JOURNAL OF MECHANICS OF CONTINUA AND
MATHEMATICAL SCIENCES
www.journalimcms.org

ISSN (Online) : 2454 -7190 , Special Issue, No.-10, June (2020) 684-704 ISSN (Print) 0973-8975

DEVELOPMENT AND TESTING OF AUTONOMOUS PORTABLE SEISMOMETER DESIGNED FOR USE AT ULTRALOW TEMPERATURES IN ARCTIC ENVIRONMENT

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https://doi.org/10.26782/jmcms.spl.10/2020.06.00043

Abstract

This paper is concerned with solving one of the issues of the general problem of designing geophysical equipment for the natural climatic environment of the Arctic. The relevance of the topic has to do with an increased global interest in this region. The paper is aimed at considering the basic principles of developing and the procedure of testing seismic instruments for use at ultralow climatic temperatures. In this paper the indicated issue is considered through the example of a seismic module designed for petroleum and gas exploration by passive seismoacoustic methods. The seismic module is a direct-burial portable unit of around 5 kg in weight, designed to continuously measure and record microseismic triaxial orthogonal (ZNE) noise in a range from 0.1 to 45 Hz during several days in autonomous mode.

The functional chart of designing the seismic module was considered, and concrete conclusions were made for choosing the necessary components to meet the ultralow-temperature operational requirements. The conclusions made served for developing appropriate seismic module.

In this case, the components and tools used included a SAFT MP 176065 xc low-temperature lithium cell, industrial-spec electronic component parts, a Zhaofeng Geophysical ZF-4.5 Chinese primary electrodynamic seismic sensor, housing seal parts made of frost-resistant silicone materials, and finely dispersed silica gel used as water-retaining sorbent to avoid condensation in the housing.

The paper also describes a procedure of low-temperature collation tests at the lab using a New Brunswick Scientific freezing plant. The test results proved the operability of the developed equipment at ultralow temperatures down to -55°C. In addition, tests were conducted at low microseismic noises in the actual Arctic environment. The possibility to detect signals in a range from 1 to 10 Hz at the level *close to the NLNM limit (the Peterson model) has been confirmed, which allows monitoring and exploring petroleum and gas deposits by passive methods.*

As revealed by this study, the suggested approaches are efficient in developing high-precision mobile seismic instruments for use at ultralow climatic temperatures. The solution of the considered instrumentation and methodical issues is of great practical significance as a constituent of the generic problem of Arctic exploration.

Keywords: Seismic instrumentation; microseismic monitoring; Peterson model; geological exploration; temperature ratings; cooling test.

I. Introduction

Nowadays, the creation of geophysical equipment for use at ultralow climatic temperatures is a problem gaining ground; in particular, this is conditioned by an increased interest in the Arctic region [XIX, XXIV] known for its severe natural environment.

The principal line of geophysical research in this region is represented by seismic investigations. Moreover, the most in-demand and advanced of these investigations are the ones carried out by passive methods. They are used in various monitoring observations, passive microseismic sounding [III], microseismic emission tomography [VIII, XXI, XXXI], seismoacoustic petroleum exploration [XVIII], etc. Unlike conventional seismic exploration, the application of these methods does not entail any harmful environmental impact because in this case the information comes with microseismic background noises of natural origin. The stationary component of this noise has a very low intensity, which is why its recording makes it necessary to take high-precision measurements.

The conditions necessary for such highly sensitive measurements are provided to the full at permanent stations. The research works using seismic stations have gained wide use in geophysics. Stations can form local small-aperture seismic aerials [XXXIII] or regional seismic groups and be part of global branched networks [XII].

In practice, however, surveys at permanent stations are deprived of mobility, whereas in real life on-the-fly measurements are often a must. For example, this need may arise during the exploration of petroleum and gas fields in concrete local areas [XVIII].

