ATTENUATION OF ELECTROMAGNETIC WAVES IN LIQUID FOAMS IN THE FREQUENCY RANGE OF 1 – 1250 MHz

O. O. Drobakhin, L. A. Filins'kyy*

Oles Honchar Dnipro National University, Dnipro, Ukraine
**e-mail: leonidfil2016@gmail.com*

The purpose of this work is to study the attenuation of electromagnetic waves in the megahertz range (1 – 1250 MHz) in liquid foam structures. We consider issues related to shielding electromagnetic sources and reducing the visibility of metal objects from radar detection and tracking in this range, since such problem is poorly researched. A method of measuring the attenuation of foam structures in segments of strip lines of this range is proposed. Measurements are carried out using an experimental setup based on a vector meter and an original strip cell of samples of foam structures with different foaming ratios in the ranges of 13 – 15, 28 – 30, and 50 – 51 units for different foaming agents. The dependencies of foam attenuation on frequency and the dependence on salt additives with concentrations of 1%, 4%, and 6% are found.

Keywords: attenuation, multi-frequency measurements, foam, foam structure, liquid foam.

Received 03.11.2023; Received in revised form 28.12.2023; Accepted 15.12.2023

1. Introduction

The usual characteristics of foam formations at sea were widely known to people whose lives related to the sea. But only in 1955, G. F. Williams [1] published an article that drew the attention of scientists to an extraordinary new effect of foam formations. Thus, when the wind speed increased more than 7 meters per second, it increased emissivity of the sea surface in an ultra-wide range of frequencies compared to the surface of clean water. This effect depended entirely on the amount of foam formed.

This publication opened a new direction of scientific research. It focused on remote studies of the emissivity of the surface of seas and oceans in the ranges of electromagnetic waves with the help of aircraft, space vehicles and laboratory research.

After the first publication, many others were appeared, but we would like to dwell on only some of them. Thus, A. Stogryn in 1971 published material on the emissivity of sea foam at microwave frequencies [2], M. D. Anguelova, P. W. Gaiser, and V. Raizer [3] in 2009 considered the issue of foam emissivity models for microwave observations of oceans from space.

V. Raizer in 2012 [4] and in 2013 [5], considers scattering models in sea foam. R. Jiang, P. Xu, K.-S. Chen, S. Tjuatja and X. Wu [6] in 2018 also addressed the issue of microwave scattering by wind-blown foam on the ocean surface.

In 2019, M. D. Anguelova and M. H. Bettenhausen published a very significant results of research [7], which summarized the achievements of many years of research performed on the modern material base.

In 2020 in [8], the emissivity of the foam layer was simulated at different wind speeds and frequencies by X. Huang, S. Tjuatja, Z. Wang and J. Zhu. The considered model of incoherent multiple scattering showed better correlation at frequencies of 36.5 GHz and 6.9 GHz at wind speeds from 5 m/s to 30 m/s.

The results of very important research on nondestructive testing of the space shuttle external tank foam insulation using near field and focused millimeter wave techniques were published in [9, 10] under the leadership of S. Kharkovsky. These results of research and many others were continued with the use of holographic subsurface radar for nondestructive testing [11-13].

Very voluminous studies were reflected in paper [14]. The results of these experimental studies refer to the dielectric properties of water foam samples in a very wide microwave range of 2.5 – 3.5, 5.6 – 8.3, and 8 – 12 GHz.

In these experimental studies reflected in [15], calculations of ε and tgδ were performed based on the characteristics of VSWR and attenuation of electromagnetic waves in the corresponding samples of foam structures that filled the cross section of the waveguides.

In recent years, instead of natural foams, more and more research are being conducted on artificial foam structures. Thus, in publication [16], great attention was paid to the study of the electrical characteristics of polyurethane foams.

The aim of paper [17] was to investigate the effect of the foam layer on the propagation of microwaves at 6 and 26 GHz depending on the diameter of the bubbles, the foaming ratio of the foam layers and the properties of the material.

