form of light pulses are used. To transmit these light pulses, two LEDs are used, each emitting different wavelength light. Usage of different wavelengths separated in terms of light spectrum prevents possible interference of light pulses received by receiver.

As the system design is based on the principles used by VOR, ground system works based on the series of LEDs emitting infrared light simulating stationary antenna transmitter which is transmitting frequency modulated signal with omnidirectional pattern. This LED will emit light with a wavelength of 880 nm in the form of light pulses with a frequency of 1 Hz (FM). Second set of LEDs emitting blue light will simulate rotating directional antenna transmitter, which is in our case in the form of LEDs emitting at a wavelength of 470 nm, these will rotate on rotating platform with a frequency 1 Hz, which is imitated amplitude modulation (AM) These two emitters are synchronized so that at the moment when stationary LED (infrared) sends a pulse of light, the rotating LED (blue) will be facing toward north. This is using done by using the compass firmly attached to ground platform system, which enables platform to be set to north.

**Fig. 8 Opto-electronic VOR/DVOR model**

Recieving device contains two optical sensor, separate one for recieving infrared signal and separate one for recieving blue light signal. Optical sensors are in form of photodiodes with a sensitivity corresponding to wavelengths of infrared and blue light. After capturing and processing of these light pulses we get two signals on the receiver input:

- “red” channel signal (start)
- “blue” channel signal (signal)

In case evaluation circuit of the receiver detects the presence of his entry “red” signal, it will start time counter, which will run until “blue” signal is detected. After the detection of “blue” signal counting stops. The time difference between receiving these two signals determines measured angle. This angle will give course depending on aircraft position to the ground station.

Such and optical-electronic system can determine the course of the aircraft only if our aircraft model is turned toward the ground station. However, when using real VOR system, aircraft can be rotated in any direction and still receive information about the course on the selected radial. For this purpose, there will be magnetometer placed on aircraft model indicating the direction bearing of the aircraft model (compass bearing). This aircraft model will be firmly fixed to the magnetometer and placed on rotatable mechanism fixed to the receiver platform. This will allow point the receiver to the transmitter and select any aircraft bearing in the same time.


**Fig. 9 Opto-electronic VOR/DVOR reciever model**

### 3.2 Transmitter

#### 3.2.1 Schematic diagram of the transmitter

Schematic diagram is created in EAGLE environment. Main part of the scheme is platform Arduino UNO R2. Only two analog pins A0 and A1 and seven digital pins D7 to D13 are used on this platform.

Voltage 5V is fed to the A0 and A1 via two switches. Direction of motor rotation is controlled via analog input A0 using switch P1. Pin A1 is used for sensing stepper position by using micro switch T1. Digital pins D7, D12, D13 are defined as outputs and are used for controlling LED1, LED2 and LED3. In front of each LED there is included resistor R1 respectively R2 and R3, which are necessary to limit the current flow through the diode. Digital pins D8 to D11 are connected to stepper motor via IC1. These pins are used as outputs to control the stepper motor. The integrated circuit IC1 is an H-bridge, which ensures a rotating magnetic field between the coils of motor windings.

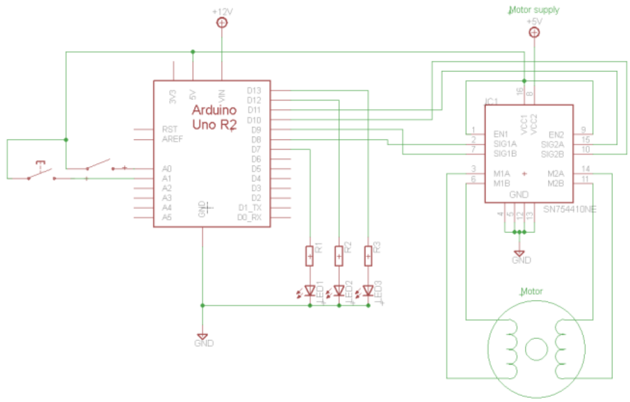


**Fig. 10** **Schematic diagram of ground transmitter**

### 3.2.2 The flowchart of the algorithm of ground transmitter

The simplified algorithm can be described in several steps. The algorithm in a way that after system startup and initialization of defined constants, variables and pins, motor movement is initiated at defined number of revolutions per minute and given number of steps corresponding to the rotation of engine of 360° (one revolution). Simultaneously it will give command to light series of blue LEDs mounted on the rotatable platform. Next it will start seeking “north” which will synchronize rotating and reference signals. This is accomplished using electrical micro switch, which provides synchronization pulse every time the rotating platform is rotated towards north. The synchronization readout occurs every time there is a change of rotation direction (VOR / DVOR). After sync pulse readout IR LED is lit and dimmed for a period of time given by interval I1.