There are several firms producing relevant precision-class posthole mobile seismometers [XXX]. This equipment is usually designed for use in a relatively moderate climatic and temperature environment. For example, despite having special thermocompensating structural elements, the classical SM-3VK seismic pickup popular in Russia can be used only at temperatures equal to or above -10^0C [XXXIV]. Many modern seismometers, including well known Guralp 6TD [XIV] are also designed for use in this temperature range. Some seismometers have a broader range of operating temperatures down to-20°C, for example, a package based on an SRi32H recorder [XXVII] and made by a UK company Landtech Geophysics Ltd. (www.landtech-geophysics.com).

The climatic conditions in the Arctic impose tougher requirements. For this environment Russian specialists have created a geohydroacoustic ice buoy that remains operable at low temperatures down to -40^{0}C [XXXV]. The Polargeophysical system made by Nanometricsinc., a company from Canada (www.nanometrics.ca), is designed for use at ultralow temperatures down to -55°C [XXVIII]. Another instrument designed for use in the Arctic at temperatures down to -55°C is a modified version of the CMG-3T Polar seismometer [IV] made by Guralp Systems Ltd. These are single and pretty much unique examples of special-purpose equipment.

The consideration provided herein confirms the relevance of the indicated problem for Arctic exploration. This paper is aimed at considering the basic principles of developing and the procedure of testing seismic instruments for use at ultralow climatic temperatures. The solution of these issues is of great practical significance as a constituent part of the generic problem of Arctic exploration.

II.Materials and Methods

II.i. Equipment

1) Seismic Module: Structural Functional Flow Diagram

This article considers the basic principles of developing instruments for use at ultralow temperatures. This equipment is designed for petroleum and gas prospecting and exploration by seismoacoustic methods [XVIII]. These methods are based on the fact that a hydrocarbons deposits naturally form a characteristic microseismic noise field in its vicinity. The particularity of this field shows in a frequency range of 1÷10 Hz. The detection and identification of this field helps reveal a hidden reservoir. This approach to hydrocarbon exploration allows performing the works much more efficiently.

The seismic module for prospecting and exploration has a standard configuration and consists of the units described below (Fig. 1). First of all, we mean a 3D unit of primary seismic oscillation sensors that must be sensitive enough to record a faint microseismic background. The frequency range must inherently overlap the above specified frequency range typical of petroleum and gas deposits.

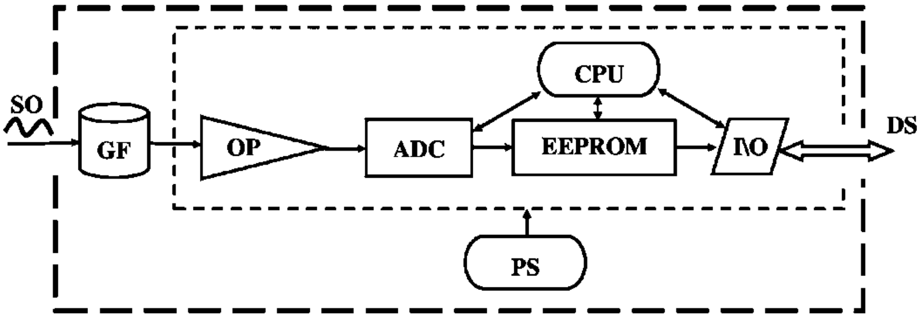

Fig.1: Seismic module: functional diagram.

SO is the measurable mechanical seismic oscillations; GFis the geophone, a primary mechanical oscillation sensor; OP is the analogous operating amplified; ADC is the analog/digital converter; EEPROM is electrically erasable programmable read-only memory; CPU is the microprocessor unit; PS is the battery power supply; I/O is the input/output computer interface; DS is the digital signal.

Then, a signal from the sensors comes to the unit of electronic instrumentation consisting of an analog signal amplifier and a microprocessor-controlled digital part. The amplifier must be low-noise, and its natural noise level must be consistent with fundamental Johnson–Nyquist noises. The analogue/digital converter must provide sufficiently high bit depths for making possible subsequent high-precision processing of noise signals and extracting low-amplitude variations.

The equipment must have autonomous power supply on electric batteries with a capacity sufficient for sustaining the seismic module’s uninterrupted operation for at least one dat. All the assemblies and units are mounted in a sealed housing convenient for manual transportation.