Using the radar measurements [18] in millimeter range, the reflection from the foam surface was studied. It was found that the finer the foam, the stronger the reflection from the surface of the foam, but the weaker the reflection from the surface of the liquid with a layer of foam.

The article [19] can be called one of the first works on the study of foam structures in a biconical resonator It considers two ways of turning on a biconical resonator. This is when the biconical resonator is included in the measurement schemes in the cases of "transmission" and "reflection" to determine the possibility of studying the characteristics of foam structures in stationary and dynamic conditions.

The latest publications [20-22] published the results of scientific research in the millimeter range. A multi-frequency method with the implementation of the Fourier holographic principle [23, 24] was used. The measurements showed that the reflection of electromagnetic waves from a layer of foam structure placed on a metal substrate was very small. This demonstrated the possibility of masking metal objects with a foam layer.

The purpose of our study is to measure the attenuation value of foam samples with different foaming ratio β from 10 to 85 and with the addition of 1, 4 and 6% salt in the frequency range from 1 to 1250 MHz.

2. The foam samples and experimental cell for research

Foam samples for research were prepared on a foam generator with grids. The last grid corresponded to the required average bubble diameter. The foaming ratio of the foam was established using the necessary consumption of foaming liquid and gas (Fig. 1).

To conduct experimental research, a standard vector analyzer of the P4-11 type was used, for which a measuring cell of the segment of a symmetrical strip line shown in Fig. 2 was made. The measuring cell consisted of coaxial-strip junctions 1; strip line 2; contact for measuring foam resistance 3; plexiglass compartment for photography 4.

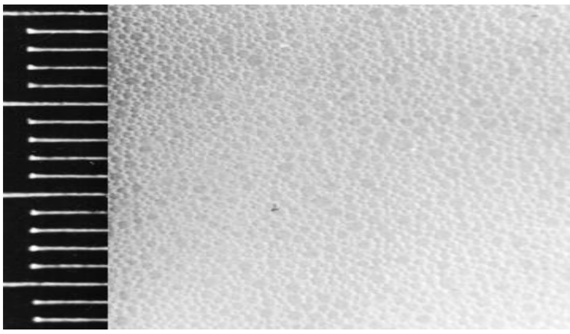

Fig.1. Foam sample.

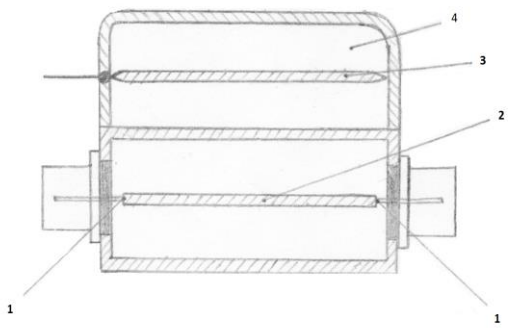

Fig. 2. Measuring cell.

The foaming liquid, which passed alternately through all the grates with the help of a gas jet, creates at the output of the foam generator foam of the required dispersion with an average foam dispersion of 0.1 – 1 mm (Fig. 1). Before starting the measurements, the foam generator was calibrated according to the foaming ratio of the obtained foam. The samples of foam structures were prepared at room temperature.

3. Experimental results

From the test study (Fig. 3) it can be seen that the attenuation in the empty cell is –0.6...–0.8 dB in the entire frequency range. This indicates a fairly high quality of the manufactured cell for measurements. The comparison of electromagnetic wave attenuation in distilled water with attenuation in soluble foam-forming substances in distilled water shows that up to 400 MHz, the attenuation values are almost negligible, and after 400 MHz molecules of surface-active foam-forming substances reduce the attenuation by several decibels compared to pure distilled water.

