A Dynamic VOR Receiver Model for Estimating the Bearing Error in the Presence of Wind Turbines

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***Abstract*—This work introduces a dynamic VOR receiver model for estimating the bearing error in the presence of wind turbines. The receiver processes time series generated by an electromagnetic simulation tool that takes into account the multipaths. This global model can reproduce the response of a VOR receiver on a realistic aircraft trajectory. The receiver is tested in a dynamic scenario where the multipaths change rapidly with time.**

***Index Terms*—VOR receiver, propagation, multipath, wind turbines**

I. Introduction

The VHF Omnidirectional Range (VOR) is a ground-based system transmitting an electromagnetic signal of frequency between 108 and 118 MHz. This signal allows aircraft to navigate. The VOR signal is sensitive to the presence of wind turbines in the vicinity of the station. The wind turbines yield multipaths which interfere with the useful signal. Therefore, these multipaths induce an error on the azimuth assessed by the receiver.

Several methods have been proposed to obtain the multipath characteristics [1][2][3]. In the literature, the bearing error is computed from the multipath characteristics by means of the analytic expression proposed by Odunaiya [4].

The Odunaiya model is static, *i.e.* it computes the error on each trajectory point as if nothing was moving. Thus, the influence of the fast variations of the multipaths on the VOR error cannot be accounted. Consequently, it is unable to reproduce the response of a realistic VOR receiver in these conditions.

In this paper, we present a dynamic model that combines a VOR digital receiver with a time series simulator. It is capable of reproducing the response of a VOR receiver in a realistic way, taking into account demodulations and filtering. In Section II, we present the electromagnetic model to compute the direct and multipath signals [3] and the time series generator. In Section III, a dynamic model of a VOR receiver is detailed. In Section IV, simulation results are presented to show the influence of the time variations on the VOR bearing error. Section V concludes this study.

II. Time series VOR error simulator

The electromagnetic model applied to compute the direct and multipath signals is detailed in [3] and illustrated in Figure 1. Firstly, the direct field received by the aircraft is analytically computed using a two-ray model. Secondly, we use the 2D parabolic equation to model the propagation above the terrain from the VOR station to the wind turbines. Thirdly, the wind turbines are meshed and equivalent currents are calculated using the PO approximation. Finally, the scattered fields are calculated at the receiver to obtain the multipaths. The EM computation is performed all along the aircraft trajectory.

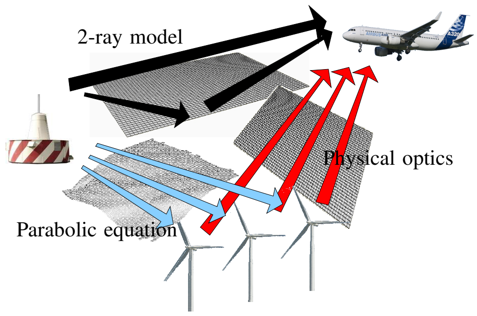


Fig. 1: Overview of the method to compute multipath [3].

To obtain times series, a realistic aircraft trajectory is sampled with a short enough time step so as to accurately model the signal variations in space. Details are given in [5].

The trajectory is a series of rectilinear or circular elements separated by way-points.

According to the Nyquist criterion, the space step must be shorter than half a wavelength

$$\Delta x < \frac{\lambda}{2}. \tag{1}$$

The time step is expressed in terms of the space step and the maximum speed along the trajectory

$$\Delta t_{min} = \frac{\Delta x}{V_{max}}. \tag{2}$$

At each point of the trajectory, we use the method proposed in [3] to compute the multipath parameters, *i.e.* their amplitude a_n, phase θ_n, azimuth φ_n and Doppler ω_{dop}. These characteristics will be sent to a digital VOR receiver to assess the influence of the multipath changes in time on the bearing error.

III. VOR receiver model

The VOR signal is composed of a reference phase REF and a variable phase VAR.

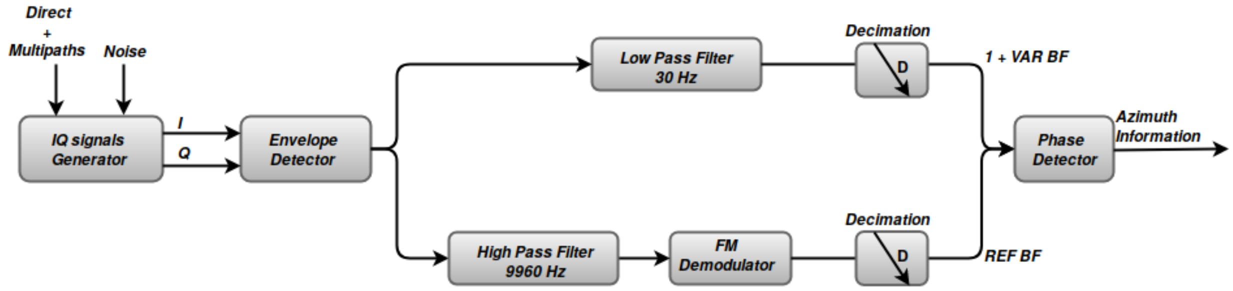


Fig. 2: Block diagram of the VOR receiver.

