About Expanding Marine Radar Possibilities

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Abstract. The advantages and limitations of methods and tools for monitoring the main parameters of the sea surface by HF radars are discussed. Methods and technical tools used in the HF range and for monitoring natural environments, including both the marine environment and the ionosphere, are compared. Their main parameters and significant differences of methods, instruments and mathematical data processing are noted. The main characteristics of the WERA and CODAR marine HF radars are given. The results of a two-point trial experiment in the vicinity of Gelendzhik were used to substantiate the methodology and instrumental solutions in order to create a domestic complex of observations in the water area of Novorossiysk. Based on the experiments carried out with both foreign and domestic radars, methods of increasing the efficiency of such radars due to their operation in the entire sounding frequency range are considered. Tests of the prototype of the multi-frequency locator confirmed the possibility of its functioning both in autonomous operation and as part of a geophysical complex, while solving a wide range of problems. In contrast to radars of the WERA and CODAR types, operating at one of the given sounding frequency, measurements can be carried out in a wide frequency range, which makes it possible to construct the fields of current velocities and sea surface waves in an extended range of distances at an appropriate resolution and determine the vertical profile of flows.

1. Introduction

Intensification of economic and military-industrial activities in local and global waters requires continuous monitoring of the sea surface state. One of the means of such monitoring is the use of HF radars, which are constantly being improved.

The first surface wave radar was used in England at a frequency of about 25 MHz since 1938 to be protected from German air raids. During the operation of this radar, in addition to the signals reflected from the aircraft, intense echoes were sometimes recorded. These signals initially were taken for interference by German anti-radar equipment. In fact, they turned out to be Bragg echo scattering when reflected from the periodic structure of the sea surface. In 1955, Crombie [1] described the physical foundations of the scattering of electromagnetic waves from a moving sea surface and experimentally established that the sea waves caused a noticeable scattering of HF radio waves of the first kind when emitting waves of vertical polarization. In 1965, he found that some reflected HF signals have a Doppler shift of less than one Hz above and below the sounding signal frequency.
Subsequently, HF radars have evolved in two ways. The first way led to the creation of a small-sized HFR-direction finder based on the developments of Barrick [2, 3], which underlies the CODAR radar. The transition from full-size antennas to compact ones, when the antenna elements make up a small fraction of the wave, turned out to be possible when compensating for the decrease in antenna efficiency due to the use of antenna amplifiers, since the decrease in the effective antenna height is proportional to the decrease in the noise level. Such transition is permissible as long as the internal noise of the receiving circuit is not will exceed external interference. This is possible in the HF range, where external noise exceeds internal noise by 40 - 70 dB. The main advantage of these solutions is a possibility to create an equipment with an antenna of relatively low cost and dimensions. This allows installing such radars on almost any area of the coast. In this case, it is possible to increase reliability of identification of reflected signals due to a connection of individual radars into a synchronized network, that is, to provide multi-point location.

The second way is characterized by the use of a phased array antenna (PAA) with a sufficiently powerful pulse transmitter, sensitive receiver and software for optimal signal processing. The main variants of such HFRs are WERA radars [4 - 10], designed to determine the parameters of sea waves and operating at one of fixed frequencies in the range from 3 to 50 MHz. The advantage of the phased array scheme is the possibility to obtain a narrow adjustable radiation pattern. The main disadvantages are associated with the large area occupied by the antennas and the rather big price of the radar. Additional difficulties are associated with the dependence of the parameters on climatic conditions, the need for protection against vandalism, and the complex tuning of the antenna-feeders.

As an example, table 1 shows the typical characteristics of such radars operating at one of the fixed frequencies [6].

| Observable          | Typical performance |
|---------------------|---------------------|
|                     | low-cost civil radar | military radar    |
|                     | Max. range (km) | accuracy | Max. range (km) | accuracy |
| Surface current     | 60 - 200          | 0.02 – 0.2 m/s | 350 - 450        | 0.02 – 1.0 m/s |
| Wave height         | 300 - 100         | 10 – 25 %     | 150 - 250        | 10 – 20 %     |
| Wind direction      | 50 - 150          | 30° - 60°     | 320 - 400        | 20° - 30°     |
| Wind speed          | 300 - 100         | 20 %          | 200 - 250        | 20 %          |

A significant disadvantage of fixed frequency radars is the impossibility to provide a potentially possible resolution and a sufficient range of distances with one measuring complex. At the same time, for most of the water areas, it is necessary to monitor the sea surface, both at a distance and in the near zone with the limited size of the free coastline. That is, to solve the problem, it is necessary to install several complexes with different sounding frequencies. The situation is dramatically worsening by limiting the length of the coastline sections suitable for installing radars.

By this time, in a number of experiments with civilian and military radars, ionospheric signals were already observed on marine radars and reflections from the sea during sounding of the ionosphere. It turned out that one and the same radar can receive information about the sea surface in a wide frequency range. So, in experiments on ships of the Academy of Sciences of the USSR, ionosondes (ionospheric radars) registered simultaneously ionograms, containing the ionospheric information, and the regular signals reflected from the sea. Figure 1 shows, that in a wide frequency range, there are diffuse reflections from the sea surface, grouping depending on the nature of waves and currents [11].