The principal aim of this paper is to provide operability to this equipment at ultralow climatic temperatures. It is necessary, therefore, to consider each unit separately and in detail from the standpoint of specific frosty environment.

2)Principles of developing assemblies and units for low-temperature seismic modules

Choosing an electric battery

In terms of temperature setting the most critical component of the described seismic module is its electric battery. The battery is a chemical current source in the form of a complex, multicomponent~~,~~ and multiphase system exceptionally demanding of temperature conditions. The system’s overcooling may result in structural disturbances and render the battery fully inoperable.

In addition, even if the system preserves the phase states of the components, the electromotive force will show an essential dependence on temperature. This dependence is determined by Nernst’s basic law for electrode potential, where temperature is found in explicit form.

It is obvious that choosing a battery for operation at ultralow temperatures is a matter of primary importance. A classical type of batteries conventionally used at low temperatures is Ni-Cd batteries. However, they do have certain flaws, first of all, poor energy efficiency. On the contrary, the operational performance of Ag-Zn batteries is much better. Unfortunately, they are fairly hard to find, too costly, and can be feasibly applied only in solving very important tasks.

Most of the flaws enumerated above are absent in batteries with lithium cells that have gained wide use nowadays. Many firms have launched their bulk production, for operation at low temperatures included [XVII]. An example of these ultralow-temperature batteries is a line of LP*LC polymeric batteries made by EEMB (http://eemb.com). These batteries remain operable at temperatures down to -40°C. There is also a line of MP176065 batteries developed by SAFT (https://www.saftbatteries.com) for use in a broad range of low temperatures. However, one should take into account that, although the battery remains operable at low temperatures, the rated operating voltage of one cell equal to 3.75 V will noticeably drop to about 2.5 V. The opportunities for applying these low-temperature batteries are considered in detail in work [XVII].

The battery chosen in this paper for ensuring a necessary reliability level is MP 176065 xc, where xc corresponds to the record-breaking low temperature of -50°C.

Electronic component parts and temperature specifications

When developing the electronic part of the equipment, one needs to consider that modern electronics is based on solid-state circuitry. The thermal actuation of charge carriers in solid-state materials is a matter of essential importance. Therefore, the selection of electronic component parts is somewhat restricted by the equipment's thermal operating conditions. In this framework, microcircuit chip manufacturers specify recommended operating conditions (ROC) for each type of items; the conventional thermal standards referred to in this case are Commercial (0…+70°C), Industrial (−40…+85°C), Military (−55…+125°C) [XVII].

Commercial standard as a popular specification can be dropped from consideration right away because it is not intended for operation at subzero temperatures. Military standard has the maximal thermal range. In addition, Military-compliant microchip circuits have an extra radiation protection. This protection is redundant for solving the considered task and entails unreasonable expenses. Because of the low demand for Military-compliant component parts or economic reasons, many firms begin to cut their production or cease it altogether. Unfortunately, this situation creates major issues with buying and using Military-compliant microchip circuits.

Industrial standard cannot boast with such record-breaking thermal parameters; however, a guaranteed operating temperature of −40°C can be quite acceptable to the task in solution. In addition, it should be considered that the enumerated standards are ROC-compliant, i.e., are only advisory in nature. An extra drop in temperature beyond the ROC within the permissible absolute maximum rating (AMR) must not violate the operability of microchip circuits [XVII]. Usually, microchip circuit data sheets provide typical characteristics in an expanded thermal range down to -55°C. This means that, basically, Industrial-compliant electronic component parts can be used at ultralow temperatures in practice. This conclusion was used to choose only Industrial-compliant electronic component parts for the given development. Now let us consider the choice of concrete component parts for each piece in more detail.

The critical piece of the electronic unit is the coupling amplifier of the signal transmitted from the primary sensor. The main requirement on the amplifier is that it must maintain the minimal level of intrinsic noises for making it possible to measure weak microseismic background signals. Microchip circuit manufacturers make a whole range of low-noise high-precision amplifiers for various purposes. A detailed consideration of how to choose an optimal model, taking account of the particularity of a concrete case, is presented in work [XXXVI]. That said, the defining parameter is the output resistance of the measured signal's source.

