HF-OTH Skywave Radar for Missile Detection

F. Berizzi, E. Dalle Mese, A. Capria, R. Soleti

Dept. of "Ingegneria dell'Informazione", Via Caruso 16, 56122 Pisa (Italy)
Phone: +390502217673, Fax: +390502217626

f.berizzi@iet.unipi.it , e.dallemese@iet.unipi.it , amerigo.capria@iet.unipi.it , rocco.soleti@iet.unipi.it

ABSTRACT TITLE

In this paper missile detection capabilities of an HF-OTH skywave will be analysed and assessed. Specifically we focus on a challenging scenarios that is the detection of ballistic missiles in their boost phase for early activation of defence systems. Missile Radar Cross Section (RCS) is calculated during target flight taking into account of frequency and viewing angle. Detection capabilities are assessed in terms of peak power estimation and discrimination in the range-Doppler domain.

1.0 INTRODUCTION

A very wide area surveillance capability is becoming a crucial requirement in order to deal with national and international safety issues such as clandestine immigration, naval and air traffic control, illegal actions surveillance (e.g.: oil spill, building abusiveness, chemical pollution, etc). Moreover, a system with the aforementioned features can be particularly suitable for large-scale environmental monitoring and common military user requirements, such as target detection, recognition and identification.
Two approaches are currently in use in order to provide a practical solution for these kind of requirements: 1) A satellite constellation or a fleet of airplanes placed in permanent flight with onboard radar sensors, 2) A very dense radar network distributed over the national territory.
Even though both solutions are practically feasible, they imply some disadvantages. Firstly, a satellite constellation does not allow a continuous surveillance over the whole area, although it usually ensures a short revisit time. Secondly, an airplane fleet is generally a very costly solution that can provide only a limited coverage. Finally, a network of radar sensors ensures a continuous surveillance with the drawback of a poor coverage capability. As a matter of fact the national costal radar network cannot provide an effective surveillance further than 100-200 km from the coastline.
A different approach to this problem, that is efficient against the above mentioned downsides, makes use of a HF skywave (ionospheric reflection) Over The Horizon (OTH) radar [1]. Distances well beyond the horizon can be reached by exploiting the effect of ionosphere reflection, since in the HF band the e.m. waves are gradually bended through the ionosphere [2-3]. The ionosphere acts like an electromagnetic mirror at these frequencies. The signal is reflected back by the Earth to the radar system that can perform the detection operations.
This type of radar achieves the remarkable advantage of a very wide and time continuous coverage that ranges from 600 km up to 3000 km. The cost-effectiveness of such a system is outstanding if compared with the aforementioned configurations. Moreover, the advent of 2D-array HF skywave radar [4] has offered some new capabilities in terms of detection and tracking performance as well as low probability of intercept (LPI). In this case, different radar functionalities can be imaged: 1) Theatre surveillance of ship or slowly moving surface targets; 2) Air traffic monitoring in regional areas; 3) Detection and tracking of missiles launched from a relative large local area; 4) Other.
The goal of this paper is to assess the missile detection capabilities of a 2D-array skywave. The analysis will be conducted on ballistic missiles launched from 2000-3000 km far from the radar site.

Peak power and missile Range-Doppler echoes map are calculated during the target flight in the boost phase to see whether detection is possible.

2.0 2D-ARRAY HF-OTH SKYWAVE RADAR SYSTEM

A 2D-array HF radar is a very complex system because it is characterized by a set of features which are very unusual if compared to ordinary microwave radars:

1. Transmission frequency must be selected upon the ionosphere propagation behaviour in the wide band [3-30 MHz].
2. Long radar coverage is allowed up to 4000 km corresponding to a zero antenna elevation angle. In practical applications it is convenient to limit the maximum distance to about 3000 km to avoid low antenna elevation angle as well as layer ionosphere internal multipath.
3. When the ionosphere e.m. incidence angle is greater than a critical value, the transmitted signal is not reflected and no returns occur. This phenomenon produces a blind area for distances less than about 400-600 km.
4. Ionosphere channel behaviour depends on date, sun activity and spatial coordinate. Therefore, ionosphere propagation is very changeable from night and day.
5. In the HF band, radar performances are heavily affected by background noise, which is mainly due to external noise [5]. More precisely, the external noise is composed by atmospheric noise, cosmic noise and man-made noise. Internal noise caused by thermal effect is almost neglectable.
6. We must deal with heavy propagation losses due to the very long travelling distances as well as strong absorption losses mainly due to the D layer of the ionosphere. The whole loss contribution can be up to 100-150 dB.
7. The apparently simple propagation mechanism hides the complexity of the ionosphere structure. This implies a challenging target localization that could be achieved by a smart system calibration combined with a three dimensional reconstruction of the signal path through the ionosphere.
8. OTH radar system functionalities are strongly dependent on the ionosphere and on the environment noise level that means geographically dependent performances. Accordingly the radar siting represents one of the key choices.
9. The principle of operation for an HF OTH skywave radar shows a spatial resolution cell that is range dependent.
10. The antenna system requirements are particularly demandingly. It is remarkable that the radiating system should operate on a very wide frequency range (HF band) and a 2D-array requires an area of a few square km to be installed.
11. High values of peak power are necessary in such systems to deal with strong losses. This requirement makes the antenna siting more constrained in order to comply with the national laws on e.m. radiation limits.
12. HF radar cross section (RCS) of targets is regulated by different mechanism than in microwave regions. Targets lie in the Rayleigh and Mie region reporting a wide range of values. It is essential a simulative approach that can provide a predicted RCS variability as a function of the operating frequency and of the aspect angles that are unusual for ordinary radar systems.