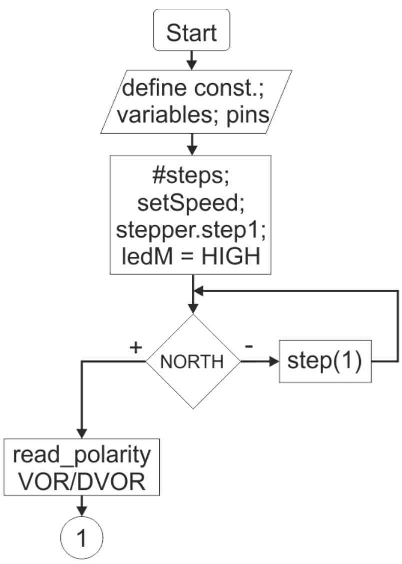


**Fig. 11** **The flowchart of the algorithm of ground transmitter**

After readout of the “polarity” value based on position of VOR / DVOR switch, direction of the rotation is set. In the event of change of polarity, transmitter will return to searching “north” and IR LED reset, which is a resynchronization procedure.

### 3.3 Receiver

### 3.3.1 Schematic diagram of the receiver

The main part of the scheme is again Arduino platform but in version NANO. Six analog pins A0 to A5 and six digital pins D2 to D5, D11 and D12 are used.

Analog inputs A0 and A1 are fed by a voltage signal from the optical sensors in form of a photodiode D3 and D4. There is a photodiode amplifier included with gain setting of 100 for one channel and 10 for second one. Analog input A2 is used for sensing of battery voltage drop. Since analog input can hold maximum 5V, battery voltage is not measured directly but via voltage divider formed by resistors R1 and R2. Voltage 5V is fed to the analog input A3 via switch S1. The switch toggles between VOR / DVOR mode. Pins A4 and A5 are used for communication over I2C bus. A three-axis magnetometer is connected to that bus. Magnetometer pins SDA and SCL are connected to 5V drawn from Arduino through two pull-up resistors R3 and R4.This voltage ensures the disconnected input logic level 1.

Digital pins D2 to D5, D11 and D12 are reserved for the LCD display. LCD is powered by five volts drawn also from Arduino. LCD contrast control is provided by potentiometer R6. The display brightness is set fixed by resistor R5.

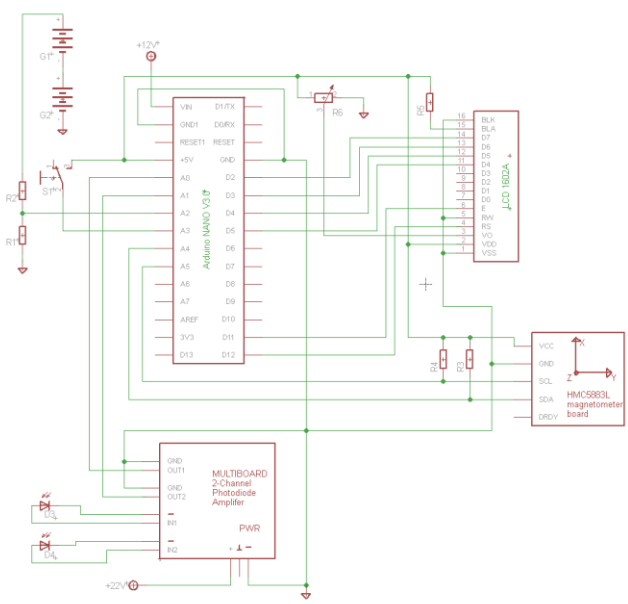

**Fig. 12** **Schematic diagram of the receiver**

### 3.3.2 The flowchart of the algorithm of receiver system

Only basic functional structure of the program is described by the algorithm flowchart. After the program is started, initialization takes place. All inputs, outputs and variables given by the program are loaded. After initializing the system will evaluate presence of the signal received from input required.