This seismometer development makes use of a classic electrodynamic sensor with a resistance of several hundred Ohms (for the sensor selection issue see below).

The optimal variant for a source with this resistance is the AD797 microchip circuit made by Analog Devices Inc. (https://www.analog.com/en/index.html). Thus, for example, the microcircuit chip's intrinsic noise at a frequency of 10 Hz is set to a level of 1.7 nV/√Hz[XXXVI]. This is much weaker than the classical sensor's Johnson–Nyquist noise of about 2.5 nV/√Hz (for R=375 Ohm at T=20°C). Thus AD797 provides the lowest possible level of intrinsic noises and meet the requirements on the given development.

The digital part of the equipment was developed according to the standard pattern based on AT89C51ED2, a popular and reliable microcontroller made by Atmel Corporation (https://www.microchip.com/). An AD7734 (Analog Devices Inc.) four-channel 24-bit microchip circuit was used as a high-precision ADC unit. The sampling rate is approximately 100 Hz.

The source of current for energizing this electronic unit must have a voltage of 9 to 18 V at a consumed current of 120 mA, which is necessary to consider when configuring the battery bank. The problem with ensuring long-term monitoring is that it requires sufficiently powerful electric batteries. The development of low-consuming equipment was considered in work [XXXVI], where a record-low power consumption was attained. In that case the autonomous uninterrupted equipment operation period exceeded six months. This task was not set forth for this development; however, such solutions can also be applied when long-term monitoring is needed.

Seismic sensor

Among the various types of primary seismic sensors conventional electrodynamic sensors are the ones that have become pretty popular. They are used in prospecting surveys, monitoring observations, microseismic probing, characterized by high-level operational consistency, high sensitivity, and manufactured using streamlined technologies.

The two essential factors defining the basic specifications of electrodynamic sensors are the elasticity of the sensor system suspension and the magnetic field induction of the system of converting mechanical oscillations to electric signals. The elasticity of the metals used in the suspension's structural members is almost independent from temperature in the entire range of possible climatic temperatures. The field induction is also maintained stable due to the fixed domain structure of magnet metals at sub-Curie temperatures (T_{Curie} for iron is 769°C). The operability of such sensors is usually set for the Industrial-compliant range of temperatures, i.e., down to -40°C. However, it is reasonable to suppose that these sensors can be used at lower temperatures without any essential restrictionsюThere is obviously no need for additional grounds for choosing an electrodynamic sensor to solve the formulated task.

When choosing a concrete sensor model, one should take into account that there are various models in different price ranges. The most cost-effective option for the tests will be a ZF geophone sensor made by the Chine company Zhaofeng Geophysical Co., Ltd(www.zfgeo.com).The applicability of ZF sensors to microseismic measurements was confirmed by specialized research [XXXVI].These sensors are made with various frequency specifications and designed for operation in respective frequency ranges, depending on their natural frequency. The model most suitable for recording the noise field of hydrocarbon deposits is ZF-4.5 with a natural frequency of 4.5 Hz. This was exactly the model used in this paper.

It should be noted that, essentially, the current choice in favour of the classical electrodynamic sensor will not rule out the possibility of using other types of sensors, e.g., electrochemical and molecular electronic [XVI]. However, this will require respective grounds and additional low-temperature tests.

Module housing requirements

Reliable protection against environmental influences must be provided to the units and components of mobile seismic module both, with direct ground burial and installed an ice pit in the expedition conditions. The housing must be sealed and strong. One can use a ready-made solution for the purpose. For example, an empty housing designed for an SM-3VK Russian commercial seismic pickup [XXXIV]allows placing all the necessary units of the seismic module in development and, at the same time, is small and convenient enough for manual transportation.

This housing is a thick-walled cast aluminum item and does not raise any questions as to the operability at low temperatures. The item consists of two dismountable parts, namely the base and the upper part. The structure of their connection requires a more focused consideration.

