Over-the-horizon detection radar ionosphere support system

S Litvinov
Head of laboratory, Russian Technological University (MIREA), Moscow, Russia

E-mail: Litvinov_S@mirea.ru

Abstract. The article raises the problem of fine tuning over-the-horizon radars with relevant information about the parameters of the ionosphere. To improve the accuracy of the radar, it is proposed to create a system of remote positions, which are ionosondes of vertical and inclined sensing. The results of the operation of such ionosondes serve to adjust the global model of the ionosphere. Thus, the quality of the radar is significantly improved, allowing more accurately determine the coordinates of air targets.

1. Introduction
Over-the-horizon radar originates from the moment Soviet scientists and designer Nikolay Kabanov discovered the possibility of probing radio beams at a wavelength of 10-100 m to reflect from the ionosphere, irradiate the target and return along the same path to the radar. In 1946, he put forward the idea of early detection of aircraft in the short-wave range at a distance of up to 3,000 kilometres.

Over-the-horizon radars are designed for ultra-long range reconnaissance of airspace. The intensive development of over-the-horizon detection tools is an objective process, due to their demand as a highly effective means of monitoring the air and surface conditions at a great distance.

The radars bounce their outgoing signals off the bottom to the ionosphere which reflects the signal to the target. The return signal follows a similar path in reverse. On receiving the return signal at the receiver station the data is converted to digital format and processed to provide a useful image of the target. The processing requires very powerful computers and complex software.

The radars can be aimed at any particular location where a search is required. This area is termed a ‘search box’. The OTHR radar does not scan like a conventional radar but is directed to the area of interest by the operators. This mechanism is illustrated in the graphic below.

The greatest success in the development of technologies for over-the-horizon detection was achieved by countries such as Russia, the United States of America, Australia, France, and certain achievements are also observed in the UK and China. All over-the-horizon radars use the short wavelength range (3 ... 30 MHz), however, in each case, the operating frequency range is adjusted depending on the technical features. [1]

Systems that use the spatial distribution of radio waves in their work are very dependent on the state of the ionosphere, since such systems use the effect of reflection of decimeter radio waves from the ionosphere. To select the optimal radiation frequency, it is necessary to know the parameters of the ionosphere. It should be borne in mind that it is constantly changing both throughout the year and throughout the day. In addition, accurate information about the parameters of the reflecting layer, such as the critical frequency and effective altitude, is important for calculating the flight path of aircraft.

These guidelines, written in the style of a submission to J. Phys.: Conf. Ser., show the best layout for your paper using Microsoft Word. If you don’t wish to use the Word template provided, please use the following page setup measurements.
2. OTHR in USSR/Russia and Australia

2.1. DUGA-2 (USSR)
USSR had also studied OTH systems starting as early as the 1950s. Serious Soviet project was DUGA-2, built outside Nikolayev on the Black Sea coast near Odessa. [2] Aimed eastward, DUGA-2 first ran on 7 November 1971, and was successfully used to track missile launches from the Far East and Pacific Ocean to the testing ground on Novaya Zemlya. This was followed by their first operational system DUGA-3 known in the West as STEEL YARD which first broadcast in 1976. Built outside Gomel, near Chernobyl, Ukraine, it was aimed northward and covered the continental United States. Its loud and repetitive pulses in the middle of the shortwave radio bands led to it being known as the "Russian Woodpecker" by amateur radio (ham) operators. The Soviets eventually shifted the frequencies they used, without admitting they were even the source, largely due to its interference with certain long-range air-to-ground communications used by commercial airliners. A second system was set up in Far East, also covering the continental United States, as well as Alaska.

2.2. KONTAYNER (Russia)
In early 2014, the Russians announced a new system, called 'Контейнер' [KONTAYNER] that is designed for a range or over 3000 km. This radar is thought to be the type termed 29B6. It is understood that this radar was turned on in December 2013 [3].

The Department of Information and Mass Communications of Russia of the Ministry of Defense on December 1, 2019 announced the interception of the “Container” overhead detection radar station on combat alert. [4] Since December 1, 2018, the radar has been on pilot combat duty; in 2019, it successfully passed state tests and entered service. The radar detects the mass take-off of aviation and cruise missiles, determines the trajectory parameters of individual targets, such as tactical and strategic aviation aircraft, hypersonic aircraft and aircraft made using the Stealth technology. Information on the ionospheric support of the radar in open sources could not be found, however, there is reason to believe that there is a technology of reciprocating-tilting sounding of the ionosphere. Such technology was implemented in the Krug radar, which served the 5H32 Duga over-the-horizon radar (Chernobyl), the predecessor of the Container. Since the Ministry of Defense does not report the presence of remote positions, this procedure is probably implemented in the operating mode of the radar itself on the same hardware as the detection mode.
2.3. JORN (Australia)
In any case, at least one successfully working system for over-the-horizon detection is known. This is the Jindalee Operational Radar Network (JORN) in Australia.

