DOI: https://doi.org/10.52651/sam.a.2022.2.11-17

ANALYSIS OF RELEVANT ENERGETIC PROPORTIONS FOR ELINT ACTIVITIES IN THE HF FREQUENCY BAND

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Abstract: Intelligence as a warfighting function is a continuous process. It is carried out before planning the mission, during the preparation of the mission, and during its execution as well. The results of the intelligence warfighting function enable commanders to predict the course of action for potential threats and facilitate the commander´s decision-making process. If intelligence information is derived from foreign communication (Communication Intelligence) and noncommunication (Electronic Intelligence) electromagnetic radiations by other than intended recipients, we are speaking about Signals Intelligence. Communication and noncommunication foreign emitters might be also denoted as Radio-Electronic objects. This paper presents an algorithm for analysis of some relevant energetic proportions of a skywave propagation, with consideration of Electronic Intelligence in the high-frequency band. In terms of Electronic Intelligence, Radio-Electronic object is represented by the Over-The-Horizon radar.

Keywords: Electronic intelligence; Radio-electronic object; Over-the-horizon radar; Energetic proportions; High-frequency band.

1 INTRODUCTION

Over-the-horizon (OTH) radars operate in the high frequency (HF) band (3÷30 MHz). They are using the reflection of electromagnetic (EM) energy from the ionosphere (ionized layer of the atmosphere) for their operation. Detection and tracking of airborne, maritime, and ground targets by OTH radars is usually done by a far larger distance than by radars operating on the Line-Of-Sight principle. That fact also represents the main advantage of OTH radars- to execute surveillance over a distance exceeding thousands of kilometers from its own territory [1],[2].

The main application of OTH radars is within ballistic missile early warning systems for long-range detection. Such a system is composed of varied technical means, which detect the launch of an intercontinental ballistic missile (ICBM), estimate its probable trajectory, and provide given information to the higher level of command or to the predefined entities (military units or decision makers). That kind of early warning system has usually two main components, a ground-based component (OTH radars), and a space component (space-based surveillance) [3].

All components of the ballistic missile early warning system are usually on high alert and are working in continuous operation in order to provide information about possible adversary´s ICBM. Essential information for early warning systems is mainly gathered during tests of newly developed ICBM or during regular periodic tests of ICBM already deployed within strategic rocket forces [3].

2 ELECTRONIC INTELLIGENCE

When conducting Electronic Intelligence (ELINT) activities, gathered intelligence is derived from intercepting noncommunication signals. The value of ELINT is that it provides timely information about threatening systems, such as radars that guide aircraft or missiles to targets [4].

For successful fulfillment of given tasks, it is necessary to configure ELINT receivers in space and time in a way, that enables proper interception of Radio-Electronic objects (REO). Configuration of REO on the one hand and ELINT receivers on the other hand, both in space and time, together with some necessary preconditions for processing radio signals might be called the ELINT chain. An example of the ELINT chain for the OTH radar operating in the HF frequency band is shown in Figure 1.

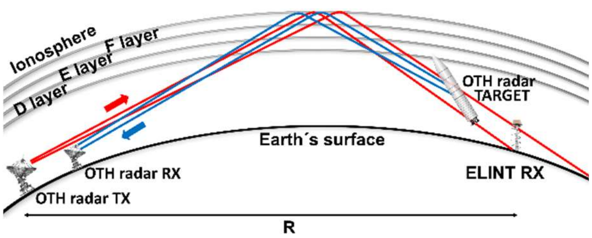

Fig. 1 An example of the ELINT chain for the OTH radar operating in the HF frequency band
Source: author.

The proposed example of the ELINT chain illustrates the basic principle of the EM energy propagation between the transmitter (TX) antenna of OTH radar (representing REO in this specific scenario) and the antenna of the ELINT system (intercepting OTH radars).