This connection uses a flange mating the tightness of which is ensured by a rubber sealing gasket. The mechanical properties, elasticity, and strength of rubber are known to heavily depend on temperature and remain operable only in a restricted thermal range. Operation at low temperatures makes it necessary to use special rubber grades. In this work a gasket of special group 7 GOST 18829-2017 frost-resistant rubber was used [XVI] supplied by company «Valkar Co» (http://valkar.com/index.php). The manufacturer-specified range of temperatures in which the gasket retains its sealing properties extends down to -50°C.

Before installation on the flange, the gasket was additionally treated with sealing silicone lubricant. Usually, these lubricants retain their properties at quite low temperatures. For example, the popular GLS 795/N2 lubricant made by the German company ELKALUB (https://www.elkalub.com/home.html) retains its properties at low temperatures of down to -40°C. The MS-SPORT special viscous silicone lubricant with fluoroplastic[XXVIII] made by company OOO «VMPAUTO» (www.smazka.ru) retains its properties at temperatures down to -50°C. This lubricant was exactly the one used in this paper.

To solve the sealing issue, it is also necessary to take into account that the housing has a passthrough, piggyback multiway electric service connector necessary for preparing the seismic module for autonomous operation in the field without decapsulation. This connector also requires extra confinement steps.

In this work the specified means of sealing the flange connection and electric socket must fully protect the module's internal components against external influences and penetration of atmospheric air, dust, snow, ice, water steam, fresh and sea water. The module of this version can be used in the expedition for direct burial into the ground or ice without extra protection. In that case the main attention was focused on using sealing means designed for operation at low temperatures.

In-housing moisture condensation

The above exposed discussion covers only those low-temperature factors that directly affect the running mode of the equipment. However, such an indirect cooling effect as in-housing moisture condensation should also be taken into account. Although the module has a sealed housing without the need for decapsulation, the assemblage of the module at the lab will mean that the housing will contain some atmospheric air of certain humidity.

Thus, for example, the equipment verification procedures are governed by GOST under normal conditions, i.e., at T=20°C and a relative humidity of 60% [XXIII]. This humidity level corresponds to a water steam content of 10.37 g/m^3. This steam will begin to condense at a temperature drop to the dew point of 12°C [XX]. This is unacceptable for using the instrument in the expedition.

A known way to solve the problem is to fill the housing with pressurized dry inert gas during the assemblage or evacuate a certain amount of air from the housing. However, this solution imposes tough requirements on the housing sealing quality and is insufficiently reliable. It will be more efficient to mount inside the housing solid water-retaining sorbents used as dessicants.

Thus, for example, sorbent with porous silica gel granules provides a fairly deep dehumidication of air with a final moisture content of about 0.02 g/m^3. The dewpoint at this dehumidification level significantly drops to -50°C. Moreover, the dehumidification ensured by special-purpose finely dispersed silica gel with pores of 1 to 1.5 nm in size can be even more efficient, right down to a dewpoint of –70°C [I]. This is well in compliance with the requirements of the stated task.

In this work the condensation inside the seismic module housing was prevented by placing in it a container with fine-pored silica gel granules.

Final module assemblage

The conducted analysis and the requirements formulated above were used for developing the individual units and configuring the respective seismic module. This module is a functionally complete instrument for autonomously and continuously detecting and recording seismic signals. The main focus was maintained on keeping the equipment operable at ultralow climatic temperatures. The necessary mobility for operation (Fig. 2) is ensured by the module's small dimensions (23x15x15 cm) and weight (~5 kg). To take measurements in a given territory, the seismic module can be installed right to a shallow and small pit in the ground or on an ice cake surface, while observing 3D orientation in space.

Fig.2: Seismic modules manually carried for onsite installation in hard-to-reach locations

II.ii. Frost Testing Procedure

1) Aims and Objectives

Rationale for testing

A peculiarity of the development in question is that the equipment was designed specifically for operation at low-temperatures. Each unit and element was created in light of temperature requirements. However, it is also necessary to consider that the operability of each of the elements of this system is not yet the sufficient guarantee of the equipment's correct overall operation. In nearly maximum permissible conditions all the elements of the system begin to run in critical mode, which means extra burden on conjugate pieces. This situation may lead to a cascade synergetic effect, and the system's correct overall operation may move beyond permissible limits. This is why, a necessary phase of the considered work involves testing the equipment for overall operability at ultralow temperatures. The procedure of these tests requires special consideration.

