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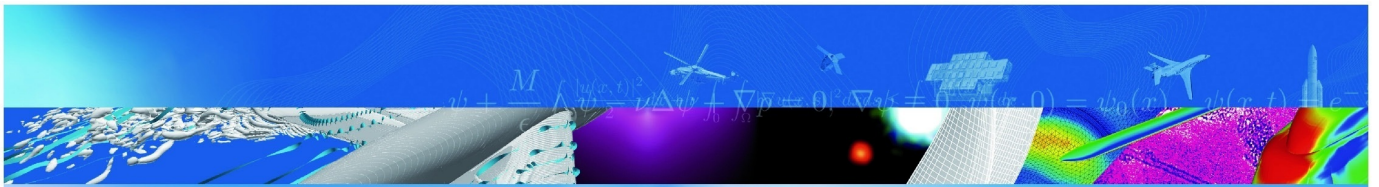
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ARTICLE DE REVUE

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Modelling the Ionospheric Effects in HF Radar Long Term Integration

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Abstract—High Frequency radars usually use reflected waves from ionosphere to perform continuous surveillance of very large and far off areas. In the case of long term integration, the ionosphere instability affects the radar image and thus induces poor detection and high probability of false alarm. This problem appears in surveillance issues dealing with slow targets such as vessels. Such an issue is also present in surface wave radar due to the lack of directivity of the transmitting antennas. In this paper, we introduce probabilistic models of the ionosphere effects assuming that only the phase path fluctuation has a meaning in the radar point of view. A first model has been built and compared to a real case. It appears that the deviation in range and Doppler are meaningful. That model will be integrated in the radar processing in order to synthesize highly realistic radar data and estimate the radar parameters in case of turbulent ionosphere (i.e. range-Doppler shifts and uncertainties as well as detection and false alarm probabilities). The obtained results will be presented during the EuCAP 2016 conference.

Index Terms— High Frequency radars, ionosphere, probabilistic models, radar processing, maritime surveillance.

I. INTRODUCTION

In order to detect targets over the radio electric horizon, most of High Frequency (HF) radars operate in the frequency range from 5 to 25 MHz. Sky wave radars transmit waves that can be reflected on the ionosphere and then reach far regions beyond 1000 km. Besides, surface wave radars transmit waves that propagate along the sea surface to detect targets up to 400 km. In both cases, the radar image can be affected by the irregularities in the ionosphere and their displacement. In the sky wave case, the propagation path is affected by the ionization turbulence hence, when a long time integration is performed, a shift in Doppler is induced, as shown in Fig. 1.a. In the surface wave case, the lack of directivity of the antennas results in the appearance of ionospheric clutter, as shown in Fig. 1.b.

The ionosphere cannot be considered invariant in the above cases. It is considered here as variable from time to time. Consequently, the issue is to render the spatial and temporal variations of the ionosphere with regards to the radar processing. Indeed, all physical phenomena are averaged by the radar due to the large cell resolution in the HF band.

In a previous work, the sea clutter has been modelled with a statistical approach in order to be more representative of the real data [1]. We are working now on a model of the ionosphere irregularities, by means of a statistical approach of them, taking into account the electron density only. The well-

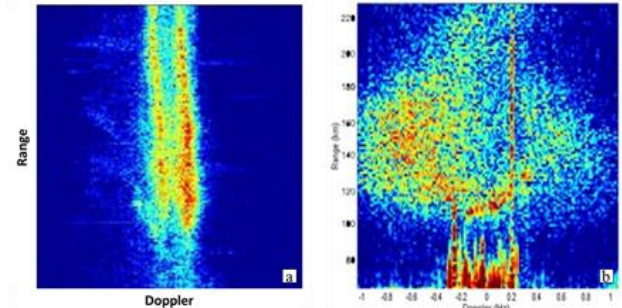


Fig. 1. Ionosphere effects on actual measured radar images:
a. Doppler Shift b. Ionosphere clutter

known MQP [2] model, where we introduce fluctuations, will be used as well as ray tracing in order to evaluate the effect of fluctuating ionosphere on the radar signal.