2.1 Basic aspects for properly functioning ELINT chain

The basic attributes for a properly functioning ELINT chain are as follows:

1. Securing mutual directivity of antenna arrays, for both REO antenna and ELINT system antenna.
2. Securing frequency tuning of ELINT receiver to the carrier frequency of the REO signal.
3. Having sufficient power level of transmitted EM energy by OTH radar, so the power level of a signal on the ELINT receiver input $P_{inELINT}$ is sufficient for further processing. This precondition is denoted by

$$P_{inELINT} \geq P_{P\min} \,, \tag{1}$$

while the sensitivity of the ELINT receiver P_{Pmin} is expressed as [4]

$$P_{P\min} = k \cdot T_0 \cdot F \cdot B \cdot \frac{S}{N} \,, \tag{2}$$

where k is the Boltzmann constant, T_0 is the absolute temperature, F is a noise factor, B is a signal bandwidth and S/N is the required ratio between signal to noise at the receiver input.
4. Securing the same mode of operation (modulation) for both- REO and ELINT system.
5. Securing identical polarization of EM energy for both- REO and ELINT system.

Basic energetic parameters for a properly functioning ELINT chain are as follows:

1. $P_{inELINT}$ is the power level of a signal on the ELINT receiver input.
2. P_{TX} is the power level of a signal on the REO TX output.
3. G_{TX} is the antenna gain of REO TX.
4. $G_{inELINT}$ is the antenna gain of an ELINT receiver.
5. R is the distance between the REO TX antenna and the ELINT receiver antenna.

3 SKYWAVE PROPAGATION

The ionosphere is a part of Earth's upper atmosphere with a high concentration of electrons to such a degree, that it can affect the propagation of EM energy. It is a result of the ionization process caused mainly by solar activity. According to the current ionization degree, it may vary from 60 ÷ 600 km above the Earth's surface, while at approximately the height of 600 km it fluently transitions to the magnetosphere (600÷2000 km). Under specific conditions, the ionosphere can reflect EM energy with an exactly defined carrier frequency. [5],[6]

Up to the height of 100 km, the composition of the atmosphere is constant; while 78% is represented by N_2, 21% is represented by O_2, and the rest is represented by other gases. At higher altitudes, molecules of oxygen and nitrogen are dissociated by solar activity to the atoms accordingly by [7]

$$\begin{aligned} O_2 + h\omega &\rightarrow O + O \,, \\ N_2 + h\omega &\rightarrow N + N \,, \end{aligned} \tag{3}$$

where $h\omega$ is a quantum of incident energy, ω is the angular frequency of the radiation and h is the Planck constant.

4 ANALYSIS OF ENERGETIC PROPORTIONS FOR HF FREQUENCY BAND

There are two propagation modes for the HF frequency band, groundwave propagation, and skywave propagation. Skywave propagation is used for transmissions over long distances when EM waves are reflected from various layers of the ionosphere. The carrier frequency of an EM wave determines from which ionosphere layer will be EM wave reflected. When considering skywave propagation, it is also necessary to take into account variations of the ionosphere based on time and space (geographical) conditions.

The highest carrier frequency when the reflection from the ionosphere is still taking place is called critical frequency f_{CR} denoted by [7]

$$f_{CR} = \sqrt{80.8 \cdot N_{\max}} \,, \tag{4}$$

where N_{max} is the maximum electron density.

The critical frequency is one of the basic parameters, which determines the condition of the ionosphere. For every layer within the ionosphere, there is a critical frequency. Critical frequencies usually vary in a range of 1 ÷ 16 MHz. EM energy with a carrier frequency higher than the critical frequency would not reflect from the ionosphere but will penetrate the upper layers of the atmosphere.

For a successful mode of operation in the HF frequency band, maximum usable frequency is defined as [8]

$$MUF = \frac{f_{CR}}{\cos(\varphi)} = f_{CR} \cdot \sec(\varphi) \,, \tag{5}$$

where φ is the oblique incidence angle striking the ionosphere.

The electric field strength E at the distance R from the REO (at the ELINT receiver) for one-hop skywave propagation is denoted by [9]

$$\begin{aligned} E_{[dB]} = 136.6 + 20\log(f)_{[MHz]} + 10\log(P_{TX})_{[kW]} + \\ + G_{TX[dB]} - L_{is[dB]} \,, \end{aligned} \tag{6}$$

where the f is a carrier frequency, P_{TX} is a power level on the TX output, G_{TX} is a TX antenna gain and L_{is} is the loss of the EM energy for a skywave propagation.