There are three radar stations in the network, each consisting of a separate transmitter and receiver separated by some hundreds of kilometers. This ensures that there is no interference between outgoing and incoming signals. JORN consists of: two active radar stations: one near Longreach, Queensland (JOR1) and a second near Laverton, Western Australia (JOR2); a control center at RAAF Base Edinburgh in South Australia (JCC); seven transponders; and twelve vertical ionosondes distributed around Australia and its territories. See below map for locations.

DSTO uses a radar station near Alice Springs, Northern Territory (JFAS) for research and development and also has its own network of vertical/oblique ionosondes for research purposes. The Alice Springs radar can be patched into the JORN to provide a third active radar station [5].

![Figure 2. Locations of the JORN Radar Stations and the areas covered.
Image: Key Publications Ltd Aviation Forum.](image)

The Jindalee story is well documented however the high security status of JORN makes some data difficult, if not impossible, to obtain. Only time will rectify this limitation.

A related issue is the need to bring the public knowledge of Jindalee more into the public domain. All Australians should be proud to live under the watchful eye of Jindalee, a truly amazing Australian invention which should be as well-known as Vegemite, Australia II and the Sunshine harvester. Achieving this remains a challenge for Engineers Australia and Engineering Heritage Australia.

Australian scientists and engineers, primarily from the Defence Science and Technology Organisation (DSTO) who persisted and achieved the breakthrough represented by the Jindalee Project. Perhaps this breakthrough would never have been possible before the advent of larger digital computers and the technology which saw solid-state radar receivers become a reality.

Despite the commissioning of JORN in 2003 the technology is far from mature. Scientists are now looking for improvements of greater range, an order of magnitude increase in resolution and other developments [6].

The challenge for Australian scientists now is to remain in the vanguard, and retain their reputation as the premier OTHR scientists on the planet.

For a country like Australia, with its huge land and sea areas to patrol, but supported by a relatively small economy the technical achievements of Jindalee are even more breathtaking.
The JORN radar system is regarded at the most capable radar in the world.

Few countries have attempted to build and operate an Over-the-horizon radar network and none has achieved such a comprehensive and competent coverage as Australia has achieved, covering all our northern approaches out to a range of 3000 - 4000 km.

JORN/Jindalee is unique and the existing system should be retained for posterity when its present operational use is over. It may be Australia’s most significant technological feat, is unique in Australia and rare in global sense.

3. Ionosphere support system

Thus, we can conclude that the ionosphere system of the radar should include ionosondes of vertical and inclined sounding of the ionosphere. Such a system should be optimal in terms of technical and economic components. For the correct operation of the radar, information on the parameters of the ionosphere in the reflection zone of radio waves is necessary. This will allow you to choose the operating frequency at which the signal is most effective at the required range, and the exact value of the effective height of the reflecting layer will minimize the error in determining the coordinates of an air target.

In an ideal system, vertical ionosondes are located in large numbers in the reflection zone from the ionosphere, and oblique ionosondes in the constructive viewing zone. However, the placement of an unlimited number of vertical ionosondes in the reflection zone is impossible for both economic and technical reasons, and inclined ionosondes in this case fall on the territory of other countries, which also makes them impossible to place.

In an optimal system of ionospheric support for a radar station with a 60° azimuth, minimum of four vertically inclined ionosondes, the arrangement of which is conventionally shown in Figure 3, is enough, the analysis showed that the ionosphere at middle and low latitudes can be considered relatively unchanged at a distance of about 500 km, so-called area of responsibility of the ionosonde. Four vertical ionosonde located at the corners of the reflection zone will be the most informative sources, according to the current data of which the regional model of the ionosphere is adjusted. Inclined sounding between the ionosonde will supplement with fairly reliable data on the zones between them, and sounding along the ionosonde-radarg path, although it does not provide separate useful information, can also be used to correct the model.