Near the meridian of 15°, there are several ionospheric stations, which allow us to trace the latitudinal dependence of the influence of space weather on the ionosphere. With higher resolution, this effect can be traced using TEC, since TEC shows the latitude of the transition from positive/negative to negative/positive phase.
Figure 1. Examples of ionograms with reflections from the sea surface recorded during the ship Akademik Korolev cruises in 1979 - 1982 (trips 26 – 31 Pacific Ocean, Western equatorial region) by the AIS ionosonde. Frequency labels (horizontally) are through 1 MHz, Altitude (distance) - through 50 km.

HF surface wave radars - High Frequency Sea Wave Radar (HFSWR) - due to the common radio range, methods of transmitting and receiving radio signals, receiving and recording equipment and information processing facilities, were developed in parallel with the improvement of technical tools for studying the ionosphere. Now, for remote sensing of the ocean surface, the HF radio frequency range is used, the advantages and disadvantages of which are presented in table 2.

Table 2. Advantages and disadvantages of using the HF range.

| advantages | disadvantages |
|------------|---------------|
| 1 range of observation in the lower part - up to 300 km due to surface wave refraction; monitoring area - up to a thousand square km; spatial resolution depending on the sounding frequency - from kilometers to hundreds of meters | high level of interference from broadcasting, office, amateur near and far radio stations, which is explained by both surface and ionospheric propagation of radio waves |
| 2 the length of the emitted wave is commensurate with the characteristics of the waves, which makes it possible to use physical laws (Bragg, Buster, Doppler) when determining the direction, flow velocity and wave height | the need of additional cleaning of signals reflected from the sea surface, both from interference of HF radio stations and instrumental noises |
| 3 many years of research experience, proven measurement techniques and continuously improving technologies for monitoring, processing measurements and analyzing results | difficulties in analyzing the sounding results due to the nonlinearity of sea surfaces, the depth of the reservoir, the dependence on the salinity (conductivity) of water |
| 4 when using complex signals (usually chirp probing), the radiated power can be reduced to tens of watts | the need to issue a permit for radiation in the frequency range |

At present, this idea has been implemented in the development of a "small-sized multi-frequency radar (MFR)" Vector" of decimeter range, intended for monitoring the ocean and ionosphere" in a wide frequency range [12-17]. The MFR operates in the frequency range from 1 to 25 MHz (with an extension to 40 MHz), includes the formation of broadband sounding signals and the processing of echo signals reflected from the sea surface.

2. Statement of the problem
The task is to use the results of a two-point experiment carried out in 2015 in the vicinity of Gelendzhik with the help of the "Vector" MFR model to assess the possibility of expanding the
frequency range. A feature of the experiment was the limitation of the area along the front for installing the antenna array and significant glide angles of the beam.

3. Solution of the problem
The solution to the problem is associated with the improvement of software: the development of algorithms and programs for digital signal processing and algorithms for the operational control of the receiving and transmitting complex. Both transmitting and receiving circuits, antennas are designed to work in a wide frequency range and are based on modern circuitry. The operator can select the type of modulation (for example, chirp, Barker code), the quantitative ratios of the probing signal, the number of receiving channels (up to 16) and the modes of processing echo signals. To compensate for the effects of radio interference of different classes, memorization of "noisy" parts of the range and automatic selection of probing frequencies and modes of the "floating threshold" type are provided.

An assessment of the potential capabilities of such a system for monitoring the sea surface and the actual results of experiments (crosses) are shown in Figure 2.

Blue and light blue lines represent calculated (model) values for the spatial range and resolution (km) in the frequency range of sounding frequencies (MHz), green circles are generalized literature data for the WERA radar, crosses - measurements (at the Southern Branch of Institute of Oceanology of the Russian Academy of Sciences) on the prototype of a multi-frequency radar.

![Figure 2](image)

**Figure 2.** Evaluation of the dependence of the range on the frequency of sounding for the model of a multi-frequency radar based on the results of trial experiments.

It is seen that the principle of multi-frequency sounding can be successfully implemented.

4. Conclusion
Based on the experiments carried out with the model of a multi-frequency HF radar, the possibility of increasing the radar efficiency was confirmed, which consists in the fact that on a smaller section of the coastal site, when operating in the entire range of sounding frequencies from a few MHz to tens of MHz, obtaining the field of currents and waves on the sea surface in range at the appropriate resolution is provided. Such a radar has a number of advantages [18]: it uses complex signals (chirp, FCM) with autocorrelation functions that have a (characteristic) high ratio of the main lobe to the side lobes; signal generator provides various shapes and durations of probing signals; broadband active receiving antennas are used; two-position monitoring and remote transmission of measurement results to consumers are possible.

The radar allows constructing an experimental model of the vector field of surface currents velocities and covers an area with an outer boundary from 100 to 200 km from the coast and provides
measurement of: wave characteristics (ball and amplitude, space-time spectrum); flow velocity towards the conventional center of the receiving antenna; direction and speed of the current as part of a complex consisting of two or more radars; vertical profile of currents to a depth of 4 m.

In recent years, HF radars are more and more widely used all over the world: systems of 50 radars have been created in Europe [19], an American system of 150 radars operating along the coast from Canada to Mexico [20], systems in Asia [18], India [21]. Using the principle of multi-frequency radar will allow obtaining more information on a limited coastal area and conducting more accurate monitoring of the sea surface in large water areas.

In 2021, it is planned to conduct joint experiments with WERA radars and a prototype of a multi-frequency marine radar for comparative tests of the complex at the proving grounds of the Southern Branch of Institute of Oceanology of the Russian Academy of Sciences and Southern Federal University.

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