Therefore, it is evident that an HF radar must be an adaptive system, where transmitted waveforms, antenna beamwidth and gain, as well as signal processing, must be tuned according to the external environment. A 2D array skywave radar allows this level of flexibility jointly with the capability of controlling the beam pattern in elevation. A large number of single antennas in a planar configuration permits a narrow beam forming, and as a consequence a significant performance improvement. That is, higher signal to noise ratio, low probability of intercept, multi hop rays avoidance and ionosphere propagation stability.

The main functionalities of the radar are reported in the diagram block of Fig. 1. A distributed architecture is considered with centralized processing and control. The core of the system is the Radar Management and Control (RMC) block whose task is to manage all the radar sub-systems functionalities.

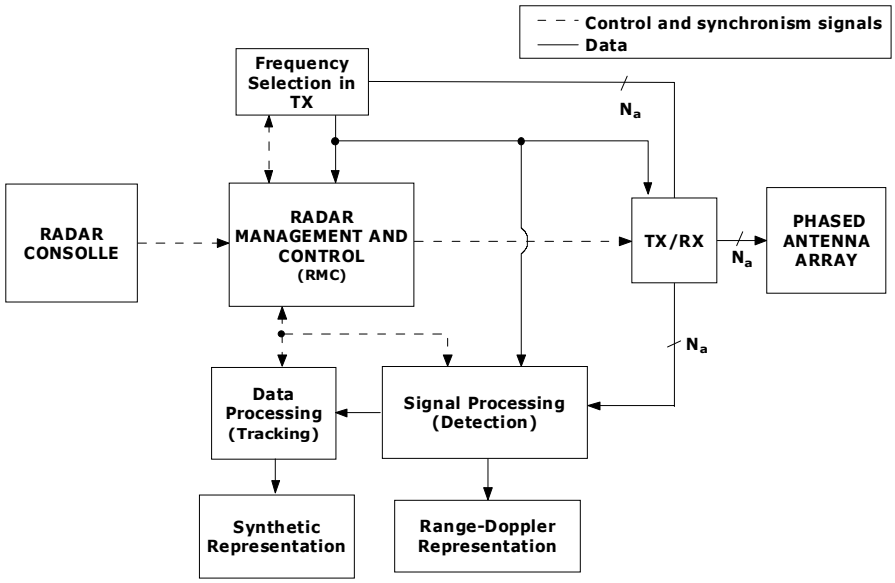

Fig.1 – 2D array HF radar architecture

The other main elements are:
1) Frequency selection block, that decides what frequencies must be transmitted according to the ionosphere behaviour, spectral occupancy and noise level.
2) Phased array antenna, whose elements must be suitably feed in amplitude and phase in order to form different beams and scan all the radar coverage area.
3) Transceivers are integrated into each single antenna of the array. Because of low operating frequency (HF band) fully digital architecture can be conjectured. Use of Direct Digital Synthesizer (DDS) for waveform generation and Digital Down Conversion (DDC) for digital received signal pre-processing make the fully digitization affordable.
4) The detector must take into account of the space-time variability of external scenarios and channel. Space Time Adaptive Processing (STAP) with reduced rank seems to be a promising technique for target detection.
5) Tracking is a complicated task and it requires dedicated resources of the system. The additional information provided by a 2D array might support an operationally useful altitude estimation capability. Moreover a specific micro-multipath technique could be used in order to improve target altitude measurement accuracy.
6) A number of visualizations is available for the user: range-Doppler and frequency-angle domain and synthetic representation that allows a deep insight on the point or area of interest.

3.0 RCS OF MISSILES

In order to assess the detection performance of a 2D-array HF-OTH radar system, RCS of missile during flight time must be computed in accordance to transmitted frequencies, ray-paths and target trajectory.

3.1 Missile trajectory

By referring to Fig.2 and denoting the missile polar coordinates as $\left(r_B(t),\phi_B(t)\right)$, the missile trajectory is governed by the following parametric equations:

$$\begin{cases} \dfrac{d^2 r_B(t)}{dt^2} - r_B\left(\dfrac{d\phi_B(t)}{dt}\right)^2 + \dfrac{g_m}{r_B^2(t)} = 0 \\ r_B^2(t)\dfrac{d\phi_B(t)}{dt} = \mathrm{R}_E\, v_B \cos\gamma \end{cases} \tag{1}$$