This paper deals with a study performed on the phase path. Different types of random function will be added to the ionosphere electron density distribution in order to disturb the propagation. The corresponding ray tracing is then calculated to obtain the phase path which will give us information on the range of the target. The time derivative of the phase path will provide us with the Doppler shift. Preliminary results will be discussed in this paper as well as the results to come which will be presented during the Eucap conference in April 2016. These results will be validated with real data sampled from ONERA's HF radar demonstrator near Paris and near Toulon, shown in Fig. 2.

II. THE REFRACTIVE INDEX AND THE PHASE PATH

A. Relation between the refractive index, Doppler and the phase path

In this work, we will consider the phase path variation

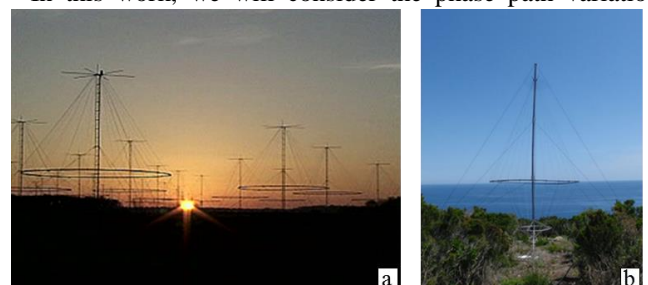


Fig. 2. HF biconical antennas of the High Frequency Radar demonstrator:
a. Sky wave b. Surface Wave demonstrator ROS

instead of working on the detailed ionization process which includes the actual particles in presence as well as the winds and the motions along the magnetic field [3]. The range resolution of HF radars obviously depends on the transmitted bandwidth and does not exceed 500 m, in most of the cases. In azimuth, a very good resolution of 1 degree represents more than 3 km at a distance of 200 km. Hence, working at a very low scale would be meaningless even if the actual phenomenon is at low scale. Considering that, the ionosphere clutter and the Doppler shift can be fully described only by the temporal variation of the refractive index along the wave path; we start from the study performed by Dyson [4] on the relationship between the phase path, the refractive index and the Doppler.

In the general case, the phase path P of a ray between points A and B is given by (1)

$$P = \int_A^B n \cdot ds \quad (1)$$

where n is the refractive index at a point on the ray path. The integration is carried out along the ray path. In our case we use the well-known 3D ray tracing [5] to perform this calculation.

According to the above mentioned ray theory, the time derivative of the phase path is related to the Doppler frequency shift Δf and given by (2)

$$\Delta f = -\frac{f}{c} \frac{dP}{dt} \quad (2)$$

where f is the frequency of the signal and c the light velocity.

Taking into consideration (1), (2) and the time constants of the radar, we will focus on the phase path instead of the refractive index which is rigorously modelled by means of an intricate mathematical equation [6]. Proceeding this way, we will be able to get information on the ray path and the Doppler shift. The objective is also to find statistical information related to the refractive index variation as well as the consequences on range and Doppler statistics.

B. Preliminary approach with radar processing

The ionosphere behaviour is obtained while varying the phase path in the received radar signal. The first step consists in adding the random phase directly to the radar signal equation and then applying the radar processing (Fig. 3). An

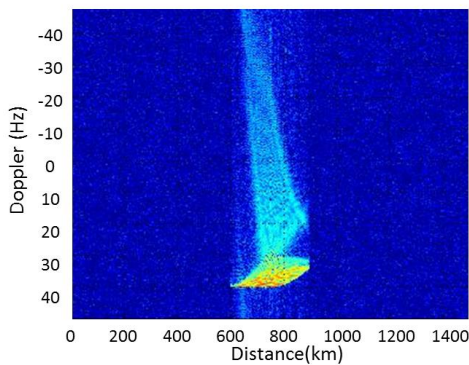


Fig. 3. Example of ionosphere clutter

obvious spread in range and a Doppler shift is observed. This latter result provides, if need be, evidence on our previous assumption concerning the sole need of phase perturbation.