A. IQ signals

The VAR signal contains the azimuth information. The REF signal is the reference signal to which the aircraft compares the VAR signal to know the azimuth on which it is located (relative to the magnetic North). For a conventional VOR, the signal REF is modulated in phase and the signal VAR in amplitude. For a Doppler VOR, the modulations are reversed. The airborne VOR receiver calculates the phase shift between the reference signal and the variable signal. Note that the same receiver can demodulate the conventional and Doppler VOR signals.

Our model is based on an I/Q signal generator to obtain the data received by a VOR receiver. These signals are defined by

$$I(t_k) = \sum_{n=0}^{N} M_n(t_k)\cos(\omega_{dop}^{n} t_k + \theta_n(t_k)) + n_I(t_k), \quad (3)$$

$$Q(t_k) = \sum_{n=0}^{N} M_n(t_k)\sin(\omega_{dop}^{n} t_k + \theta_n(t_k)) + n_Q(t_k). \quad (4)$$

Note that the multipath $n = 0$ corresponds to the direct signal. The n-th multipath signal M_n is defined by

$$M_n(t_k) = a_n(t_k)[1 + REF(t_k) + VAR_n(t_k)], \quad (5)$$

with

- $REF(t_k) = m_a \cos(\omega_{sc} t_k + m_f \sin(\omega_{BF} t_k))$ the reference signal.
- $VAR_n(t_k) = m_a \cos(\omega_{BF} t_k - \varphi_n)$ the variable signal of the n-th multipath.
- n_I et n_Q the AWGN noises associated to the I/Q signals, respectively.
- ω_{sc} the subcarrier pulse (9960 Hz) in rad/s.
- ω_{BF} the BF pulse (30 Hz) in rad/s.
- m_a the modulation index (= 0.3).
- m_f the modulation rate (= 16).

The sampling frequency in the propagation computation is set typically to few hundreds of Hz using (2). In the receiver, we need a sampling frequency of at least 20 kHz because the VOR signal bandwidth is 10 kHz. Thus, we perform an oversampling using a linear interpolation on the multipath parameters.

B. Receiver components

The block diagram of our receiver is presented in Figure 2. The envelope detector carries out an AM demodulation in order to recover the VAR and REF signals. The complex envelope is defined by

$$A(t_k) = \sqrt{I^2(t_k) + Q^2(t_k)}. \quad (6)$$

A low-pass filter extracts the VAR signal at 30 Hz. Similarly, the REF signal is extracted using a 9960 Hz high-pass filter.

For a conventional VOR, the signal REF is modulated in frequency, the Figure 3 shows a block diagram of the FM demodulator used to extract this signal.

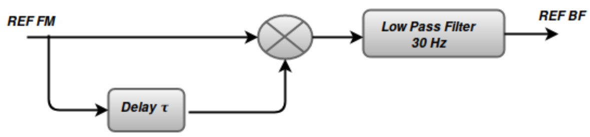


Fig. 3: Block diagram of the FM demodulator.

In order to reduce the computation time, a decimation operation is applied. This downsampling step consists in keeping a number of samples as small as possible to fulfill the Shannon criterion at 30 Hz.

The phase detector calculates the phase difference between the AM and FM 30 Hz signals. As illustred in Figure 4, the first step consists in creating a quadrature signal by a phase shifter. Then, products are performed on both paths. The next step is to sum the products and perform a low-pass filter to recover the DC component. The azimuth information is the phase of the filtered signal.

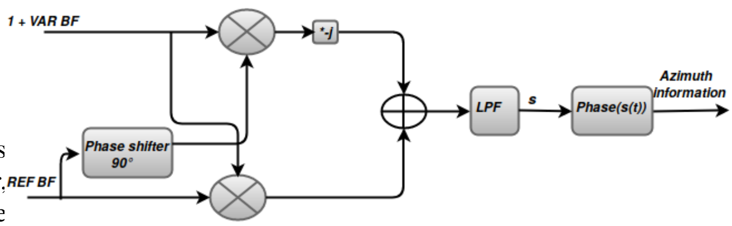


Fig. 4: Block diagram of the phase detector.

IV. Simulation results

We consider a VOR station operating at a frequency of 113.8 MHz with a power of 25 W. A wind turbine type ENERCON E82 is placed at 1 km from the VOR station, yielding one multipath. In order to be able to simply analyse the results, a straight trajectory of 6 km is considered here, although the model can deal with more complex trajectories. Firstly, the aircraft is motionless for 5 s to ensure the end of the receiver transient period. After that, it starts at low speed until reaching the second waypoint at 216 km/h. We consider a space step of $\frac{\lambda}{5}$.

