THE SCIENTIFIC LABORATORY OF DIELECTRIC METHODS IN PETROPHYSICS

HISTORICAL NOTE

The scientific Laboratory of dielectric methods in petrophysics was formed by the order of rector of Omsk State Pedagogical University in February 2016. It was made for good reason. During some last years and especially in 2015 the lab was provided with modern equipment to perform dielectric measurement in a wide frequency band from 20 Hz to 20 GHz. The methods of soils and rocks measurement in this frequency band were worked out and patented. The investigation let discover, explore in detail and explain the phenomena of changing the frequency spectrum of dielectric permittivity of the moist rocks in time and in the processes of imbibition and drying which were unknown earlier or were not connected with each other. This led to understanding of the fact that the estimation of such important characteristics of the oil-saturated rocks as general porosity, pore size distribution, specific surface area and other could be possible with the +dielectric method. To investigate in parallel, the same phenomena with the nuclear magnetic resonance method the NMR-relaxometer was obtained. The equipment of the lab permits to perform measurements at world level.

Modern achievements of the lab staff are based on a rich experience of the radio-physical investigations of the natural environments.

In 70s of the previous century in the USSR the investigation of the heat radiation of the natural objects in a microwave range was started led by academician Basharinov to get the information about their properties remotely. The using of the microwave method to determine the soil moisture was firstly made in the Institute of Radio-engineering and Electronics of the Russian Academy of Science (IRE RAS). In 1982 the staff of this institute got the Government Premium for development the radiometric method of the remote soil moisture determination. It turned out, however, that far not all the problems were solved and till 90s in the USSR the tens of scientific groups were performing investigations in a microwave radiometry area. Also the same investigations expanded on a broad front abroad. Many European and most of American universities have scientific units engaged in method of remote sensing of the Earth from space. Space agencies of Europe, the USA and Japan have satellites on the near-earth orbit with microwave radiometers working in different ranges of wavelengths.

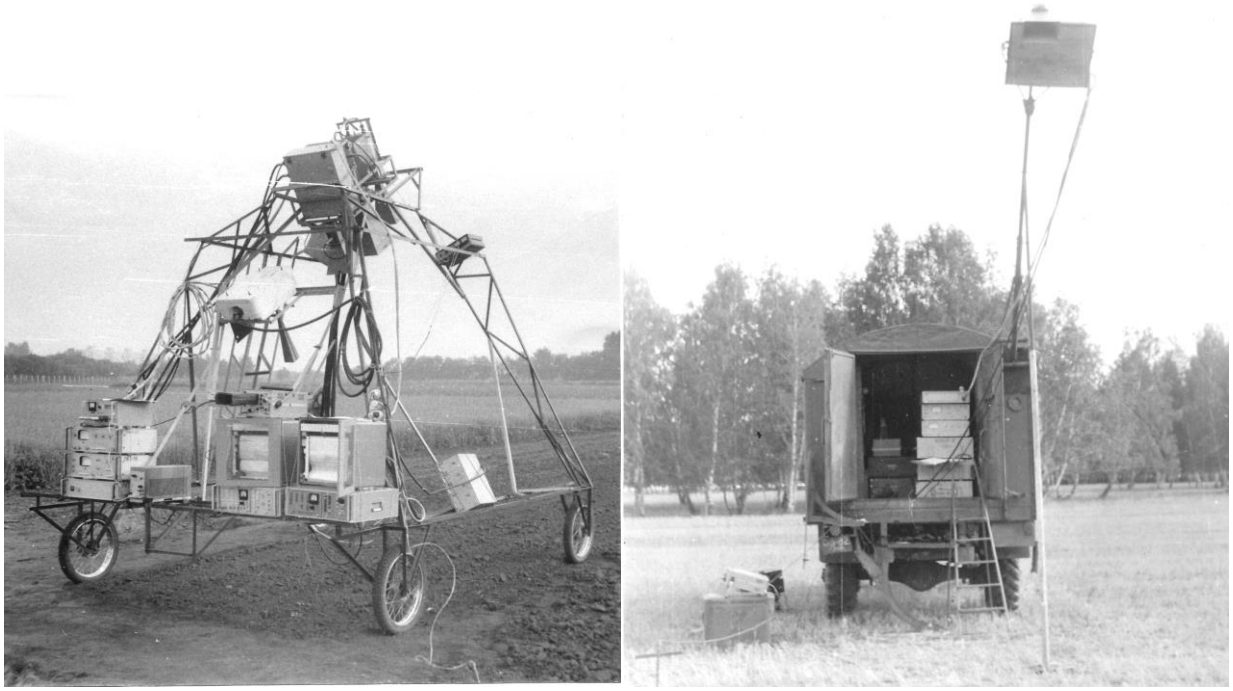
Nowadays in Russia few groups are occupied in radiometric method of the earth surface study. Space Research Institute of the Russian Academy of Sciences (SRI RAS) studies atmosphere of the water surface research, the IRE RAS studies snow cover, Institute of the natural resources, criology and ecology of the Siberian Branch of the Russian Academy of Science (INREC SB RAS) studies cryosolic formations and Omsk State Pedagogical University (OSPU) conjointly with Trofimuk Institute of Petroleum Geology and Geophysics (IPGG SB RAS) and with Kirensky Institute of Physics (IPH SB RAS) studies soils and rocks.