Figure 3. Optimal ionosphere support system

The procedure for selecting the operating frequency is divided into three stages: the exclusion of forbidden frequencies, the choice of free frequencies, tuning according to ionospheric conditions.
3.1. Exclusion of forbidden frequencies

The regulation of the use of the radio frequency spectrum in Russia is regulated by the Federal Law of 07.07.2003 № 126-ФЗ (as amended on 06.06.2019) “On Communications” (as amended and additional, entered into force on 01/01/2019). The distribution of radio frequencies among users is determined by Decree of the Government of the Russian Federation dated September 18, 2019 No. 1203-47 “On approval of the Table of distribution of radio frequency bands between radio services of the Russian Federation and recognition as invalid of certain decisions of the Government of the Russian Federation”. The decree determines the frequencies at which radiation is strictly prohibited. These are dedicated channels of the land, naval and air armed forces of Russia, channels of radio navigation, radio astronomy, space communications, etc.

The allocation of radio frequency bands is carried out by the State Commission on Radio Frequencies (SCRF), and the decision to assign radio frequencies or radio frequency channels for civilian RES is made by Roskomnadzor, with the supervisor is the Federal State Unitary Enterprise “Main Radio Frequency Center” (FSUE “State Reserves Center”). Thus, on the basis of laws and regulations, a list of frequencies is determined that are excluded from further selection of the working frequency of the radar.

3.2. Exclusion of occupied frequencies

Popov’s invention of the method of wireless transmission of information through radio waves in 1898 laid the foundation for the development of radio facilities. The organizations mentioned above regulate the operation of radio facilities not only to determine forbidden frequencies, but also to determine specific subbands for specific purposes, such as cellular networks, walkie-talkies, etc. For the operation of over-the-horizon radar, a short-wave band is suitable in which reflection of radio waves from ionosphere. However, short waves are also used for other purposes, for example, radio communications, broadcasting, etc. In order to comply with electromagnetic compatibility, many radio systems use a search channel for working channels.

The task of such a system is to check the necessary frequency range for the presence of signals from other sources, which radar radiation can interfere with, or which themselves can interfere with the station. Depending on the current need, this can be a check in the entire available range of operating frequencies or in a small range selected for operation at a particular moment in time.

After taking a panorama, an analysis is performed, i.e. comparing the received signals with a given threshold, regarding which a conclusion is drawn about the presence of a radiation source or its absence. All frequencies at which the presence of a signal is recognized are excluded from further work. An example of the result of the search procedure for working channels in the frequency range from 1 to 20 MHz is shown in Figure 4. Thus, the search procedure for working channels allows you to determine a list of frequencies that are currently free and suitable for use.

![Figure 4. Frequency distribution diagram](image)
3.3. Adjustment for heliogeophysical conditions

The choice of the operating operating frequency does not end with the exclusion of prohibited and occupied subbands. The ionosphere has a considerable influence on the operation of radar.

For the over-the-horizon radar to work effectively, it is important to have real-time propagation path characteristics, as well as frequency band occupancy data. It is also important that the environmental parameters are optimally consistent with the radar parameters. For the initial assessment of the ionosphere parameters, a regional model of the ionosphere is used, which is corrected by the results of vertically inclined sounding. This method is widely used in over-the-horizon radar. So, one of the possible solutions to the problem of matching the radar parameters (such as the operating frequency) with the characteristics of the propagation path (amplitude-frequency and range-frequency) consists in introducing into the radar a special path for determining the optimal operating frequency sub-band. The purpose of this path is to select a frequency sub-band in which attenuation on the propagation path is minimal in order to optimize the operation of the useful signal detection path. The basic information that is used in such a path is based on the dependence of the amplitudes of the signals of reciprocating sensing and the magnitude of the delays on the operating frequency. These dependencies are determined by the amplitude-frequency and range-frequency characteristics. Structurally, this path can be an independent radar, which is part of the main radar, with its pathogen and individual receiving devices. As, for example, the Krug radar, which was part of the over-the-horizon 5N32 Duga radar (Chernobyl). Also, this path is implemented in the operating mode of the radar itself on the same hardware as the detection, this mode performs reciprocating sensing and refines the parameters of the radar.

4. Ionosphere research

As a primary assessment of the state of the ionosphere, it is possible to use a statistical method, for example, the ionosphere model IRI-2016 (International Reference of Ionosphere). This system allows you to simulate and find out the parameters of the ionosphere in a particular place and at a specific time. It is a global median model of the ionosphere (that is, it allows you to build long-term forecasts anywhere in the world). It has a rather high accuracy of long-term forecast when compared with actual vertical sounding data.