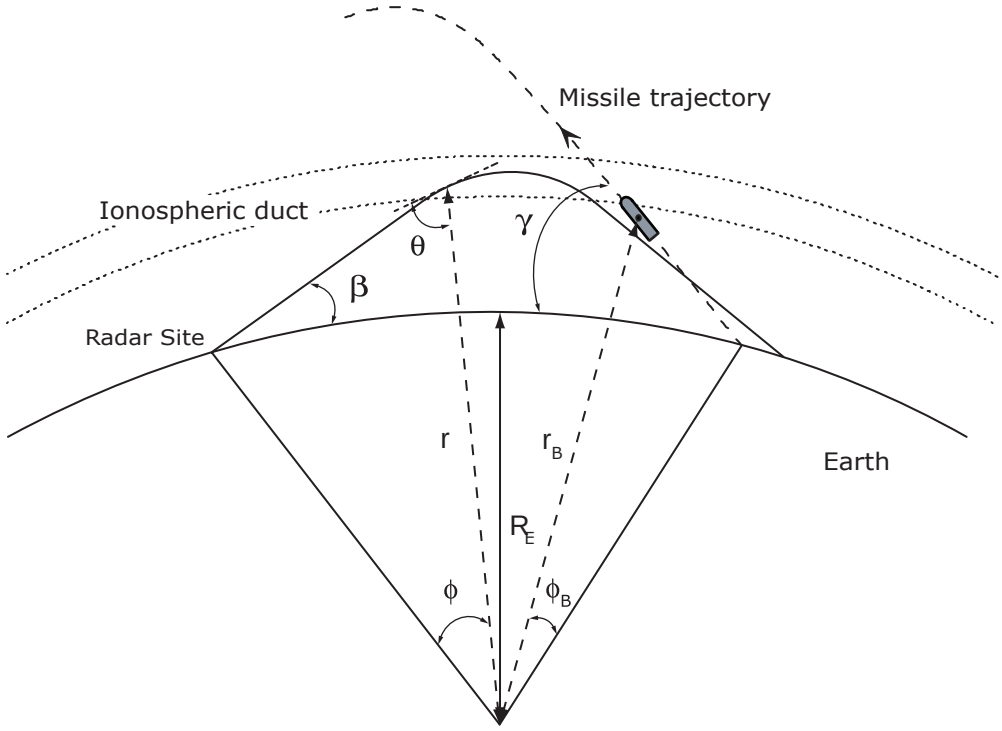

Fig.2 – Reference system

In eq. (1) v_B is the missile the initial velocity, γ is the launching angle, R_E is the Earth's radius and g_m is the gravitational acceleration. By skipping mathematical passages [6], eq.(2) provides the closed form solution of the flight trajectory $\{r_B(t),\phi_B(t)\}$:

$$\begin{cases} r_B(t) = \dfrac{R_E \lambda \cos^2\gamma}{1-\cos\phi_B(t)+\lambda\cos\gamma\cos\left(\phi_B(t)+\gamma\right)} \\ \lambda = \dfrac{R_E v_B^2}{g_m} \end{cases} \tag{2}$$

The expression of the flight time t_f (time interval from missile launch) for a given point $\left(r_B,\phi_B\right)$ of the flight trajectory can be obtained by integrating the second equation in (1), as follows:

$$\int_0^{\phi_B} r_B^2 d\xi = \int_0^{t_f} \mathrm{R}_E\, v_B \cos\gamma dt \tag{3}$$

By substituting eq. (2) in eq. (3), the analytical expression of the flight time is obtained:

$$t_f = \frac{1}{R_E v_B \cos\gamma} \int_0^{\phi_B} \frac{R_E \lambda \cos^2\gamma}{1 - \cos\xi + \lambda \cos\gamma \cos(\xi + \gamma)} d\xi \qquad (4)$$

3.2 Ray tracing

Ray-paths of the e.m. waves that propagate from the radar antenna via ionosphere reflection towards the target and back to the radar antenna depends on ionosphere electron density. Such an operation is necessary for determining whether the target is visible to the radar and for the calculation of the radar-target aspect angle.

Several techniques have been carried out that deal with the ray tracing problems[7], [8], [9], [10], [11], [12]. Such methods can be classified as numerical or analytical. The former approach usually adopts a form of Haselgroves' equation [12] while the latter makes an extensive use of an explicit equation that provides directly the required parameter (e.g. ground range, phase path, reflection height).

In this paper a simple two-dimensional (2D) analytic form is used that makes use of well known theoretical results given in [13]. This method is accurate enough for the purpose of evaluating frequencies and target aspect angles for any given ionosphere propagation.

In Fig.3 there is an example of ray paths with target trajectory intersections for the case of a ballistic missile launched from the radar at a ground distance of 3000 km . The figure also reports the value of the "illumination time interval" T_{ill} defined as the maximum missile flight time for which at least an e.m. ray hits the target. For $t_f > T_{ill}$ the target is not illuminated anymore. This parameters is very important to establish the maximum integration time available to detect the target. It is worth seeing that ray paths are almost tangent to Earth surface at that distances.

In Fig. 4, the plot of frequencies associated to ray paths impacting the missile is presented. As expected, high frequencies greater than 15 MHz are needed to illuminate long range targets.