These investigations in Omsk State Pedagogical Institute (the name of the Omsk State Pedagogical University – OSPI that time) began in 1983 when under the auspices of the head of an SRI RAS department professor Etkin V.S. an economic contract on a performance of the investigation of the radio-heat radiation of the soils, covered with stubble was made. The leader of the work in OSPI was the head of General Physics Department Bobrov P.P.

The first time the serial receives of the PK7 type were used, they didn't really approach for the field measurements, later radiometers at wavelengths of 3.6 and 15 cm were made in-house. During even the first field measurements it was revealed that zenith radiation of the soils, covered by stubble, is polarized. The explanation to this phenomenon wasn't found at once. Subsequently the theoretical articles explaining the polarization of the zenith radiation with the presence of the periodical structure on the soils surface have appeared. In the case that we were studied this structure was made by rows of the stubble and generated due to the root activity of the grain crop, which were planted in a row way, periodical surface imperfections. Sometimes later the features of the radiation of the periodically rough soils were investigated by us on the experimental field of the Omsk Agricultural Institute. Post graduate of the professor Etkin V.S. and now docent of the physics department Belyaeva T.A. (Sologubova) and scientific staff of the lab Kulmametiev R.A., Pavlenko V.I. were take part in these investigations. The experimental setups used that time are given in Fig. 1.

On the basis of the data obtained both in this experiment and on fields of the Omsk region by means of automobile mounting the following manners were developed: the way of definition of a sign of a moisture gradient and assessment of its value by measurement of a degree of polarization of radiation of periodically irregular soils [1, 2] and the technique of moisture determination in the upper layers of the soil by means of a multifrequency radiometric complex [3]. During autumn and winter seasons of 1986 and 1987 the SRI RAS provided in our order the IL-14 aircraft by which we together with the INREC SB RAS placed the radiometers. Flights at the height of 50-200 m were made over the southern areas of the Omsk region. Teachers and research associates of the Omsk state pedagogical institute Gidlevsky A.V., Shchetkin I. M.,

Pavlenko V. I. worked as operators on a board. Land measurements of soils' moisture, conditions of a surface and depth of a freezing were made by students of biological faculty of OSPI under the leadership of associate professor Pirogova T. I.



a *b*

Figure 1. Three-channel mobile radiometric caravan (ranges of 18 cm, 3.6 cm, 1.5 cm), used on the experimental field of the Omsk agricultural institute (a) and the radiometric installation in the range of 2-4 GHz (1984) mounted on the car (b).