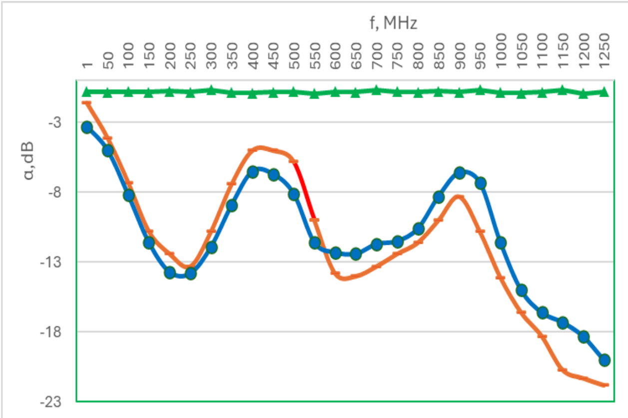

Fig. 3. Attenuation degree values for: Δ - dry cell; ─ - distilled water; ○ - foaming agent in water.

Figures 4 – 7 show the results of experimental measurements of the dependence of the foam attenuation when using different foaming liquids: PO-1, PO-2, PO-3, PO-4, which differ in the concentration of surface-active substances from 1 to 4 percent, respectively, in distilled water. The foam samples have a foaming ratio β of the following values: □ - β = 13 – 15, Δ - β = 28 – 30, : ○ - β = 50 – 51 units.

Figures 4 – 7 show the amplitude-frequency characteristics of electromagnetic wave attenuation on a symmetrical strip cell filled with foam samples of different foam densities. The lowest curve corresponds to the smallest foaming ratio β = 13 – 15 units, the middle curve corresponds to the foaming ratio β = 28 – 30 units, and the upper curve corresponds to the largest foaming ratio β = 50 – 51 units.

In all figures, except 6, the curves have the appearance of clearly resonant curves. The different curves of indicated figures have the largest attenuation in the regions of 450, 500, and 650 MHz, respectively, and the minimum attenuation in the regions 1 – 200 and 850 – 1200 MHz. In Fig. 6 the curves have the appearance of a transitional character, which indicates a non-sharp, but smooth dependence of the attenuation on the foaming ratio, which gradually shifts in frequency.

It can be seen from Fig. 4 that the attenuation values for PO-1 with a foaming ratio β = 13 – 15 units are in the range of –1...–4.8 dB, with a foaming ratio of β = 28 – 30 units – within the range of –0.75...–3.25 dB, and with a foaming ratio β = 50 – 51 units – from –0.6

to –2.25 dB. That is, the higher the foaming ratio, the less the electromagnetic wave attenuation.

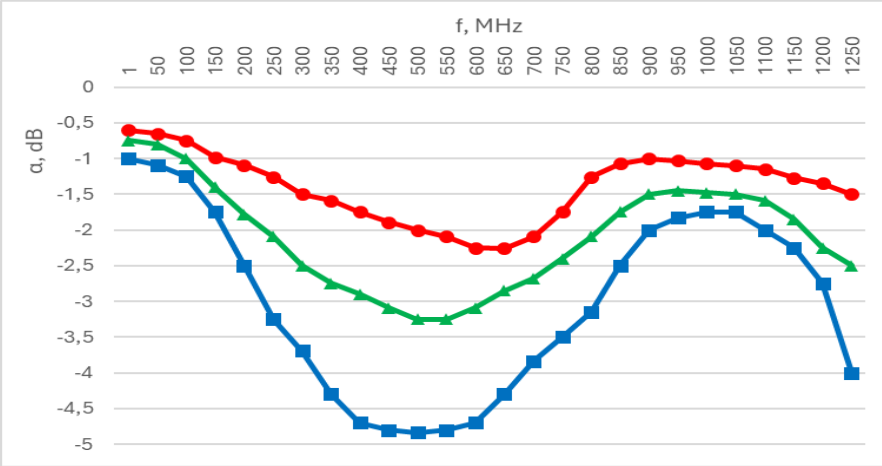

Fig. 4. Wave attenuation as a function of frequency for a foam sample based on PO-1 foaming agent. The foaming ratio β has the following values: □ - β = 13 – 15, Δ - β = 28 – 30, ○ - β = 50 – 51.