III. RESULTS AND DISCUSSION

Gherm *et al.* propose different fluctuation models adequate to the variation of the ionosphere properties in the HF communications [7]. From their results, we will integrate a disturbing ionosphere profile inside the path of the HF radar signal. To do so, the electron density distribution [8] should be disturbed according to (3):

$$N(r) = \langle N(z) \rangle (1 + N_f(r)) \quad (3)$$

where $\langle N(z) \rangle$ is the regular part of the electron distribution which characterizes the background value of the ionosphere profile and $N_f(r)$ the random part, called the fractional electron density fluctuation.

To create a disturbing ionosphere profile, and to stay coherent with the results in Fig. 3, we choose to compute 3096 iterations applying a Monte Carlo approach. For one iteration, the ray path will be calculated for one fixed elevation angle. At the end of the whole computation, the Doppler shift will be calculated using equation (2). Further, Martyn's theorem [9] is applied to calculate the ground distance.

In order to evaluate the impact of $N_f(r)$ on the spread Doppler shift and the spread range shift, we plotted a Doppler-range shift map. The results will be presented later in this paper.

In general, the random variables used to perform this work follow a Gaussian law. We began by adding Gaussian random variables on different points of the profile and then we interpolate them over the whole profile shape. This approach cannot be continued due to the excessive fast variations between the modified points, as shown in Fig. 4.a, which does not correspond to actual ionosphere variations; or due to the excessive correlated variations, as shown in Fig. 4.b, resulting in a non-spreading in the Doppler-range shifts map.

The next approach consists in applying a Gaussian random profile to modify the ionosphere electron distribution. Moreover, the random part is altered from time to time. At

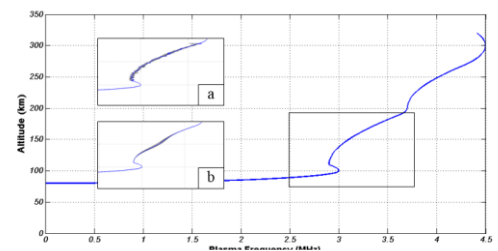


Fig. 4. Representation of the ionosphere electron distribution following the MQP Model. a and b represent perturbations overlay caused by:

- a. interpolating the Gaussian random variable.
- b. adding a random Gaussian variable and resulting plasma

each iteration of the computation, the amplitude of the Gaussian function in height is altered by a second Gaussian function in time as shown in Fig. 4.b. Since we are dealing with radar, the time here represents the fast time, that is to say the range cells. This approach is more realistic than the previous one. Yet, the random variations are uncorrelated between the range cells. The consequences were too high level of shifts, especially when looking to the Doppler shift which was exceeded 1 kHz by deriving the phase path. That behavior is obviously not realistic at all. Therefore, we gave up that model.

The last approach evaluates the effects on the diffusion in Doppler and distance, elaborating an electron density profile from random samples generated with correlated slopes built from a stationary process with an exponential correlation function [10], as shown in Fig.5. In a manner conforming to the radar processing, we are adding realizations of that random process, not only spatially to the ionosphere electron density or time to time, but also in between time slots of each range cell. In fact, considering the propagation, the waves will travel through the ionosphere level from time t_1 to time t_2 . Those waves will reach the target and will return back to the source at time t_3 and travel again through the ionosphere from time t_4 to time t_5 . Between t_1 and t_2 as well as t_4 and t_5 , the ionosphere will fluctuate. This fluctuation will affect the distance measured inside the range cell. In other words, quite logically, the ionosphere does not stop to fluctuate between two radar recurrences.

A. Numerical application

In this section, a numerical example illustrating a hopeful result is presented. Considering the previous random function, we compute 3096 different realizations that are in accordance with the integrated number of iterations in the radar processing. Each realization, a recurrence in fact, represents 20 ms of signal. The coherence of the irregularities lasts over few dozen of milliseconds [11] hence it is quite logical to use the same statistical model inside a recurrence of 20 ms but with an amplitude modulation and then change for the next one.