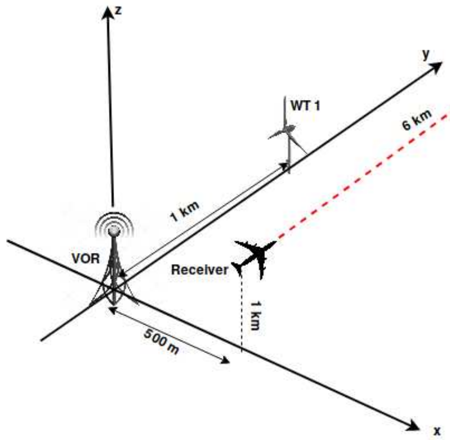


Fig. 5: Configuration.

In Figure 6, the azimuth of the multipath is plotted with respect to time. The color indicates the power of the multipath relatively to the direct path. We observe that a single multipath exists.

The multipath is powerful during the first part of the trajectory from 0 s to 50 s and significant at the end from 200 s to 250 s. This is because the aircraft is in the specular reflection zone of the wind turbine.

In Figures 7a and 7b, we display the VOR errors obtained with the Odunaiya expression and with the VOR receiver model. During the first 2 seconds, the receiver response changes rapidly. It is due to the filters. The receiver response converges to the Odunaiya model during 5 s when no dynamic effects are involved.

The aircraft moves slowly and the receiver response remains close to the static model of Odunaya. During this phase, there is a delay between the two models that is due to the filtering response. When the aircraft accelerates, both models do not give the same response from 25 s. It is due to the fast variation of multipath. When the aircraft moves away from the VOR and the wind turbine, the phase difference between the direct and the multipath changes in a slower way, which explains the slower fluctuations of the VOR error. Hence, the dynamic model converges again to the static model despite the high speed of the aircraft.

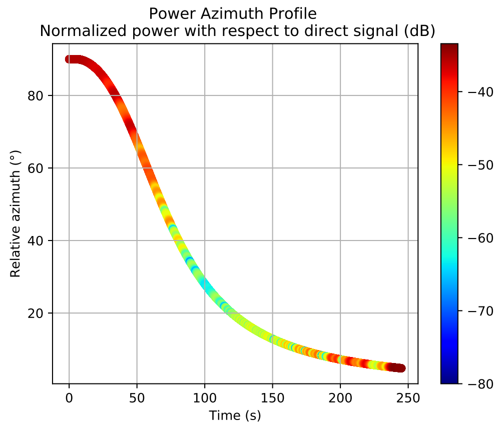
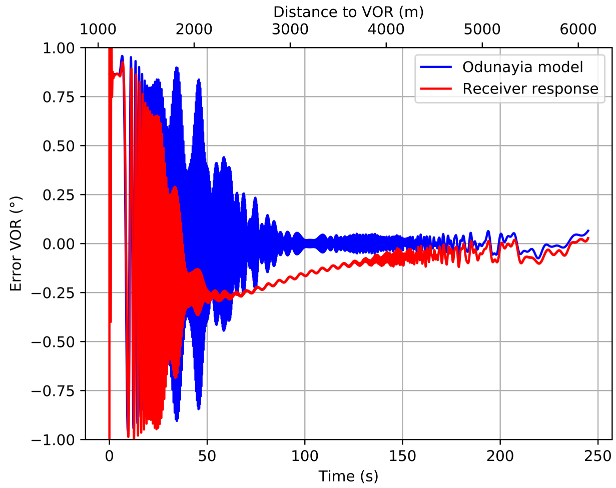
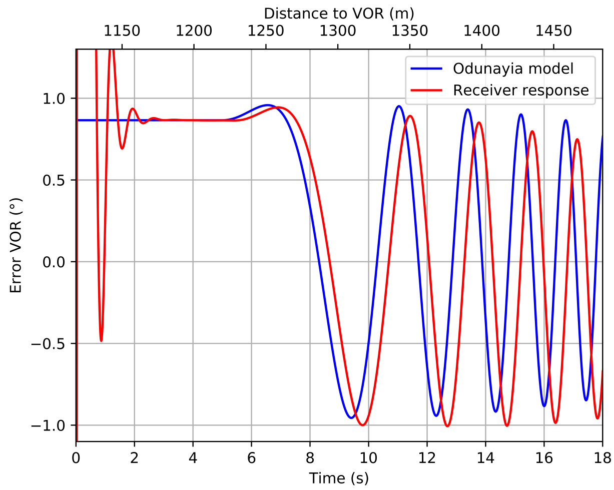


Fig. 6: Power Azimuth Profile of the multipath along the trajectory.



(a) Receiver response from 0 s to 250 s



(b) Receiver response from 0 s to 18 s

Fig. 7: Receiver response along the trajectory.

V. Conclusion

In this article, a dynamic VOR receiver model for estimating the bearing error in the presence of wind turbines has been studied. The computation of times series for VOR signals in the presence of multipaths has been presented. These times series have been sent to a digital VOR receiver to evaluate the influence of the multipath changes in time on the VOR error. The model has been tested in a dynamic scenario.

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