It can be seen from Fig. 5 that the attenuation values for PO-2 with a foaming ratio β = 13 – 15 units are in the range of –0.8 ... –3.9 dB, with a foaming ratio β = 28 – 30 units – within the range of –0.6...–2.4 dB, and with a foaming ratio β = 50 – 51 units – from –0.5 to –1.65 dB. That is, the higher the foaming ratio, the less attenuation of the electromagnetic wave in this case also.

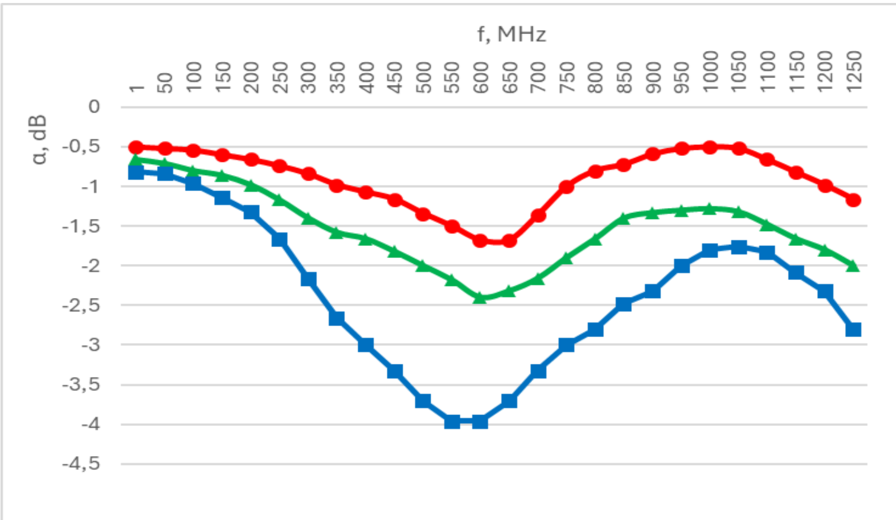

Fig. 5. Wave attenuation as a function of frequency for a foam sample based on PO-2 foaming agent. The foaming ratio β has the following values: □ - β = 13 – 15, Δ - β = 28 – 30, ○ - β = 50 – 51.

It can be seen from Fig. 6 that the attenuation values for PO-3 with a foaming ratio β = 13 – 15 units are in the range of –0.55...–2.25 dB, with a foaming ratio β = 28 – 30 units – within the range of –0.48...–1.5 dB, and with a foaming ratio β = 50 – 51 units – from –0.3 to –1.2 dB. That is, the higher the foaming ratio, the less attenuation of the electromagnetic wave. It is an important law for a foam.

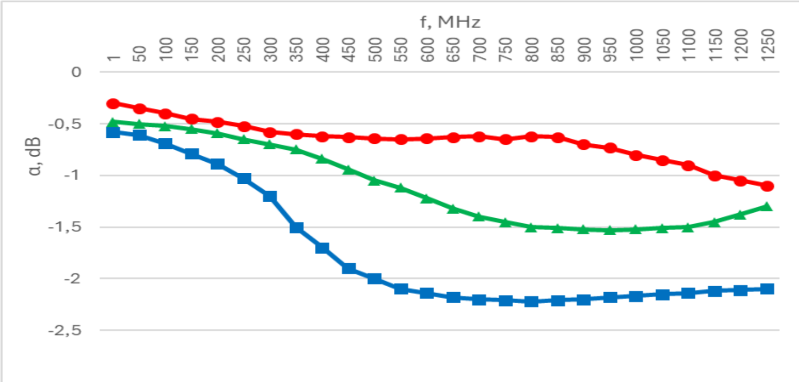

Fig. 6. Wave attenuation as a function of frequency for a foam sample based on PO-3 foaming agent. The foaming ratio β has the following values: □ - β = 13 – 15, Δ - β = 28 – 30, ○ - β = 50 – 51.