Loss of the EM energy for a skywave propagation $L_{is[dB]}$ is denoted by [9]

$$L_{is[dB]} = L_{0[dB]} + L_{a[dB]} + L_{M_{[dB]}} + L_{g_{[dB]}} + L_{h[dB]} + L_{z[dB]} \,, \tag{7}$$

where L_0 is the free-space path loss, L_a is the ionosphere absorption loss, L_m is the above MUF loss, L_g is summed ground-reflection loss at intermediate reflection points, L_h is auroral and other signal losses in terms of the geomagnetic latitude and L_z is another non-specified loss (current recommended value is 9.9 dB).

4.1 Free-space path loss

In terms of Free-space EM energy propagation, Free-space path loss (spreading loss) is expressed as [10]

$$L_0 = \left(\frac{4 \cdot \pi \cdot R}{\lambda}\right)^2, \tag{8}$$

where R is the transmission distance and λ is the wavelength of the carrier signal.

The formula for spreading loss determined in dB is characterized as [9]

$$L_{0[dB]} = 20 \cdot \log\left(\frac{4 \cdot \pi \cdot R}{\lambda}\right), \tag{9}$$

or by the so-called Friis transmission formula [10]

$$L_{0[dB]} = 32.45 + 20\log(f)_{[MHz]} + 20\log(R)_{[km]}, \tag{10}$$

where f is the frequency of the carrier signal and R is the transmission distance.

The transmission distance R, which also represents the effective length of the transmission link is in the case of skywave propagation defined as the trajectory of EM energy over the distance D (oblique path distance) by the formula [9]

$$D = 2 \cdot n \cdot \sqrt{\left(\frac{R}{2}\right)^2 + h^2}, \tag{11}$$

where n is the number of reflections from the ionosphere, R is the ground distance between TX (OTH radar) and RX (ELINT receiver), and h is the height of the ionosphere layer used for reflection.

Adding equation (11) into equation (10) yields

$$L_{0[dB]} = 32{,}45 + 20\log f_{[MHz]} + \\ +20\log\left[2 \cdot n \cdot \sqrt{\left(\frac{R}{2}\right)^2 + h^2}\right]. \tag{12}$$

The elevation angle is determined by [7]

$$tg(\alpha) = \left[\cos(\psi) - \frac{R_Z}{R_Z + h}\right] \cdot \sin(\psi) = \frac{2h}{R} - \frac{R}{4R_Z}, \tag{13}$$

where h is the reflection height of the ionosphere and ψ is the half of an angle within a circular segment illustrating the ground distance between TX and RX and R_Z is the Earth radius.

Angle ψ is defined by an equation [7]

$$\psi = \frac{R}{222.4}. \tag{14}$$

The incidence angle striking the ionosphere is expressed as [7]

$$\varphi = \arctan\left\{\frac{R_Z \cdot \sin(\psi)}{h + R_Z \cdot [1 - \cos(\psi)]}\right\}. \tag{15}$$

A basic principle of skywave propagation is shown in Figure 2.

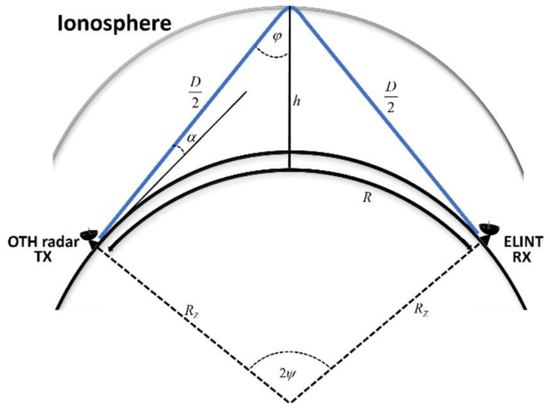

Fig. 2 A basic principle of skywave propagation
Source: author.

In the case of planning skywave propagation for very long distances (for over 10 000km – which is not the case for OTH), it is necessary to consider also so-called focusing gain G_f denoted as [9]

$$G_f = 20 \cdot \log\left(\left|1 - \frac{n \cdot \pi \cdot R_Z}{R}\right|\right), \tag{16}$$

where n is the number of reflections from the ionosphere, R_Z is the Earth radius, R is the transmission distance and π is the ratio of a circle's circumference to its diameter.

In that specific case, equation (10) will be modified to [9]

$$L_{0[\mathrm{dB}]} = \left[32.45 + 20\log_{10}(f)_{[\mathrm{MHz}]} + 20\log_{10}(D)_{[\mathrm{km}]}\right] - \\ -G_{f[\mathrm{dB}]}, \tag{17}$$

where f is the frequency of the carrier signal, D is the oblique path distance and G_f is the focusing gain.