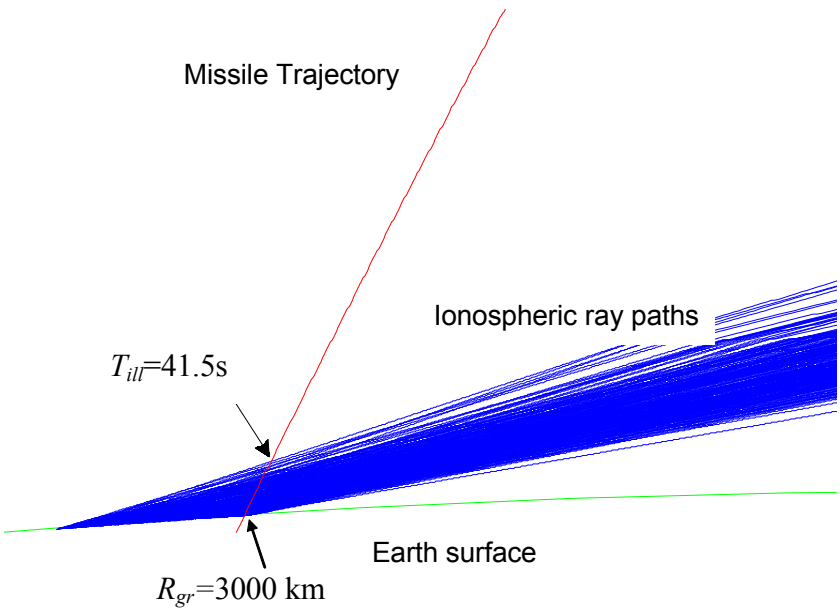

Fig.3 –E.M. ray paths and missile trajectory

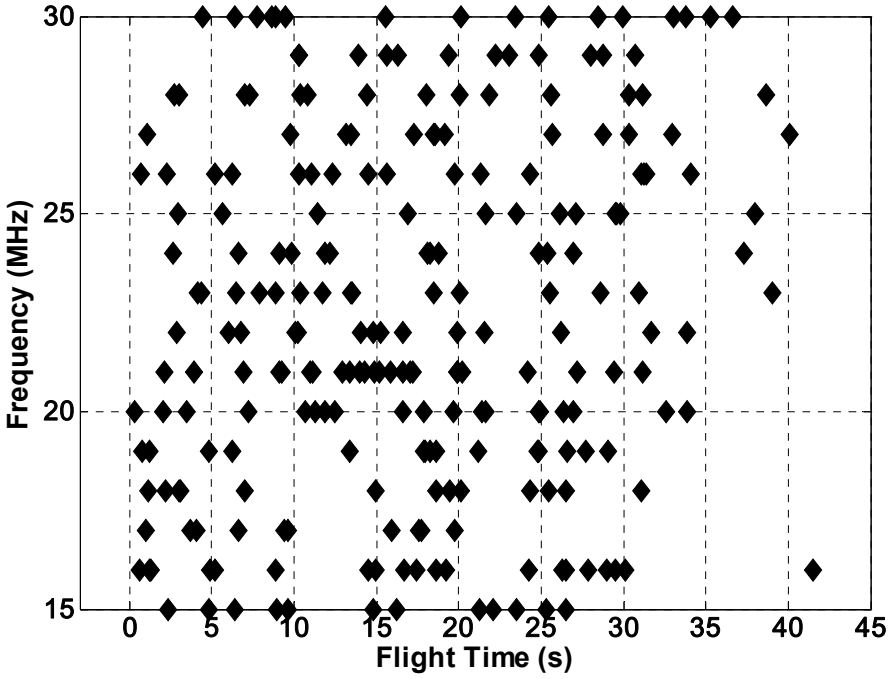

Fig.4 – Frequency of ray paths impacting missile as a function of flight time

3.3 RCS estimation

The ionosphere characteristics depend on the time (hour), the season, and the Sun Spot Number (SSN). In the following simulations a periodical model of the ionosphere is considered (11-year period). Specifically, a total of 72 ionospheric density profiles that span across the entire solar cycle are used. Such a combination of profiles is obtained by considering six hours within a day, three values of SSN and four months, namely January, April, July and October. Each ionospheric electron density profile is obtained by means of the prediction model implemented in NeQuick [14], [15]. Ray tracing is based on such simulated profiles.

The RCS is calculated by considering a medium range ballistic missile 21m long with a diameter of 2.30m. A launching angle of $\gamma = 60°$ is considered. The launch site is placed at a distance of 3000 km from the radar site.

In Fig. 5 , the scatter plot of missile RCS is reported against time flight for all ionosphere propagations. RCS is computed by considering frequencies associated to any ray path and missile viewing angle (the angle formed by the longitudinal missile axis and the ray direction at the missile interception time). Also note that the effect of plume is taken into account because it behaves as a plasma at the HF band and it affects the RCS value strongly [16]. Most of values are lower than 30 m^2. The mean RCS against frequency is plotted in Fig.6. For high frequencies the mean values tends to about 10 m^2. Graph of Fig. 6 will be used to estimate peak powers for missile detection.