It can be seen from Fig. 7 that the attenuation values for PO-4 with a foaming ratio β = 13 – 15 units are in the range of –1.35 ... –5.8 dB, with a foaming ratio β = 28 – 30 units – within the range of –0.8... –3. 4 dB, and with a foaming ratio β = 50 – 51 units – from –0.5 to –2.2 dB.

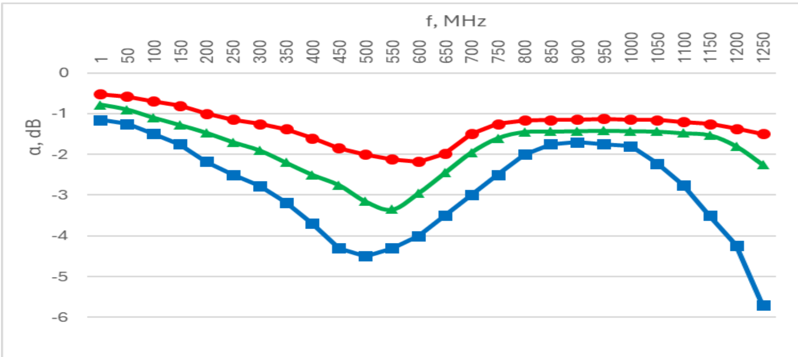

Fig. 7. Wave attenuation as a function of frequency for a foam sample based on PO-4 foaming agent. The foaming ratio β has the following values: □ - β = 13 – 15, Δ - β = 28 – 30, ○ - β = 50 – 51.

In Fig. 8, 9, and 10 the dependences of wave attenuation on frequency are shown for agent PO-4 at different foam ratios β (ratio ranges from 10 to 15, from 30 to 35, from 50 to 55, and from 80 to 85 units) with the addition of 1, 4 and 6% salt.

From Fig. 8, it can be determined that the amplitude-frequency characteristic of the attenuation of the foam sample with a foaming ratio β from 10 to 15 units in the range from 1 to 1250 MHz is within –3.5…–7.0 dB.

For a higher foaming ratio of the foam sample (from 30 to 35 units), the amplitude-frequency characteristic of the attenuation is already in the range from –2.5 to –5.4 dB. That is, with an increase in the foaming ratio of the foam, the damping decreases.

At the increase of the foaming ratio of the sample to values from 50 to 55 units, the amplitude-frequency characteristic of the attenuation proves to be in the range of –1.8…–4.2 dB. That is, with a further increase in the foaming ratio of the foam, the absolute value of the damping continues to decrease.

Finally, for the largest foaming ratio of the foam sample from 80 to 85 units, the attenuation value decreased to –1.5…–2.7 dB.

We can draw a general conclusion that for the addition of 1% of salt to the foam structure, the electromagnetic wave attenuation in it increases with increasing frequency for all foaming ratio ranges, but the dependence on the foaming ratio of the foam is inverse: the lower β, the greater attenuation growth (it reaches –7 dB), and for higher foaming ratio, the attenuation value barely reaches –2.7 dB per measuring cell length of 35 mm.