4.2 Skywave propagation loss

The skywave propagation loss is mostly dependent on the directional properties of an antenna, elevation angle, and incidence angle. Overall loss of skywave propagation L_{is} has multiple components, such as free-space path loss, ionosphere absorption loss, above *MUF* loss, summed ground-reflection loss, auroral and other signal losses in terms of the geomagnetic latitude, and other non-specified losses.

4.2.1 Ionosphere absorption loss

The highest absorption of EM energy in the ionosphere occurs in the D layer at a height of approximately 50÷90 km. Electron density in this layer is two to three times lower than in the E and F layers. That level of ionization is not sufficient for the effective reflection of EM energy in the HF frequency band. If the direction of EM energy propagation is not affected, we are speaking about non-deviative absorbing. The highest absorption in the D layer is present during summer at noon. [11]

On the other hand, deviative absorbing significantly changes the direction of EM energy. That is typical for the E layer of the ionosphere. In practice, overall absorption at the D and E layers is approximately 1 dB. As mentioned before, absorption is mostly dependent on electron density, which differs day and night. Daytime absorption for the D and E layers is expressed as [9]

$$L_a = n.\frac{6.667 \cdot \sec(i)}{(f + f_L)^{1,98} + 10.2} \cdot I \;, \qquad (18)$$

where f_L is the gyrofrequency in the E layer at 100 km, i is the incidence angle at 100km and I is the absorption coefficient.

The absorption coefficient is denoted as [9]

$$I = (1 + 0.0037 R_{12}) \cdot \left[\cos(0.881\chi)\right]^{1/3} \;, \qquad (19)$$

where R_{12} is a 12-month smoothed sunspot number and χ is a solar zenith angle.

The incidence angle at 100km i is calculated by [9]

$$i = \arcsin\left[0.985 \cdot \cos(\varphi)\right] \;. \qquad (20)$$

Night-time absorption for the D and E layers is expressed as [9]

$$L_a = \frac{(7 + 0.019 \cdot D) \cdot (1 + 0.015 \cdot R_{12})}{f^2 + 10} \;. \qquad (21)$$

4.2.2 The above MUF loss

Using a higher carrier frequency than *MUF* results in a considerable loss L_M. If the carrier frequency is equal to or lower than *MUF*, then $L_M=0$. In other cases, the above *MUF* loss L_M is expressed as [9]

$$L_M = 130 \cdot \left[\frac{f}{MUF} - 1\right]^2 \;. \qquad (22)$$

4.2.3 Summed ground-reflection loss

For more than one hop skywave propagation, summed ground-reflection loss L_g must be taken into account. Ground-reflection loss L_g is denoted by [9]

$$L_g = 2 \cdot (n - 1) \;, \qquad (23)$$

where n is a hop number.

4.2.4 Auroral and other signal losses

Auroral loss L_h depends on geomagnetic latitude G_n and local time. If geomagnetic latitude meets criterion $G_n \leq 42.5°$, then auroral loss $L_h=0$. In other cases, auroral loss L_h is determined by an empiric table [9].

4.2.5 Non-specified losses

Non-specified losses L_Z are defined as other types of losses, which may occur during EM energy propagation. The recommended value for L_Z during planning the HF propagation path is 9.9 dB [9].

4.3 Power level on the receiver input

For communication links using skywave propagation up to 7000 km, the power level on the receiver input $P_{inELINT}$ is [9]

$$P_{inELINT[\mathrm{dBW}]} = E_{[\mathrm{dB}]} + G_{RX[\mathrm{dB}]} - 20\log(f)_{[\mathrm{MHz}]} - 107.2 \;, \quad (24)$$

where E is the electric field strength in distance R from the REO (transmitting antenna) calculated by (6) and G_{RX} is an ELINT receiver antenna gain.

The given formula does not comprise eventual losses caused by the line transmission losses, neither for the transmitter nor for the receiver.

A defined mathematical model describes energetic proportions. It also gives assistance to the theoretical evaluation of skywave propagation in order to conduct electronic intelligence. An illustration of energetic proportions in the ELINT chain for the OTH radar is shown in Figure 3.