So large volume of data was received as a result that their processing dragged on for years. Also the compelled break in scientific research in 90th years, of course, affected.

In parallel with field measurements laboratory researches of dielectric properties of different soils, information on which is necessary for distant moisture determination, were made. Belyaeva (Sologubova) T.A. stated the interesting ideas [4-6] on model of the dielectric permittivity of soils considering dielectric properties of the water connected on a surface of soil particles. Subsequently on a basis of these ideas the staff of the Altai State University and IPH SB RAS created refractive model, that is now in use in an algorithm of data processing of the satellite of the European Space Agency launched in 2009 according to the SMOS (Soil Moisture and Ocean Salinity) program for a research of moisture of soils and salinity of the ocean.

The next stage of researches began in the changed conditions in the late nineties. Because of the decreased financing scientific work began to be carried out only by teachers of physical faculty and graduate students. Costs of acquisition of the new equipment decreased sharply. And though the situation changed for the better, the level of financing remained lower, than in Soviet period (in the comparable prices).

The stock of the inventory acquired in the late eighties saved for some time. Quite good results on this inventory were received.

The possibility of distant detection of soils with the increased salinization was shown. Evaporation in such soils is slowed down due to swelling, and it is reflected in dynamics of an emissivity with the centimetric wave band [7, 8].

At the beginning of 2000 on an agro station of OSPU the scientific ground for a research of the brightness characteristics of different soils in a microwave range (Fig. 2) was created. Application of radiometers at different wavelengths allowed to define the moisture gradients in the thin surface layer of soils arising at evaporation. In soils with the high humus content the thin surface layer dries up quickly because of features of structure. The breaking of capillary communications leads to sharp delay of evaporation from an underlying layer therefore moisture gradients are stronger in such soils, than in soils with the low humus content [9 - 11]. Graduate students Krivaltsevich S.V. (nowadays the deputy director of ONIIP on science) and Ivchenko O.A. were engaged in this subject. And (nowadays associate professor of Siberian State University of Physical Culture and Sport).

Fig. 2. The ground for a research of a radio –heat radiation of soils in a frequency range of 2.7-8.3 GHz (the agrostation OSPU of 2001-2005).

Graduate students of Bobrov A.P., Galeyev O. V., Krasnoukhova (Mandrygina) V. N. took dielectric measurements of soils with the different humus content and for the first time found significant influence of a humus on dielectric permittivity [12].

Fig. 3 Krasnoukhov V. N. (Mandrygina) at laboratory installation for measurement of dielectric permittivity of soils in the range of 0.1-17 GHz (2002).

MAIN RESEARCH DIRECTIONS

In the last decade researches are conducted in cooperation with IPH SB RAS (the head of Radiophysical Remote Sensing Laboratory, the corresponding member of RAS Mironov V. L., Krasnoyarsk). The general cooperation agreement was concluded in 2002 and works so far. In 2006 the radiometers of new generation on the frequency of

1,4 GHz (SMOS satellite frequency) and 6.9 GHz with computer management and data recording were made for Kirensky Institute of Physics in SRI RAS.

The research of radiation of the freezing and thawing soils showed that the remote control of depth of a freezing is possible [13 - 15]. Besides, measurements of emissivities just before freezing and after freezing on depth exceeding thickness of the probed layer allow to define a share of the bound moisture in the soil and consequently, to specify moisture of the soil by a radiometric method more precisely. On the basis of the results received on the ground OSPU, and later and on the ground near Krasnoyarsk (Fig. 4), the graduate student Yashchenko A. S. defended the master's thesis on a radiophysics. Now he is engaged in processing of space pictures from the devices SMOS, GCOM-W1, MODIS and makes comparison of these data with land data, received on the installation located in the village of Gvozdevka of the Omsk region (Fig. 5) [16, 17].