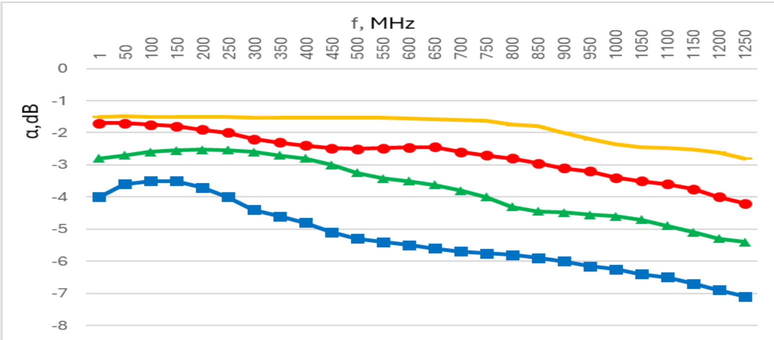

Fig. 8. Wave attenuation as a function of frequency for a foam sample based on PO-4 with the addition of 1% salt at foaming ratio β values: □ – 10 – 15, ∆ – 30 – 35, ○ – 50 – 55, ▬ – 80 – 85.

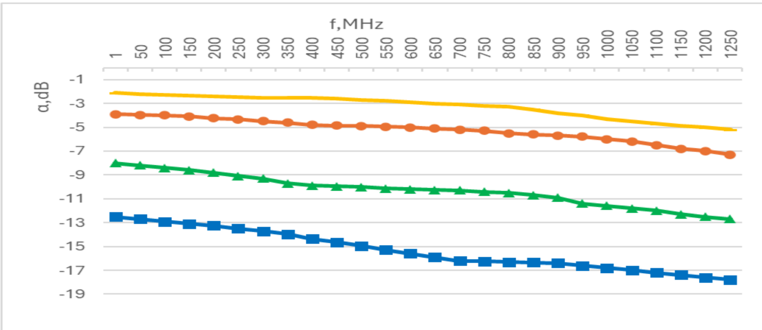

Fig. 9. Wave attenuation as a function of frequency for a foam sample based on PO-4 with the addition of 4% salt at foaming ratio β values: □ – 10 – 15, ∆ – 30 – 35, ○ – 50 – 55, ▬ – 80 – 85.

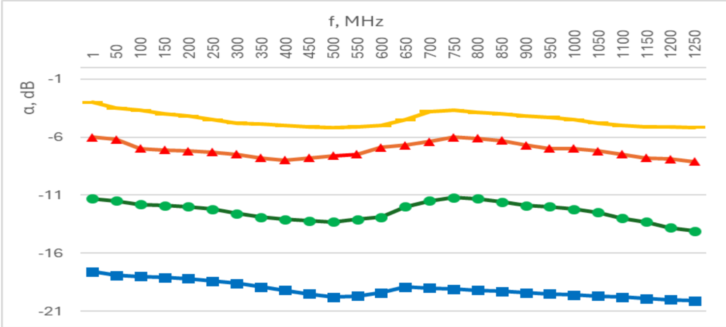

Fig. 10. Wave attenuation as a function of frequency for a foam sample based on PO-4 with the addition of 6% salt at foaming ratio β values: □ – 10 – 15, Δ – 30 – 35, ○ – 50 – 55, ▬ – 80 – 85.

In other words, adding 1% of salt to the foam structure increases its electrical conductivity for all foaming ratio ranges, and the maximum attenuation of –7 dB (Fig. 8) is achieved at the minimum foaming ratio. With the addition of 4% salt, the electrical conductivity of the foam increases even more, and even at the minimum foaming ratio, the maximum attenuation value of –18 dB is reached (Fig. 9). With the addition of 6% salt, the maximum attenuation already reaches the value of –20 dB (Fig. 10). That is, to obtain large attenuation values, it is necessary to create foam with a low foaming ratio and add substances that sufficiently increase its electrical conductivity (for example, using salt).

4. Conclusions

From the analysis of the results obtained because of numerical modeling, it is possible to determine the sensitivity of dimming, the addition of distortions in the dimming frequency, which can affect the generator, the transient attenuation of the signal, the number of points of dimming, and verify the value of the signal with theoretical models.

References

1. **Williams, G. F.** // Journal Geophys. Res. – 1955. – Vol. 74, No.18. – P. 4501.