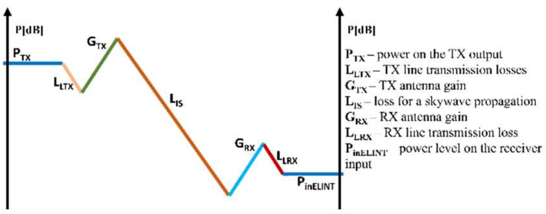

Fig. 3 Illustration of energetic proportions in the ELINT chain for the OTH radar
Source: author.

5 ALGORITHM FOR ANALYSIS OF RELEVANT ENERGETIC PROPORTIONS OF A SKYWAVE PROPAGATION

Energetic proportions of the skywave propagation were described in previous chapters. In practical applications, those calculations might be done in one sequence. In that case, the proposed algorithm might be used. Having such an algorithm enables the prediction of propagation losses, thus yielding awareness about energetic proportions for the ELINT chain. The proposed algorithm for analysis of some relevant energetic proportions of a skywave propagation is shown in Figure 4.

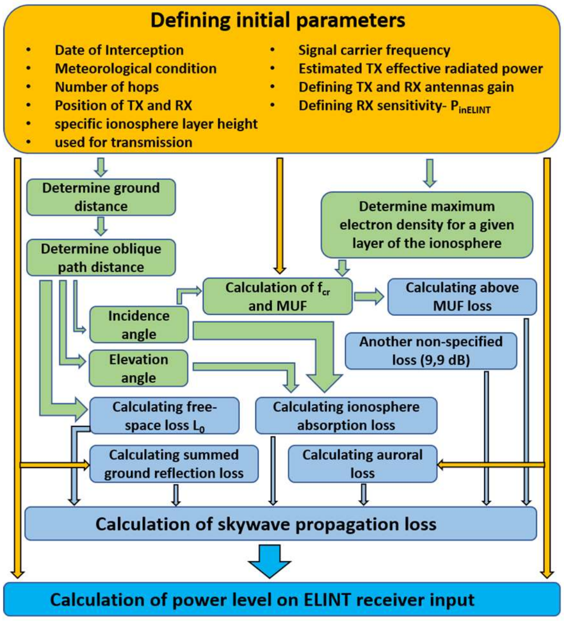

Fig. 4 Algorithm for analysis of some relevant energetic proportions of a skywave propagation
Source: author.

The proposed algorithm consists of four stages. During the 1st stage, the definition of initial parameters is taking place. Because the status of the ionosphere varies not only during the day but also during the seasons, a specific date for the model must be determined. Meteorological conditions might be also determined, but for the illustration of the algorithm, we will not take them into account. Based on the specific measures executed by meteorological institutions, we can define the current height of the ionosphere layer for the specific geographical location (including maximum electron density). The rest of the initial inputs are more of a technical consideration, such as the signal carrier frequency of the TX, estimated TX effective radiated power, assumed TX and RX antenna gain, and sensitivity of the ELINT receiver.

After the initial parameters are defined, the 2nd stage of the proposed algorithm is taking place. During that stage, it is necessary to calculate the ground distance between RX and TX. Based on the height of the specific layer within the ionosphere, elevation and incidence angles are calculated. Based on the given values, the calculation of an oblique distance of a skywave is determined. Calculation of f_{CR} and MUF might be executed according to the current status of the maximum electron density or be provided by the meteorological institution.

During the 3rd stage of the proposed algorithm, the calculation of losses and their additional summation is taking place. For the calculation of summed ground reflection loss, it is necessary to know how many hops will be used, and for the auroral loss, geomagnetic latitude is derived from the point, where the reflection from the ionosphere is assumed. All the losses are calculated by the equations shown in Chapter 4.

The final stage of the proposed algorithm is calculating the power level on the ELINT receiver input. Based on the calculated power level on the ELINT receiver input, we can determine if the interception of the REO is feasible.

The proposed algorithm was designed in the MATLAB computing platform.

6 THE ALGORITHM VERIFICATION FOR ANALYSIS OF RELEVANT ENERGETIC PROPORTIONS OF A SKYWAVE PROPAGATION

The results of the proposed algorithm were verified by the VOACAP software. VOACAP software is free software used for the prediction of HF communications links. For verification purposes, the initial parameters for both, the proposed algorithm and VOACAP, were as follows:

1. Date of interception was 291200ZJUL22.
2. No extreme meteorological conditions.
3. No failure is expected on the RX and TX.
4. One hop of a skywave is considered.
5. REO is not using a higher frequency than *MUF*.
6. F2 layer for reflection will be used.
7. The height of an F2 layer is 245 km.
8. MUF for the F2 layer on a given day is 16 MHz.
9. $G_{TX[dB]}$=0 and $G_{RX[dB]}$=0.