The most complete and easily interpreted information about the state below the maximum electron concentration of the ionosphere is provided by vertical radio sounding of the ionosphere. The main advantage of the VZ method is the possibility of obtaining the profile of the electron concentration of the lower ionosphere (N (h) profile) from direct measurements using model ideas only about the electron concentration depression unobservable during vertical sounding between regions E and F. The accuracy of obtaining the N (h) profile From vertical sounding data, it has been verified by many years of research and is a reference in the absence of direct rocket measurements. The disadvantage of the vertical sounding method, which is compensated by the installation of a network of stations, is the locality of the method, and the on-line presentation of data on the Internet global network allows them to be used to solve most applied problems.

The method of oblique radio sounding of the ionosphere, the essence of which is the spatial separation of the receiving and transmitting systems of the ionosonde and synchronizing the processes of radiation and reception, makes it possible in principle to directly experimentally study the propagation of radio waves at a fixed distance, and to assess the state of the ionosphere in the region of the midpoint of a radio path with single-hop propagation. If the frequency change occurs over a sufficiently wide range, the result is an ionogram of oblique radio sounding of the ionosphere, which reflects the frequency dependence of the group delay of signals transmitted in various ways in the ionosphere at the receiving point, i.e. mode structure of the wave field.

Since 2011, a network of vertical ionosphere radio sounding stations has been actively deployed in Russia, based on the latest domestic-made ionosondes. Currently, ten such stations are deployed throughout the country: from Kaliningrad to Kamchatka. During the entire period of operation in round-the-clock mode, the ionosondes deliver every 15 minutes up-to-date information on the state of the ionosphere. The carried out modernization and subsequent experiments showed that these ionosonde are also capable of performing oblique sounding. This result was achieved by linking all individual stations
to the Single Time System (SEV), as well as a powerful emitter (10 kW), the signal of which propagates through the side lobes of the radiation pattern and can be received at a distance of up to 2000 km [7].

4.1. Combined sounding of the ionosphere
The author was given the opportunity to conduct an experiment on oblique sounding of the ionosphere on the equipment of the Roshydromet ionosphere monitoring network. In total, at present, ten such ionosondes have been deployed: Troitsk, Rostov-on-Don, Elektroguly, Podkamennaya Tunguska, Magadan, Kaliningrad, Salekhard, Novosibirsk, Khabarovsk, Petropavlovsk-Kamchatsky. Since the task of the network ionosonde is to continuously deliver sensing results to interested subscribers, it is not possible to disable it. The opportunity to conduct an experiment appears during servicing and in cases where this does not interfere with its regular operation. As a result, a completely unique result was obtained, expressed in that traces of oblique sounding are superimposed on traces of vertical reflection (the so-called combined sounding) [8].

An example of combined sounding of the ionosphere is presented in Figure 5. In the figure, in addition to the ionogram of vertical sounding, there are also so-called “Repeaters”. Such reflections are obtained when pulses pass from 2 to 3 times (and sometimes more) between the station and the ionosphere. In addition to the ordinary component (red - on the left), the ionosonde also detects the non-ordinary (polarized) component (green). The unusual component repeats the dependence of the ordinary, the frequency shift is due to the influence of the geomagnetic field.

The most interesting in the figure are the tracks starting at a frequency of ~ 6 MHz and located at an altitude of 500 km. These are the results of receiving a signal from another ionosonde, namely: the Parus-A ionosonde receiver located in Moscow registers the traces of the Parus-A transmitter located in Kaliningrad, and vice versa. The distance between the ionosondes is 952 km. Altitudes of 600 km are determined by the fact that the ionosonde measures not the altitude directly, but the signal delay. Some other experimental results are presented in the works of the author published earlier [9].

5. Determination of propagation conditions of radio waves
A review of radiophysical methods of ionospheric observations indicates that the determination of the parameters of the ionosphere and the forecast of ionospheric disturbances remains a serious and urgent problem. Only recently, due to the advent of space tomography of the ionosphere, a general understanding of the dynamics of changes in the electron concentration in the ionosphere has appeared,
while the properties of ionospheric disturbances are not clear enough for reliable modeling, there are no statistically verified data on the parameters of ionospheric plasma inhomogeneities, especially about the characteristics of their motion.