In 2007 the laboratory equipment for measurement of dielectric permittivity was replenished with the device of new generation – a Vector Network Analyzer. In the beginning it was the ZVRE device received from Kirensky Institute of Physics in temporary use, and in 2012 superior ZNB8 device was acquired by OSPU. Use of these devices allowed to increase accuracy of dielectric measurements considerably. The unique method of measurement of dielectric permittivity of fluid and loose bodies in one cell in a frequency range from 100 Hz to 8 GHz was developed and patented [18-20]. By means of this method dielectric ranges of different breeds in the wide frequencies range were received and dielectric models [21-26] were created.

Fig. 4. Radiometric mounting on frequencies of 1.4 and 6.9 GHz on the Pogorelsky Pine Forest Ground near Krasnoyarsk (2007). From left to right: P. P. Bobrov – OSPU, D. P. Skulachev researcher of SRI RAS, V. L. Mironov is the corresponding member of RAS, the lab. head of IPH SB RAS.

a b

Fig. 5. Radiometric mounting in the village of Gvozdevka of the Omsk Region in 2011-12 and in 2013-14 (b).

The created measuring complex allowed to carry out dielectric measurements in a frequency range of 25 Hz – 8 GHz and temperature range from – 20^0C to + 120^0C (Fig. 6). In 2015 the measuring complex was replenished with two new devices that allowed to expand the frequencies range from 20 Hz to 20 GHz (Fig. 7). Also the device using the phenomenon of nuclear magnetic resonance for definition of petrophysical characteristics of breeds (Fig. 8) is acquired.

New measuring opportunities allowed to expand scope of the researches conducted in Laboratory. Now also dielectric measurements of saturated rocks in which the staff of IPGG SB RAS [27-37] are carried out. These researches are supported by the Russian Foundation for Basic Research, and results attract interest of geophysics.

Fig. 6. A type of the pilot unit for measurements in the range of 42 Hz – 8,5 GHz.
1 – LCR-meter 3532-50 HiTESTER; 2 – Rohde & Schwarz ZNB8 Vector Network Analyzer;
3 – Climatic TH-ME camera

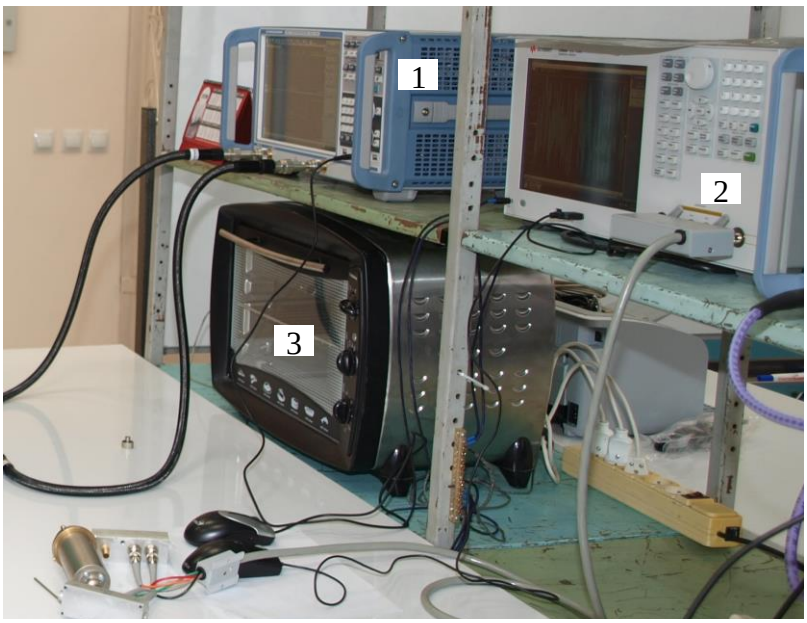


Fig. 7. A type of the pilot unit for measurements in the range of 20 Hz – 20 GHz.
1 – Rohde & Schwarz ZNB20 Vector Network Analyzer;
2 – Keysight Technologies E4990A Impedance Analyzer;
3 – Thermostat