As shown in Fig. 6, the Doppler shift varies from -5 Hz to 5 Hz and the distance echoes spread over 14 km. These results

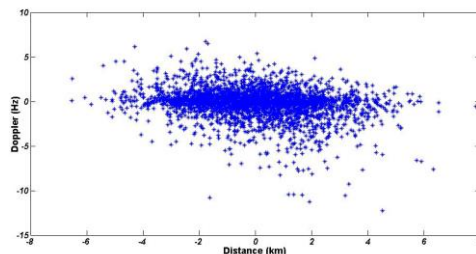


Fig. 6, Doppler and distance spread

have the same order of magnitude than usual observations from HF radar. The Doppler spread, around 3.5 Hz, is still lightly high but well better than the 100 kHz obtained with previous approach. The range spread is around 10 km. Nevertheless, these preliminary results validate the approach since such kind of clutter can be observed when a meteor goes through the ionosphere (high Doppler spread and small range spread). Nonetheless, other kinds of irregularities will be studied as well as the radar data themselves in order to simulate a radar image rather than estimating a diffusion function.

CONCLUSION AND PERSPECTIVES

In this work, we have built a modified behavioural MQP ionosphere model tuned to render ionosphere fluctuations. The random part of the density aims to provide the situation observed in HF radar while detecting slow targets (typically vessels) with sky waves and surface wave radars. The spatial and temporal ionosphere variations have been considered in order to obtain the wave phase path fluctuation. Then we studied the effect of these wave phase path modifications on the Doppler shift and the distance variation. As a result, we obtained a Doppler shift spread as a function of the range variation that can be caught by HF radar when meteors are present. This step validates our approach.

We will present, during the conference, results on other kinds of perturbation. The fluctuation will also be integrated in the radar signal and will be processed with the same algorithm than the one used in our HF radar demonstrators in order to render, as far as possible, the situation just before

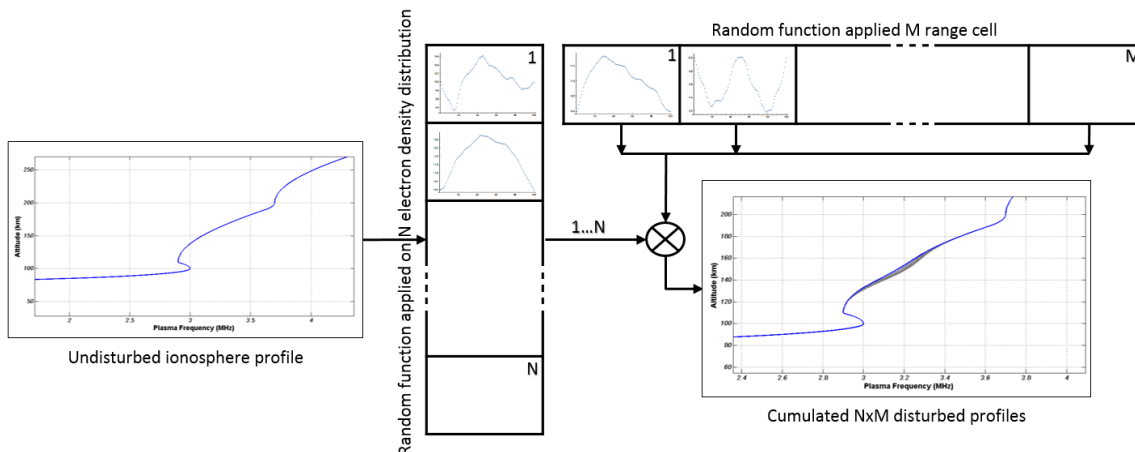


Fig. 5, Procedure used to add the random function with correlated variables on the profile and on the range cells.

CFAR (Constant False Alarm Rate) detection.

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