In Russia, the functions of monitoring the heliogeophysical situation are distributed between Roshydromet in the person of the IPG, which is responsible for monitoring the ionosphere and the Scientific Research Institute of the Russian Academy of Sciences (IZMIRAN, IKI, ISZF SB RAS, etc.), which are responsible for solar activity. Space and ground-based means measuring the necessary characteristics of solar activity are poorly presented at the Scientific Research Institute of the Russian Academy of Sciences, for the most part information on solar activity is taken on the Internet from foreign sites. As for IPG ionosondes, it is likely that they are located away from the control zone required for an over-the-horizon radar. The operating mode of these ionosondes is strictly regulated - once every 15 minutes the stations go to the vertical sounding of the ionosphere and, after a short time of processing the received information, delivers the data in clear form to the Internet. Such data can be of great help in adjusting the global ionosphere model. Also now, the Parus-A ionosonde of this network is conducting successful experiments on oblique sounding, which is also promising from the point of view of using the ionosphere. Regularly working lines of oblique sounding are in the circumpolar region as part of the Institute of the Arctic and Antarctic.

Given the existing ionospheric stations, it makes sense to create autonomous monitoring tools for specific over-the-horizon radars. This follows from the indicators of technical and economic criteria (cost and quality of measuring instruments), the need to ensure regular work at a given pace and format. In the future, all the information obtained by these complexes of geophysical means can be combined in a central control point and used by all interested radio-electronic and optical means of the Ministry of Defense of the Russian Federation.

Let us consider the structure of construction and the composition of the system for determining the propagation conditions of radio waves presented in 6.

**Figure 6.** System for determining the propagation conditions of radio waves

The composition of the ionosphere parameter measuring instruments includes ionosondes of vertical and inclined sensing, placed according to the developed ionosphere support system where the territory
and the possibilities for its maintenance allow. The external heliogeophysical data necessary for the operation of the global dynamic model of the ionosphere comes from the official control services of the ionosphere, magnetosphere and the Sun, which are responsible for providing input information on the solar and magnetic activity of the ionosphere model. In addition to data on the Sun, magnetometer data are used for forecasting, information from which is also a harbinger of the beginning of disturbances in the ionosphere. In addition to geophysical data acquired from a system that is part of over-the-horizon radars, various additional geophysical data may come from other ionosondes from the regions of the control zone or the ones closest to them.

6. Conclusion

Own ionospheric support system for over-the-horizon radars is urgently needed, since the radar monitoring zone extends far from the station itself, the existing heliogeophysical sensors do not always meet the requirements, and the supply of heliogeophysical data from official services is associated with certain difficulties.

Such a system includes ionosondes of vertical and inclined sensing, a hardware-software complex, etc., the exact placement of the positions made is determined in each case.

The main purpose of this system is to increase the reliability and accuracy of the operation of an over-the-horizon radar station in various heliogeophysical conditions.

Already existing near-horizon detection radars, in the absence of their own ionosphere support system, can use Roshydromet ionosphere stations to determine the ionosphere parameters, which, according to available information, fall into the radar's zone of interest.

7. References

[1] Laurie P An eye on the enemy over the horizon (New Scientist, 7 November 1974, pp. 420–423)
[2] Pike J Steel Yard OTHR (Retrieved 8 April 2010, www.global.security.org)
[3] Diario A 29B6: Russian FMP OTH Radar KONTAYNER
[4] Chief of the General Staff of the Russian Armed Forces - First Deputy Minister of Defence General of the Army Valery Gerasimov meets with representatives of the military diplomatic corps accredited in Russia. https://eng.mil.ru/en/news_page/country/more.htm?id=12267331@eNews
[5] Jindalee Over-the-horizon Radar (Nomination for Heritage Recognition, May 2016, p. 79)
[6] Wise J C 2004 Summary of recent Australian radar developments (IEEE Aerospace and Electronic Systems Magazine 12 pp. 8-10)
[7] Litvinov S V, Panshin E A, Kachanovskii Yu M and Alekseeva A V 2019 Analysis of possible improvements of Roshydromet's government network ionozond "Parus-A" (Heliogeophysical studies. Issue 21 P 32–39)
[8] Givishvili G V, Krasheninnikov I V, Leschenko L N, Vlasov Yu M and Kuzmin A V 2013 Ionosonde "Parus-A": Features and Prospects (Heliophysical research, Issue 4 P 68–74)
[9] Vlasov Yu M, Glinkin I A and Litvinov S V 2018 Application of oblique ionospheric sounding to increase the accuracy characteristics of the over-the-horizon radar (Questions of Radio Electronics 3 pp 11-18)
[10] Saun G JP 2025 - Jindalee Operational Radar Network (JORN) Projects. Defence Materiel Organisation. Australian Department of Defence. (15 July 2009. Retrieved 19 March 2014)