Fig. 8. Apparatus for investigation of rock petrophysical characteristics by nuclear magnetic resonance method (a Nuclear Magnetic Resonance Relaxmeter HROMATEK PROTON 20 M)

Relevance of the researches which are carried out in Laboratory is confirmed by successful speeches of our employees at the All-Russian and international conferences of young scientists. In 2009 Rodionova (Kondratyeva) O. V. and Repin A. V. were awarded by the diploma of the III degree at the international conference "Student and Scientific and Technical Progress" (Novosibirsk, NSU), in 2011 Kondratyeva O. V. and Lapina A. S. at the same conference were awarded by the diploma of the II degree, in 2011 Yashchenko A. S. was awarded with a prize of the government of the Omsk region for scientific work, and in 2012 he got the first award at the "Modern Problems

of Remote Sensing of Earth from Space" conference (Moscow, Institute of space researches of RAS). In 2013 Repin A. V. was awarded by the diploma of the I degree at the Trofimukovsky Readings Conference (Novosibirsk, Trofimuk Institute of Petroleum Geology and Geophysics SB RAS). In 2015 and 2016 of Lapina A. S. made a speech at the international conferences in Prague and Florence.

Four patents for inventions over the last 5 years were taken out.

Fig. 9. Staff of Dielectric Methods in Petrophysics Laboratory of OSPU (June, 2016).

SCOPE OF THE RESEARCHES WHICH ARE CARRIED OUT WITH ASSISTANCE OF THE RUSSIAN FOUNDATION FOR BASIC RESEARCH AND THE RUSSIAN MINISTRY OF EDUCATION AND SCIENCE

1. RFBR № 15-35-50871

Joint interpretation of the NMR and the dielectric properties of water and oil-saturated rock data. 2015.

2. RFBR № 16-35-50184

Experimental and theoretical study angle and in polarimetric features of radio emission

of the soil cover in the natural cycles of freezing and thawing on the frequency 1,4 GHz. 2016.

3. RFBR № 14-05-00151
Dielectric relaxation in the gas-oil-water saturated rocks. 2014–2016.

4. RFBR № 12-05-00502-a.
Study of dielectric relaxation in oil-saturated sand and clay rocks. 2012-2013.

5. RMES (state assignment). Number of the state registration 01201254111
Research of influence of organic matter on a complex dielectric permittivity of soils and rocks with various porosity in a wide frequency range of electromagnetic waves. 2012- 2014.

6. RMES (state assignment). Number of the state registration 01201460173.
Research of the radiation, disseminating, reflective and dielectric characteristics of terrestrial covers in a wide frequency range of electromagnetic waves. 2014-2015.

LIST OF THE MAIN PUBLICATIONS OF LABORATORY STAFF

1. Beavers P.P., Kulmametyev R. A., Pavlenko V. I., Sologubova T. A., Etkin V. S. O vozmozhnosti raspoznavaniya profiley vlazhnosti po dannym dvukhchastotnykh polyarizatsionnykh izmereniy // Meteorologiya i gidrologiya. 1987. No. 7. P. 102 - 106.

2. P.P., Belyaev T. A. beavers., Shestopalov Yu. K., Shchetkin I. M. Osobennosti sverkhvysokochastotnogo izlucheniya periodicheski nerovnykh pochv // Radiotekhnika i elektronika. 2000. No.10. P. 1059-1067.

3. Beavers P.P., Gidlevsky A. V., Kulmametyev R. A., Pavlenko V. I. Povysheniye tochnosti distantsionnogo opredeleniya vlazhnosti pochv v pakhotnom sloye s pomoshch'yu trekhchastotnogo radiometricheskogo kompleksa. /Voprosy sozdaniya sistemy aerokosmicheskogo monitoringa sel'skokhozyaystvennykh resursov. M.: VNITS "AIUS - Agroresursy". 1987. P. 39 - 47.