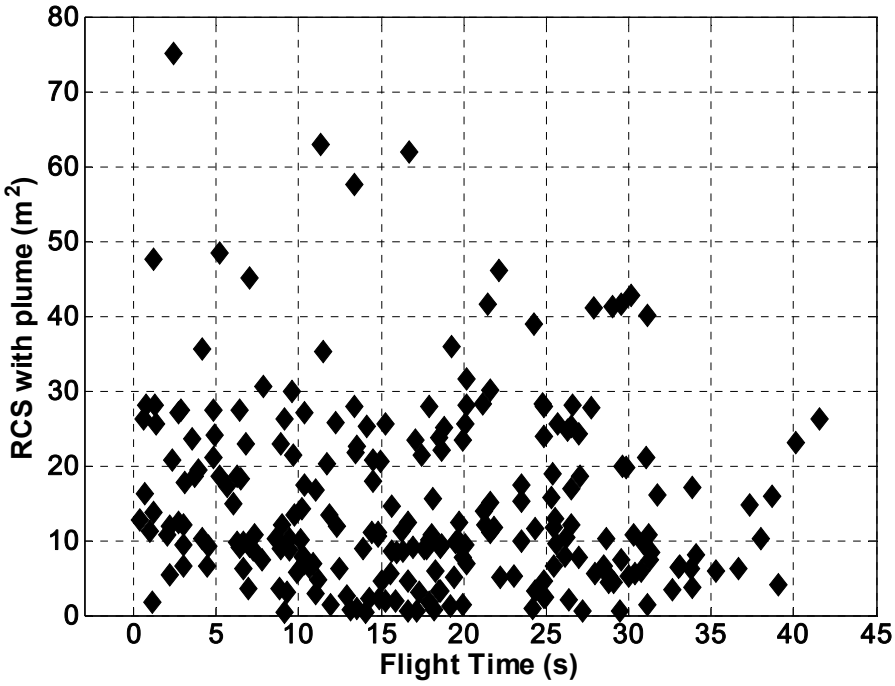

Fig.5 – Missile RCS scatter plots

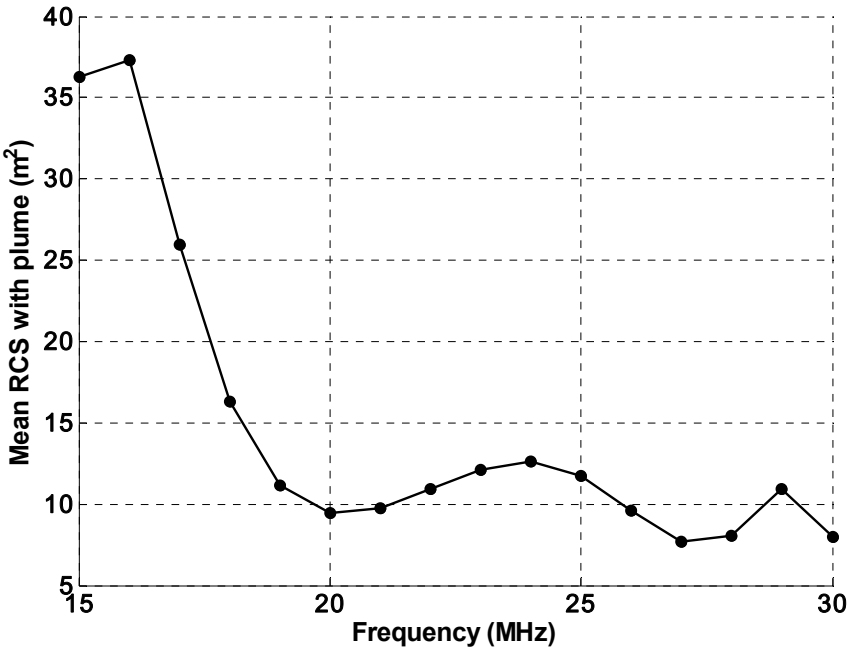

Fig.6 – Mean missile RCS vs frequency

4.0 MISSILES DETECTION

Missile detection mainly depends on three main elements:
1) Integration time T_{in}
2) Earth clutter power level C
3) Signal to disturbance ratio SDR

4.1 Integration time

Integration time is related to the missile illumination time interval T_{ill}, to the ionosphere coherence time T_{ch} and to Doppler accuracy.

As shown in Section 3, T_{ill} depends on ionosphere propagation condition, target launch distance, trajectory and missile cinematic. In Fig.3 there is an example of a ballistic missile launched at a ground distance of 3000 km from the radar. In this case the illumination time interval is 41.5 sec, which is representative of a typical ionosphere propagation situation. If the radar is pointed on the area where a missile launch is expected T_{ill} also represents the maximum integration time.

The ionosphere coherence time T_{ch} is defined as the time interval in which the phase changes produced by ionosphere propagation do not affect the target Doppler response significantly. Experimental results show that T_{ch} in quite ionosphere is of the order of a few tens of seconds, up to 100 sec in very favourable conditions. Anyway, typical values are less than 40 s.

If advanced power spectrum analysis techniques are not used, Doppler measurement accuracy coincides to Doppler bin extent $\delta f_d = 1/T_{obs}$, where T_{obs} is the observation time that is less or equal to integration time.

It is clear that radial velocity estimation also depends on frequency used to illuminate the missile. According to Fig.4 a mean frequency of 20 MHz is considered. In this case, if an accuracy on the radial velocity measurement of δv_r =10 m/s is required, an observation of $T_{obs} = \lambda/2\delta v_r$ =0.75 s is needed. This result shows that no constrains on integration time are imposed by Doppler accuracy.

According to the above remarks, simulations have been conducted for $T_{in} = 10$, 20,30,40 s.

4.2 Range-Doppler echoes mapping

Since an HF-OTH radar is coherent, detection is based on Range-Doppler analysis. Earth clutter is usually centred on zero Doppler (apart for the case of sea clutter) and its bandwidth does not exceed a few Hertz. For missile detection is very important to investigate whether target echoes are mapped outside the clutter region or not.