Particularities of natural and climatic environment of the Arctic; choosing the test mode

The choice of a necessary thermal testing mode is determined by the natural and climatic environment of the Arctic. The record-breaking temperatures taken in Verkhoyansk and Oymyakon in the Arctic region of Russia approached -68°C [XXII]. This is a fairly rare natural phenomenon beyond the allowable operating limits of electronic equipment. The equipment for such temperatures requires applying special approaches and solutions. In this paper this task is not considered.

The developed seismometer in question is intended for operation at temperatures not lower than -55°C. This ultralow temperature point was exactly the one at which the task to perform the current test was set.

In the actual natural setting the origination of a necessary weather condition with ultralow temperatures is fairly hard to foresee; even more so, they are hard to adjust. This was why the tests were conducted in a controlled laboratory environment at the necessary temperature of -55°C.

2) Testing Conditions and Procedure

Choosing a laboratory freezing plant

The tests were performed using a New Brunswick Scientific Premium U570 special-purpose laboratory freezing plant [XI]. The coolant usually applied in modern plants is type R508B that makes it possible to maintain sufficiently low temperatures right down to –86°C at a humidity of up to 98%, which confidently meets the requirements on these tests.

The considerations takenintoaccount when deciding to use the specified U570 model and the Premium series are exposed below. First of all, the design of U570 has a large effective chamber volume of 570 l that allows loosely placing the tested equipment. Secondly, a pointed reference should be made of the plant’s thermal insulation panels. In modern freezing chambers, for example, Innova U570 series, working space is often saved by means of dense and efficient vacuum panels. However, one should say that, because of spatially distributed hollow structures, these panels may display a certain acoustic resonant behavior, which will create additional interferences for seismoacoustic measurements. In the chosen Premium U570 plant this source of interferences is made absent by filling the panels with polyurethane foam, which ensures extra blanking and damping of all seismoacoustic interferences and vibrations while retaining thermal insulation properties.

The conclusion it is possible to derive from the foregoing consideration of the main parameters of the Premium U570 freezing plant is that it fully conforms to the necessary requirements and can be used in the cooling tests of the developed equipment.

Testing procedure

The cooling tests of the seismic modules were conducted in a room on the first storey of the institute’s main laboratory multistoried building. In that case, the first storey was chosen to minimize the microseisms caused by mechanical vibrations of the building structure. To abate the industrial interferences unavoidable in the urban setting it was decided to perform the test in the evening after the working hours.

The collation method used in the tests implies using two identical modules. The method’s gist is that the first module is put to the test and cooled, whereas the second one is used for reference and placed in normal conditions. Both modules are exposed to the same microseismic background existent in a given positioning point. The conclusion about the correct operation of the test module is derived by comparing its records with the records from the reference module. Their mutual correlation value serves as the numerical estimate.

In the case in question the test module was placed immediately to the freezing chamber. The other module identical to the first one was used for reference, placed in normal conditions, and not exposed to any cooling action. To ensure the maximally identical microseismic background, both modules were placed as close to one another as possible. The reference module was located outside on a solid panel of the plant housing.

II.iii. Laboratory Cooling Test Results

The modules in use had three components according to three space coordinates, including two horizontal and one vertical coordinates.The transfer characteristics of both seismic modules were previously carefully calibrated on a vibrating stand. The signals from the components were measured and recorded along independent channels. This paper provides only the results of the collation analysis of one vertical component as the most typical. The results for the horizontal components did not have any essential differences.

Preliminary control measurements at the lab under normal conditions

Before the beginning of the cooling tests, control recordings of the microseismic background were made under normal conditions at 20°C. The freezing plant was turned off. The seismic modules were placed according to the above pattern. The measurements and recording on the two modules were performed in synchronous mode.