2. **Stogryn, A.** The emissivity of sea foam at microwave frequencies / A. Stogryn // 1971 Antennas and Propagation Society International Symposium. – Los Angeles, CA, USA, 1971. – P. 169 – 171. doi: 10.1109/APS.1971.1150923

Anguelova, M. D. Foam emissivity models for microwave observations of oceans from space / M. D. Anguelova, P. W. Gaiser, and V. Raizer // 2009 IEEE International Geoscience and Remote Sensing Symposium. – Cape Town, South Africa, 2009. – P. II-274 – II-277. doi: 10.1109/IGARSS.2009.5418061.

Raizer, V. Microwave scattering model of sea foam / V. Raizer // 2012 IEEE International Geoscience and Remote Sensing Symposium. – Munich, Germany, 2012. – P. 5836 – 5839. doi: 10.1109/IGARSS.2012.6352282.

3. **Raizer, V.** Radar backscattering from sea foam and spray / V. Raizer // 2013 IEEE International Geoscience and Remote Sensing Symposium (IGARSS). – Melbourne, VIC, Australia, 2013. – P. 4054 – 4057. doi: 10.1109/IGARSS.2013.6723723.

4. **Jiang, R.** Foam-Scattering Effects on Microwave Emission From Foam-Covered Ocean Surface / R. Jiang, P. Xu, K. -S. Chen, S. Tjuatja, and X. Wu // IEEE Geoscience and Remote Sensing Letters. – 2018. – Vol. 15, No. 5. – P. 649 – 653. doi: 10.1109/LGRS.2018.2803440.

5. **Anguelova, M. D.** Whitecap Fraction From Satellite Measurements: Algorithm Description / M. D. Anguelova, M. H. Bettenhausen // Journal of Geophysical Research: Oceans. – 2019. – Vol. 124, No. 3. – P. 1827 – 1857.

6. **Huang, X.** A Study on Microwave Emissivity from Wind-Induced Sea Foam / X. Huang, S. Tjuatja, Z. Wang and J. Zhu // IGARSS 2020 - 2020 IEEE International Geoscience and Remote Sensing Symposium. – Waikoloa, HI, USA, 2020. – P. 5783 – 5786. doi: 10.1109/IGARSS39084.2020.9324688

7. **Kharkovsky, S.** Nondestructive testing of the space shuttle external tank foam insulation using near field and focused millimeter wave techniques / S. Kharkovsky, F. Hepburn, J. Walker, R. Zoughi // Mater. Eval. – Vol. 63, No. 5. – P. 516 – 522.

8. **Kharkovsky, S.** Millimeter-wave detection of localized anomalies in the space shuttle external fuel tank insulating foam / S. Kharkovsky, J. T. Case, M. A. Abou-Khousa, R. Zoughi, F. L. Hepburn // IEEE Trans. Instrum. Meas. – 2006. – Vol. 55, No. 4 – P. 1250 – 1257.

9. **Lu, T.** Evaluation of holographic subsurface radar for NDE of space shuttle thermal protection tiles / T. Lu, C. Snapp, Tien-Hsin Chao, A. Thakoor, T. Bechtel, S. Ivashov, I. Vasiliev // SPIE Proceedings, Vol. 6555, Sensors and Systems for Space Applications (Defense and Security Symposium, 2007, Orlando, Florida); 65550S (2007). https://doi.org/10.1117/12.719911.

10. **Ivashov, S.** Frequency Influence in Microwave Subsurface Holography for Composite Materials Testing / S. Ivashov, A. Zhuravlev, V. Razevig, M. Chizh, T. Bechtel, L. Capineri, B. Thomas // 2018 17th International Conference on Ground Penetrating Radar (GPR). – Rapperswil, Switzerland, 2018. – P. 1 – 4. doi: 10.1109/ICGPR.2018.8441592.