In Fig. 7, the range Doppler positions of missile echoes during its flight time are reported.

This result is really encouraging. In fact, Doppler frequencies are very high and well outside the clutter region. In other words, we can expect that missile detection is mainly affected by external noise.

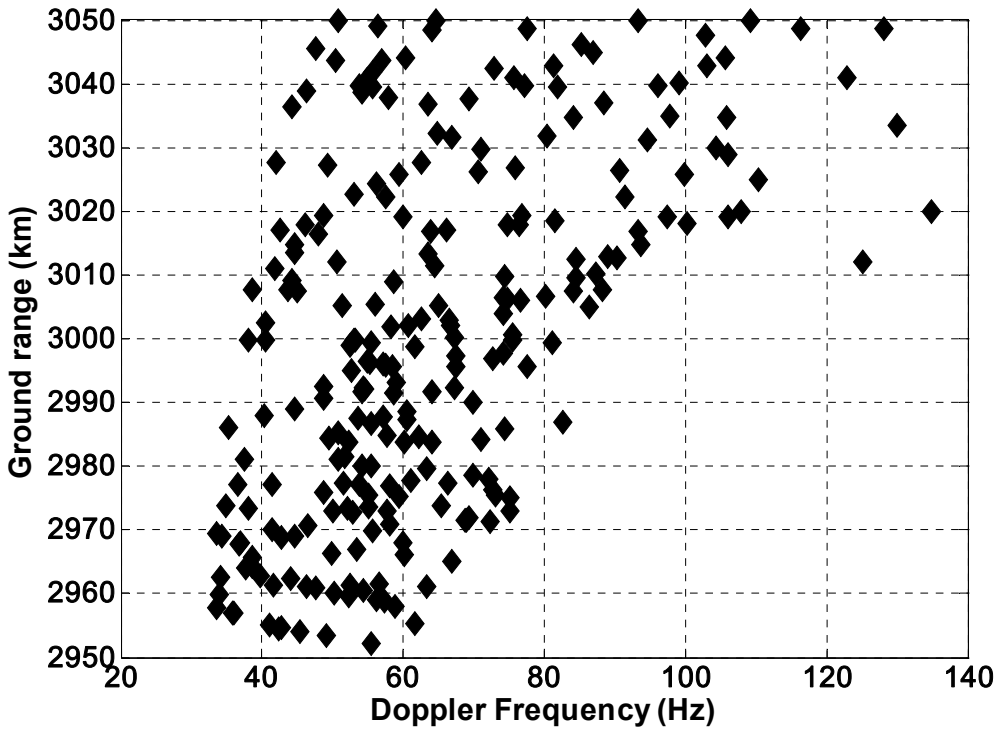

Fig.7. – Range Doppler position of missile echoes.

4.3 Peak power estimation

According to the result of Fig.7, the SDR is in practice coincident with the Signal to Noise Ratio (SNR) because target echoes are not overlapped with clutter. Therefore, target detection analysis is based on evaluating the signal to noise ratio. By referring to [17] the *normalized signal to noise ratio* SNR_N is given by:

$$SNR_N = \frac{4\pi}{c^2} \cdot \frac{g_t(f) \cdot g_r(f) \cdot \sigma(f) \cdot f^2}{L_p^2(f) \cdot (N_0(f)/2)} \tag{5}$$

where $\sigma(f)$ is the target RCS, $N_0(f)/2$ is the noise power spectral density, $L_p(f)$ is the one way propagation loss and $g_t(f), g_r(f)$ are the tx/rx antenna gains normalized to their maximum values. The SNR_N is related to the other parameters by the following formula:

$$SNR_N = \frac{SNR \cdot L_{sys}}{P_T \cdot T_i \cdot PRF \cdot T_{obs} \cdot G_{tM} \cdot G_{rM}} \tag{6}$$

where P_T is the peak power, T_i is the pulse width , SNR is the signal to noise ratio (to have a given detection probability P_D), PRF is the pulse repetition frequency, T_{obs} is the integration time, L_{sys} are the system loss and G_{tM} , G_{rM} are the maximum values of the tx and rx antenna gains against the frequency.

By taking the same radar parameters assumed in [17] and inverting eq.(6) after evaluating the SNR_N for any ionosphere propagation conditions, histograms of peak power for $T_{in} = 10$, 20,30,40 s are calculated and reported in Figg. 8-11. $P_{FA} = 10^{-6}$. From graphs of Figg.8-11, the following comments arise:

1) The maximum peak power is always less than 2 MW in the worst condition ($T_{in} = 10s$) but it decreases

to 460 kW using the whole illumination time for echoes integration ($T_{in} = 40s$);

2) The probability of using a peak power greater than 1 MW is 14% in the worst case ($T_{in} = 10s$);

3) By exploiting the whole illumination time ($T_{in} = 40s$) the probability of transmitting a peak power greater than 300 kW is less than 12%.

These values of peak power are affordable for a real system. Moreover, power distribution on all array radiating elements allows to have a few kW per element, which are easily manageable at HF band.