Based on the input data, the skywave propagation loss by the proposed algorithm was determined as $L_{is} = 131.325\ dB$. The power level of a signal on the ELINT receiver input was determined as $P_{inELINT} = -88.916\ dBW$. However, in some cases, signal on the receiver input is not specified in the power level, but in the voltage for the specific impedance *Z*. The given value expressed in dBW might be converted to the voltage value for an impedance of 50 Ω by the formula [12]

$$U_{[\mathrm{dB\mu V}]} = P_{[\mathrm{dBW}]} + 137 . \qquad (23)$$

Hence $P_{inELINT} = -88.916\ dBW$ is after conversion equal to $U_{inELINT} = 48.16\ dB\mu V$.

The skywave propagation loss by VOACAP was determined as $L_{is} = 132.5\ dB$. An example of the skywave propagation loss executed by VOACAP software is shown in Figure 5.

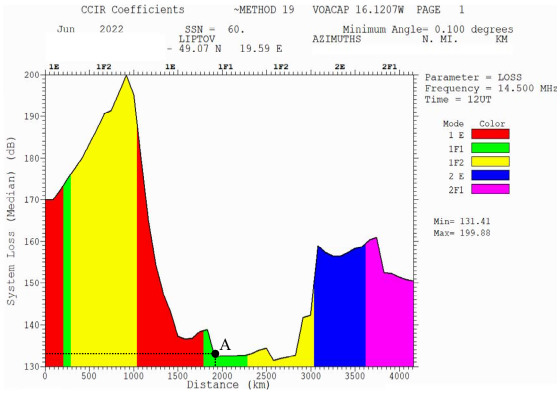

Fig. 5 An example of the skywave propagation loss executed by VOACAP software
Source: author.

The level of a signal on the ELINT receiver input by VOACAP was determined as $U_{inELINT} = 44\ dB\mu V$. An example of the level of a signal on the ELINT receiver input by VOACAP software is shown in Figure 6.

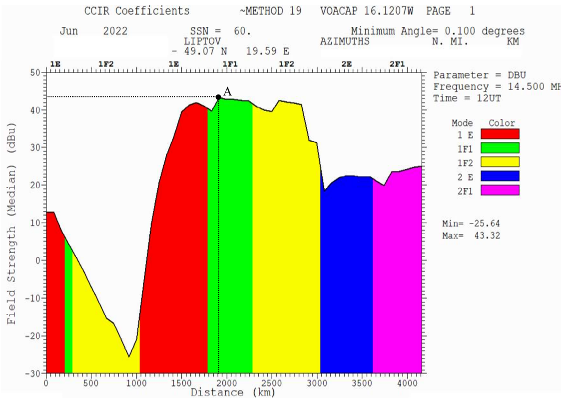

Fig. 6 An example of the level of a signal on the ELINT receiver input by VOACAP software
Source: author.

In the case of loss calculations, the proposed algorithm deviated by 1.175 dB, which is a good performance. When values of the signal level on the ELINT receiver input are compared, the difference is 4.16 dBμV, which is still acceptable. In that case, a higher difference might be caused by additional consideration of complementary effects during the skywave propagation in the VOACAP software.

7 CONCLUSION

Detection and subsequent location of OTH radars is becoming an actual issue. OTH radars as REO are providing crucial information for ELINT and subsequently for air defense and anti-ballistic missile systems, hence representing a source for the decision-making process on the strategic level of command.

When conducting ELINT activities, having awareness of energetic proportions is an inevitable precondition for a successfully executed operation.

Based on the abovementioned analysis for a specific case study, we can conclude that monitoring of OTH is possible for distances over thousands of km. OTH radars are generally bistatic systems and their transmitting power is usually somewhere around tenths of kW. When using radio frequency direction finding for OTH location, it is possible to use not only amplitude based but also phase based methods.

The proposed algorithm designed in the MATLAB computing platform provides evaluations of energetic proportions for the ELINT chain, thus enabling successfully executed ELINT operations.

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