4. Sologubova T. A. Etkin V. S. K voprosu ob uchete svoystv svyazannoy vlagi pri distantsionnom opredelenii vlazhnosti pochvy //Issledovaniye Zemli iz kosmosa. 1985. No.4. P. 112 - 115.

5. Beavers P.P., Krylov V. V., Kulmametyev R. A., Pavlenko V. I., Sologubova T. A., Etkin V. S. Opredeleniye vlazhnosti pochvy po izmerennoy radioyarkostnoy temperature s uchetom svyazannoy vlagi // Issledovaniye Zemli iz kosmosa. 1986. No. 6. P. 89-91.

6. Bobrov P.P., Maslennikov N.M., Sologubova T.A. et al. Issledovaniye dielektricheskikh kharakteristik pochv v oblasti perekhoda vlazhnosti iz svobodnoy v svyazannuyu na sverkhvysokikh chastotakh // Doklady Akademii nauk SSSR. 1989. T.304. No.5. P.1116 - 1119.

7. Bobrov P.P. Vliyaniye razlichiy v strukture zasolennykh i nezasolennykh pochv na sobstvennoye SVCH-izlucheniye //Issledovaniye Zemli iz kosmosa. 1999.No.5.P. 83-87.

8. Bobrov P.P. Issledovaniye ispareniya, vlazhnosti i struktury poverkhnostnogo sloya pochv distantsionnymi mikrovolnovymi metodami //Pochvovedeniye. 2000. No.5. P.574-578.

9. Bobrov P.P., Galeyev O.V. Dinamika radioyarkostnoy temperatury pochv s razlichnym soderzhaniyem gumusa // Issledovaniye Zemli iz kosmosa, 2001.No.4. P.74-80.

10. Bobrov P.P., Ivchenko O.A., Krival'tsevich S.V. Issledovaniye pochvennoy struktury metodom dvukhchastot-noy mikrovolnovoy radiometrii. //Issledovaniye Zemli iz kosmosa. 2005. No.2.P.82-88.

11. Bobrov P.P., Ubogov V.I. Galeyev O.V. Modelirovaniye dinamiki pochvennoy vlagi pri isparenii s uchetom vliyaniya gumusa na gidrofizicheskiye svoystva pochv i na dinamiku sobstvennogo radioteplovogo izlucheniya //Omskiy nauch. vest. Vyp.2 (23). Omsk: OmGTU. 2003. P.84-87.

12. Belyayeva T.A., Bobrov A.P., Bobrov P.P., Galeyev O.V., Mandrygina V.N. Opredeleniye parametrov modeley dielektricheskoy pronitsayemosti pochv s razlichnoy plotnost'yu i razlichnym soderzhaniyem gumusa po dannym eksperimental'nykh izmereniy v chastotnom diapazone 0,1-20 GGts // Issledovaniye Zemli iz kos-mosa. 2003. No.5.P.28-34.

13. Bobrov P.P., Krival'tsevich S.V., Mironov V.L., Yashchenko A.S Vliyaniye tolshchiny promerzshego pochvennogo sloya na sobstvennoye radioteplovoye izlucheniye v diapazone dlin voln 3,6-11sm // Izvestiya vuzov. Fizika, 2006, No.9.P. 5-10.

14. Bobrov P.P., Mironov V.L., Yashchenko A.S. Sutochnaya dinamika radioyarkostnykh temperatur pochv na chastotakh 1.4 i 6.9 GGts v protsessakh promerzaniya i ottaivaniya // Radiotekhnika i elektronika. 2010, No.4.P. 424-431.

15. Bobrov P.P., Kondrat'yeva o. V., Mironov V.L., Savin I.V., Yashchenko A.S. Izluchatel'nyye kharakteristiki pochv, pokrytykh khvoynym opadom, pri otritsatel'nykh temperaturakh //Izvestiya Vuzov. Fizika. 2010. No.9/2.P.255¬–256.