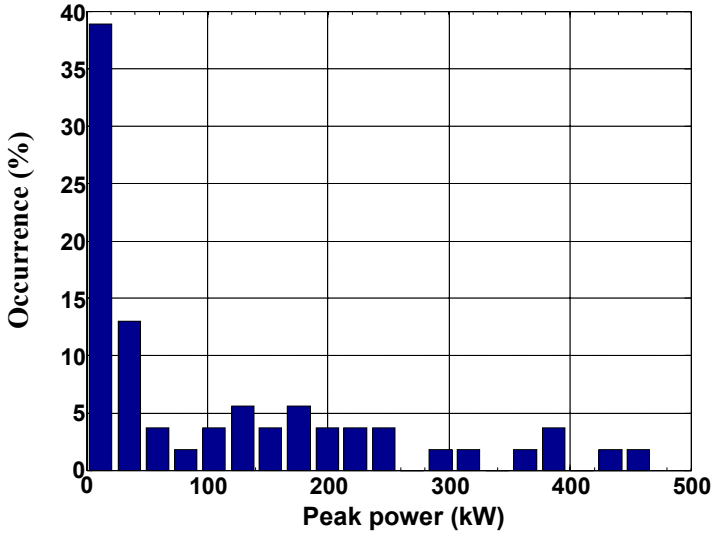

Fig. 8 – Peak power histogram for T_{in} =40s

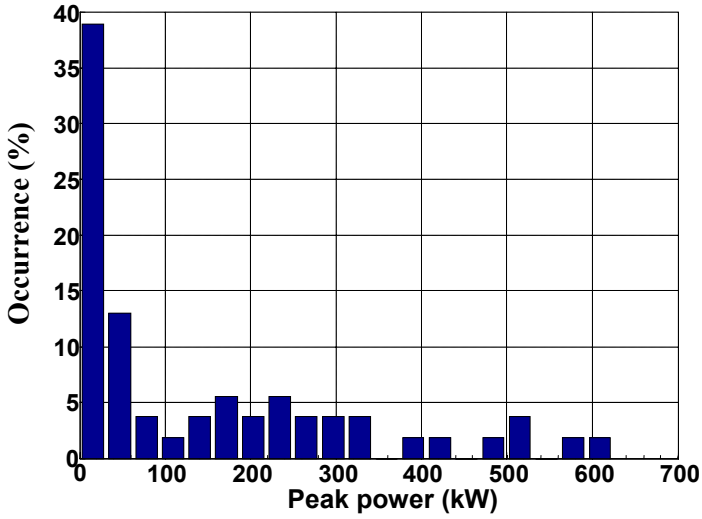

Fig. 9 – Peak power histogram for T_{in} =30s

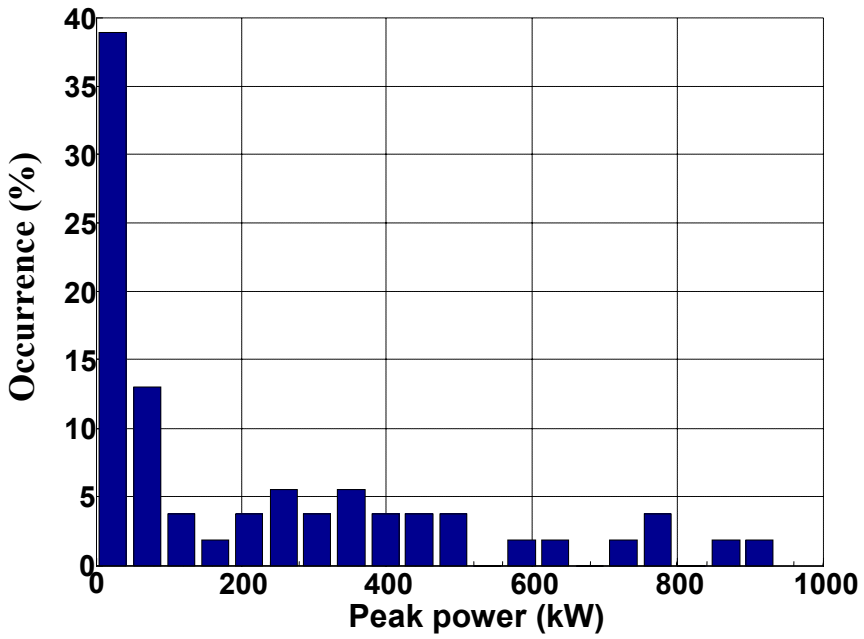

Fig. 10 – Peak power histogram for T_{in} =20s

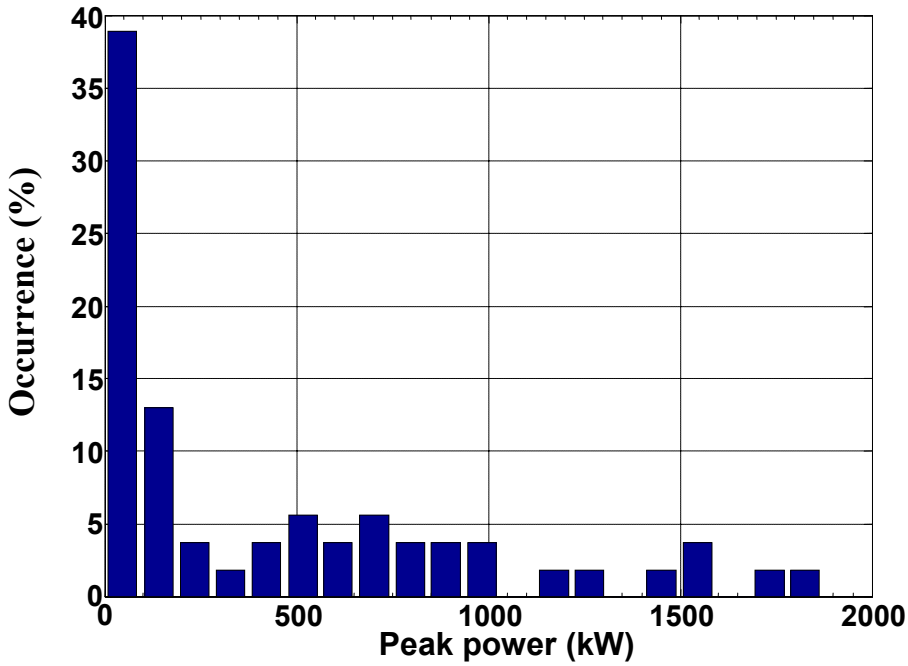

Fig. 11 – Peak power histogram for T_{in} =10s

5.0 CONCLUSIONS

In this paper, a statistical analysis of missile detection capabilities of an HF-OTH Skywave Radar has been presented. The study has been conducted by referring to a ballistic missile launched at 3000 km from the radar. The results have showed that:
1) The illumination time interval is long enough to allow detection operations;
2) Mean RCS of missile for high frequencies (the ones used to reach long distances) is about 10 m^2, which is a significant value;
3) Missile echoes in the range-Doppler domain cover a region which is outside the earth clutter ridge. Therefore, target returns only compete with external noise;
4) The required peak power is always less than 1 MW for more than 85% of the operating time, if an integration time of 10 s is employed.
Other considerations are:
1) The radar must be a priori pointed on the area where the missile launch is expected;
2) Antenna array with high directivity and gain must be used;
3) High PRFs are necessary to avoid spectrum folding in the Range Doppler domain that could be provoked by a superposition of target echoes on clutter. In other words range ambiguity can occur;
4) Tracking algorithms and performancse must be defined and analysed to see whether the radar is able to trace the missile trajectory and to alert defence systems for target interception.

REFERENCES

[1] J. M. Headrick and J. F. Thomason, "Application of high-frequency radar", Radio Science, vol. 33, pp. 1045–1054, Jul-Aug. 1998
[2] Davies K., Ionospheric radio propagation, U.S. Department of Commerce National Bureau of Standards, April 1965
[3] Budden K. G., The propagation of radio waves. The theory of radio waves of low power in the ionosphere and magnetosphere, Cambridge University Press, 1988