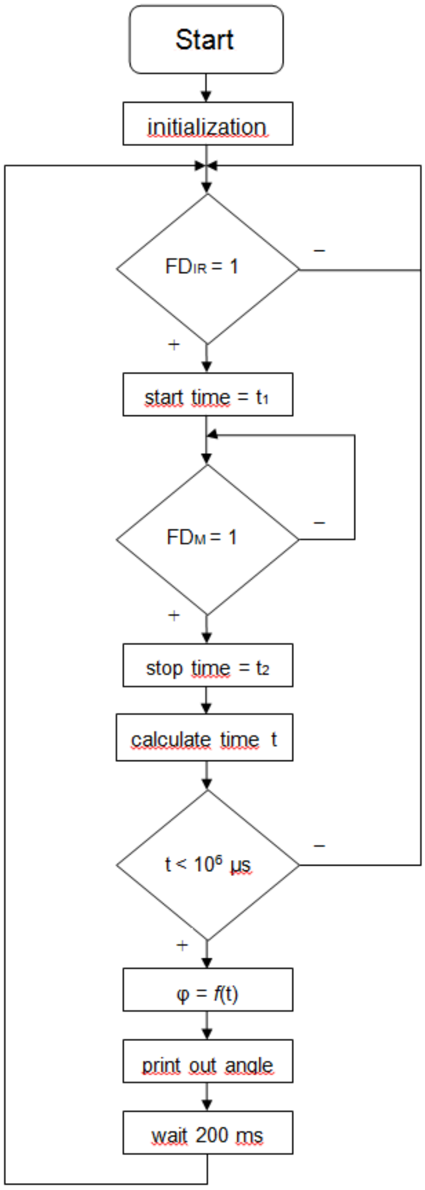


**Fig. 13 Flowchart of algorithm for determining course information**

First it starts to detect the presence of signal "start". This means system will read the value from given input and if needed level of signal is present, time readout will occur. In case receiving system is not able to capture the desired signal in a given measurement, the system repeats the value readout in the next step and adds 1 to the step counter. After 2000 steps will take place and signal will not appear in desired level, system displays message "MIMO DOSAHU" (out of range), reset the step counter and starts a new measurement (input readout). After fulfilling the conditions (successful readout of input values), the system waits for signal "STOP" in the next step. Again the values a read out and threated in the same way as in previous case. If the desired value of signal will occur on the desired step, time is read again and time difference will be evaluated in the next step.

Counting time is realized by Arduino clock being run after program initialization. This clock is reset every seven hours. Clock rate is 16 MHz, which means that this clock has resolution of four microseconds.

After program advances to the given step (start time) time t1 is read out of the internal clock and compared with time t2 readout in another step (stop time). The resulting time is determined by the relationship: t = t2 – t1.

In case resulting time t is greater than 106 µs time t is set to zero and the process is repeated again. Resulting time is used in the next step to calculate angle φ in degrees. Conversion to degrees is also implemented in program using the relation:

$$\varphi = k \cdot t,$$

where $k$ is a constant and its value is: k = 360 / 106.

Calculation of the angle φ is also dependent on the selected mode. If the receiver is operating in the VOR mode, to calculate angle φ above mentioned equation is used. If the selected mode is DVOR calculation is carried out according to relationship: $\varphi = 360 - (k \cdot t)$.

VOR / DVOR mode is selected by switch S1. After this conversion value of angle φ is displayed on LCD. After the displaying the values, system waits 200 ms and program repeats in cycle. Waiting time 200 ms is set because of refreshing LCD panel memory.

## 4 CONCLUSION

The article describes the design of three-dimensional teaching aid for visualization of determining of aircraft course information based on an optical-electronic system modeling short range VOR and DVOR navigation.

System design was based on theory how systems VOR and DVOR work. Solution using optical-electronic system was implemented in Arduino development environment and electronics design environment Eagle.

The proposed systems compared to a real working VOR systems includes a number of simplification. The system in this design, due to the components used, does not provide information such as direction of flight to or from a ground station, it also does not identify itself. However, it is possible to add more functional hardware elements that would solve these shortcomings in the future.

The design of this optical based system does not offer a sufficient high accuracy in overall, due to the limitations associated with use of electronic design elements, but it's sufficient to use as teaching didactical aid.

ACKNOWLEDGMENT

This work was funded by the European Regional Development Fund under the Research & Development Operational Programme project entitled "Construction of a research & development laboratory for airborne antenna equipment, ITMS: 26220220130."

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