16. P. P. Bobrov, A. S. Lapina, and Yashchenko A. S. Analysis of the SMOS, MODIS and GCOM-W1 Data during the Growing Season in the Southern Part of the Western Siberia //PIERS Proceedings, Prague, July 6-9, 2015. P. 1137 – 1140.

17. Yashchenko A.S., Bobrov P.P. Impact of the soil moisture distribution in the toplayer on the accuracy moisture retrieval by microwave radiometer data // IEEE Transactions on Geoscience and Remote Sensing. 2016. Vol. 54, No.9. P. 5239 – 5246.

18. Bobrov P.P., Kondrat'yeva O.V., Repin A.V. Izmereniye kompleksnoy dielektricheskoy pronitsayemosti obraztsa v odnoy yacheyke ot desyatkov gerts do yedinits gigagerts // Izvestiya Vuzov. Fizika. 2012. No.8/3. P. 23-26.

19. Bobrov P.P., Repin A.V., Kondrat'yeva O.V. Sposob izmereniya kompleksnoy dielektricheskoy pronitsayemosti zhidkikh i sypuchikh veshchestv v shirokom chastotnom diapazone. Patent RF na izobreteniye № 2474830 S1 MPK G01R27/26 ot 12.08.2011g. Zaregistrirovan 10.02.2013 g. Patentoobladatel' GOU VPU "Om-skiy gosudarstvennyy pedagogicheskiy universitet".

20. Bobrov P. P., Repin A.V., Rodionova O.V. Wideband Frequency Domain Method of Soil Dielectric Properties Measurements // IEEE Trans. Geosci. Remote Sens. 2015. Vol. 53, No.5. P. 2366–2372.

21. Bobrov P.P., Mironov V.L., Ivchenko O.A., Krasnoukhova V.N. Spektroskopicheskaya model' dielektricheskoy pronitsayemosti pochv, ispol'zuyushchaya standartizovannyye agrofizicheskiye pokazateli // Issledova-niye Zemli iz kosmosa. 2008. No.1. P.15-23.

22. Belyayeva T. A., Bobrov P. P., Kondrat'yeva O. V., Repin A. V. Dielektricheskiye svoystva kapillyarno-meniskovoy pochvennoy vlagi //Issledovaniye Zemli iz kosmosa. 2011. No.3. P. 55-64.

23. Mironov V.L., Bobrov P.P., Fomin S.V. Multirelaxation Generalized Refractive Mixing Dielectric Model of Moist Soils //IEEE Geoscience and Remote Sensing Letters. 2013. Vol. 10, No.3, P.603-606.

24. Mironov V.L., Bobrov P.P., Fomin S.V., Karavaiskii A.Yu. Generalized Refractive Mixing Dielectric Model of Moist Soils Considering Ionic Relaxation of Soil Water //Russian Physics Journal, 2013. Vol. 56, No. 3, P. 319-324.

25. Belyayeva T.A., Bobrov P.P., Mironov V.L., Rodionova O.V. Zavisimost' dielektricheskoy pronitsayemosti svyazannoy vody v bentonite ot vlazhnosti i temperatury // Sovremennyye problemy distantsionnogo zondirovaniya Zemli iz kosmosa. 2014. T. 11. No.3. P. 288–300.

26. Bobrov P. P., Belyaeva T.A., Lapina A. S., Rodionova O.V. The effect of a very small water content on the complex dielectric permittivity of sand and sand-clay rocks // Proceedings of the 11th International Conference on Electromagnetic Wave Interaction with Water and Moist Substances (ISEMA 2016). P. 213–219

27. Epov M.I., Mironov V.L., Bobrov P.P., Savin I.V., Repin A.V. Issledovaniye dielektricheskoy pronitsayemosti neftesoderzhashchikh porod v diapazone chastot 0,05–16 GGts//Geologiya i geofizika. 2009. T.50 No.5. P. 613-618.