[4] Bazin, V.; Molinie, J.P.; Munoz, J.; Dorey, P.; Saillant, S.; Auffray, G.; Rannou, V.; Lesturgie, M.;"NOSTRADAMUS: An OTH radar", IEEE Aerospace and Electronic Systems Magazine, Volume 21, Issue 10, Oct. 2006 Page(s):3 – 11
[5] ITU (International Telecommunication Union), Radio Noise, ITU-R P.372-8
[6] A. D. Wheelon: 'Free flight of a ballistic missile', ARS Journal, vol. 29, December 1959
[7] P. S. Cannon and R. Norman: 'The relative performance of numeric and analytic ray tracing', Proc. of IEE 7th Int. Conf. on HF, Radio Systems and Techniques, Nottingham, July 1997
[8] R. J. Norman and P. S. Cannon: 'A Two-dimensional Analytic Ray Tracing Technique Accommodating Horizontal Gradients', Radio Science, vol. 32, n. 2, 1997
[9] R. J. Norman and P. S. Cannon: 'An evaluation of a new 2-D analytic ionospheric ray tracing technique – SMART', Radio Science, vol. 34, n. 2, 1999
[10] R. M. Jones and J. J. Stephenson, 'A Versatile Three Dimensional Ray Tracing Computer Program for Radio Waves in the Ionosphere', Office of Telecommunications OT Report 75-76, October 1975
[11] J. A. Bennett, P. L. Dyson, and R. J. Norman, 'Progress in radio ray tracing in the ionosphere', The Radio Science Bulletin, n. 310, September 2004
[12] J. Haselgroove, 'Ray theory and new method of ray tracing', Proc. Phys. Soc. London, vol. 23, 1955
[13] J. M. Kelso: 'Radio Ray Propagation in the Ionosphere' (McGraw-Hill, New York, 1964)
[14] S. M. Radicella, R. Leitinger: 'The evolution of the DGR approach to model electron density profiles', Adv. Space Res., vol. 27, no. 1, 2001
[15] ITU (International Telecommunication Union), 'Ionospheric propagation data and prediction methods required for the design of satellite services and systems', ITU-R P.531-6
[16] M. Martorella, R. Soleti, F. Berizzi, E. Dalle Mese " Plume Effect on Radar Cross Section of missiles at HF band' in the Proceeding of the International Radar Conference, 3-5 September 2003, Adelaide (Australia)
[17] Berizzi, A.Capria, E. Dalle Mese, R.Soleti, "A Method for Peak Power Evaluation for HF-OTH Skywave Radar" in the proceedings of the 2006 International Radar Symposium (IRS 2006), Kracòw (Poland), May 2006