11. **Soldovieri, F.** A Feasibility Study for Life Signs Monitoring via a Continuous-Wave Radar / F. Soldovieri, I. Catapano, L. Crocco, L. N. Anishchenko, S. I. Ivashov // International Journal of Antennas and Propagation. – 2012. – Vol. 2012. – P. 1 – 5. doi:10.1155/2012/420178

12. **Filins'kyy, L. A.** Absorbed media dielectric permittivity research in form of water foam specimens / L. A. Filins'kyy // Proc. of 5th International Conference on Antenna Theory and Techniques. – Kyiv, Ukraine, 2005. – P. 515 – 517.

13. **Filins'kyy, L. A.** Dielectric Properties of Foam Specimens Calculated on the Base of VSWR and Attenuation Characteristics / L. A. Filins'kyy // Proceedings of 19 International Seminar/ Workshop on Direct and Inverse Problems of Electromagnetic and Acoustic Wave Theory (DIPED'14). – Tbilisi, Georgia, September 22-25, 2014. – P. 48 – 51.

14. **Liang, X.** Investigations on the basic electrical properties of Polyurethane foam material / X. Liang, Y. Shen,Y. Liu, J. Wang, Y. Gao, S. Li, M. Wang, S. Gao // 2015 IEEE 11th International Conference on the Properties and Applications of Dielectric Materials (ICPADM). – Sydney, NSW, Australia, 2015. – P. 863 – 866. doi: 10.1109/ICPADM.2015.7295409.

15. **Neagu, V.** The effects of foam on non-contacting radar-based level measurement / V. Neagu // 10th International Symposium on Advanced Topics in Electrical Engineering (ATEE). – IEEE, 2017. – P. 497 – 502.

16. **Van Delden, M.** Investigations on Foam Detection Utilizing Ultra-Broadband Millimeter Wave FMCW Radar / M. Van Delden, S. Westerdick and T. Musch // 2019 IEEE MTT-S International Microwave Workshop Series on Advanced Materials and Processes for RF and THz Applications (IMWS-AMP). – IEEE, 2019. – P. 103 – 105.

17. **Filins'kyy, L. A.** Microwave Research of Water Foams in Biconical Resonators / L. A. Filins'kyy and A. O. Chervyakov // 2020 IEEE Ukrainian Microwave Week (UkrMW), 2020. – P. 991 – 994. doi: 10.1109/UkrMW49653.2020.9252688.

18. **Filins'kyy, L**. Cloaking Study of Metal Surface by Liquid Foam Structures in the Millimeter Range / L. Filins'kyy and O. Hurko // 2023 IEEE XXVIII International Seminar/Workshop on Direct and Inverse Problems of Electromagnetic and Acoustic Wave Theory (DIPED). – Tbilisi, Georgia, 2023. – P. 186 – 190. doi: 10.1109/DIPED59408.2023.10269524.

19. **Drobakhin, O. O.** Measuring the reflection of electromagnetic waves from foam structures of varied foaming ratio / O. O. Drobakhin, L. A. Filins'kyy // Journal of Physics and Electronics. – 2022. – Vol. 30(2). P. 81 – 88. DOI 10.15421/332224

20. **Drobakhin, O. O.** Study of electromagnetic waves reflection from foam samples and determination of their dielectric permeativity / O. O. Drobakhin, L. A. Filins'kyy // Journal of Physics and Electronics. 2023. – Vol. 31(1). – P. 64 – 72. doi: 10.15421/332312

21. **Drobakhin, O. O.** Holographic approach to microwave measurement / O. O. Drobakhin and V. A. Karlov // Proc. 16-th Int. Symp. on Electromagnetic Theory, Vol. 1, 1998. – P. 109 – 111.

22. **Drobakhin, O. O.** Microwave Methods for Monitoring Parameters of Dielectrics Developed in Ukraine: Overview / O. O. Drobakhin // XXIVth International Seminar/Workshop on Direct and Inverse Problems of Electromagnetic and Acoustic Wave Theory (DIPED), 2019. – P. 6 – 10. doi: 10.1109/DIPED.2019.8882598