28. Epov M.I., Bobrov P.P., Mironov V.L., Repin A.V. Dielektricheskaya relaksatsiya v glinistykh neftesoderzhashchikh porodakh//Geologiya i geofizika. 2011. T. 52. No.9. P. 1302-1309.

29. Bobrov P.P., Lapina A.S., Repin A.V. Vliyaniye svyazannoy vody na kompleksnuyu dielektricheskuyu pronitsayemost' nefte- vodonasyshchennykh peschano-glinistykh porod //NTV “Karotazhnik”. Tver': Izd. AIS. 2013. No.8 (Vyp. 230). P. 56-68.

30. Bobrov P.P., Mironov V.L., Repin A.V. Spektry dielektricheskoy pronitsayemosti neftevodonasyshchennykh peschano-glinistykh porod razlichnogo mineralogicheskogo sostava i relaksatsionnyye svoystva vody v etikh porodakh // Geologiya i geofizika, 2015. T. 56. No.7. P. 1359-1368.

31. P. P. Bobrov, A. S. Lapina, and Repin A. V. Effect of the Rock/Water/Air Interaction on the Complex Dielectric Permittivity and Electromagnetic Waves Attenuation in Water-saturated Sandstones //Progress in Electromagnetics Research Symposium (PIERS) Proceedings. Prague, July 6-9, 2015. P. 1877-1879.

32. P. P. Bobrov, A. S. Lapina, and Yashchenko A. S. Analysis of the SMOS, MODIS and GCOM-W1 Data during the Growing Season in the Southern Part of the Western Siberia //PIERS Proceedings, Prague, July 6-9, 2015. P. 1137 – 1140.

33. Bobrov P. P., Yashchenko A. S., Rodionova O. V., Repin A. V., Lapina A. S. The Electrical Characteristics of the Rocks with Different Texture //PIERS Proceedings. Prague, July 6-9, 2015. P. 1881 – 1884.

34. Lapina A.S., Bobrov P.P. Gisterezis dielektricheskoy pronitsayemosti i ekvivalentnoy udel'noy elektroprovodnosti uvlazhnennykh poroshkov kvartsevykh granul raznykh razmerov // Izvestiya vuzov. Fizika. 2015. T. 58. No.8/2. P.17-21.

35. Shumskayte M.Y., P.P. Bobrov P.P., Lapina A.S. Izmeneniye dielektricheskoy pronitsayemosti i YAMR-signala vlazhnykh poroshkov kvartsevykh granul pri uvelichenii i umen'shenii

vodonasyshchennosti // NTZH «Geologiya, geofizika i razrabotka neftyanykh i gazovykh mestorozhdeniy». 2016 No.5. P.15-20.

36. Lapina A. S., Bobrov P.P. Elecromagnetic Waves Attenuation in the Sandstones with Grains of Different Size at Imbibition and Drying // Progress in Electromagnetics Research M, 2016. Vol. 45, pp. 9–16.

37. Lapina A.S., Bobrov P. P., Golikov N.A., Repin A.V., Shumskayte M.Y. Hysteresis of the NMR response and the complex relative permittivity of sandstones during the water imbibition and drainage // Proceedings of the 11th International Conference on Electromagnetic Wave Interaction with Water and Moist Substances (ISEMA 2016) May 23 – 27. 2016. Florence, Italy. P. 205–212.

38. Lapina A.S., Bobrov P.P., Golikov N.A. , Repin A.V. , Shumskayte M.Y. Hysteresis of the NMR response and the complex relative permittivity of the quartz granules powders and solid sandstones during the water imbibition and drainage // Measurement Science and Technol. 2017. V. 28 no. 1. 014007 doi:10.1088/1361-6501/28/1/014007.

39. Belyaeva T. A., Bobrov P. P., Kroshka E. S., Lapina A. S. and Rodionova O. V. The effect of very low water content on the complex dielectric permittivity of clays, sand-clay and sand rocks // Measurement Science and Technol. 2017. V. 28 no. 1. 014005. doi:10.1088/1361-6501/28/1/014005.