A typical fragment of the recorded signals is shown in Fig. 3. It is seen that the noise signal is quasi-stationary. The signals (the red and the blue one) from the two modules can be distinguished and their nuances found on a shortened fragment. It is seen that the oscillations are random noise; however, despite its chaotic nature, the signals from the modules replicate one another fairly precisely in general and in all minor respects. This coincidence of the signals is a visual demonstration of the synchronicity of the measurements and the correctness of the collation analysis.

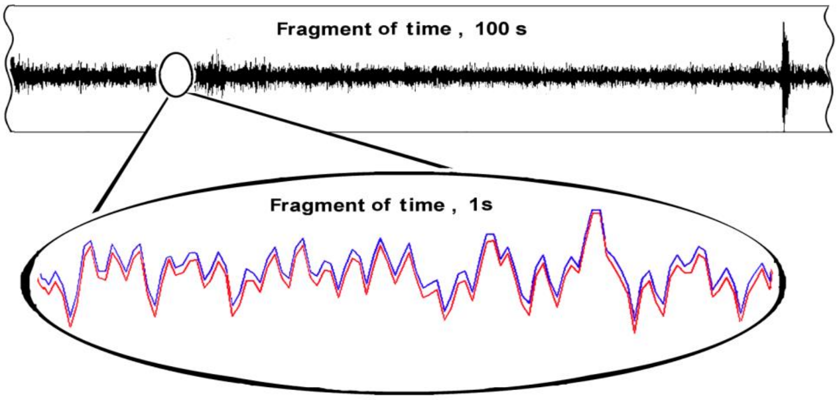

Fig. 3: Fragment of a typical microseismic noise signal

The passband is 0.1÷45 Hz. The recording was made synchronously using the two modules put in identical conditions. The signals from each of the modules can bedistinguished on a shortened fragment.

The respective Fourier spectrum of signals is shown in Fig. 4 in a range of 1÷10 Hz. This frequency range is of the utmost interest in monitoring and exploring petroleum and gas deposits. The spectrum was calculated according to the results of a fairly long record, which allowed exposing that spectrum to statistical processing, smoothening random surges, and attaining quite a sharply defined curve of the spectral image. The two curves distinguished in the plot correspond to the two collated modules. It is seen that the curves coincide with one another pretty accurately both, in their general view and in their fine structure. This also explicitly demonstrates the correctness of using the collation method in the spectral analysis.

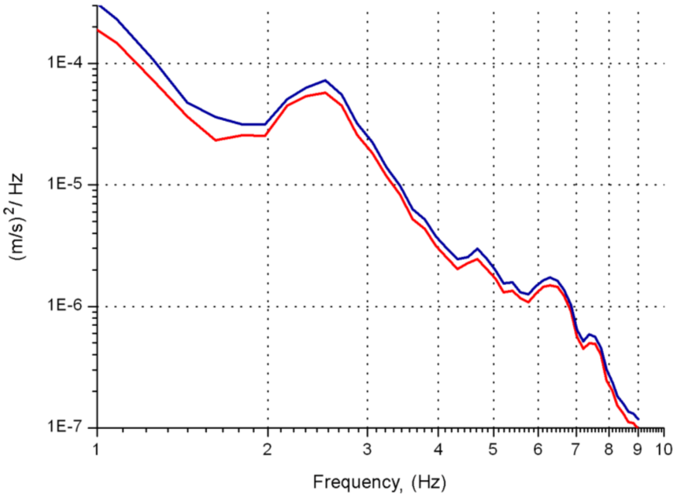

Fig. 4: Microseismic background spectrum in the laboratory building

A concrete numerical evaluation of the modules' identity can be made by correlation analysis. Curve 2 in Fig. 5 indicates the frequency diagram of the cross correlation coefficient of the recorded signals. It is seen that correlation K is pretty close to one and is in the range of 0.86÷1.00. Mind, however, that a far better correlation can be attained from to the identity of the modules by placing them on a single foundation (Fig. 5, curve1). The observed decline in correlation is determined by some difference in the seismic noises inside the freezing chamber and on its upper housing panel. Correlation analysis allows finding this difference and making a numerical evaluation.

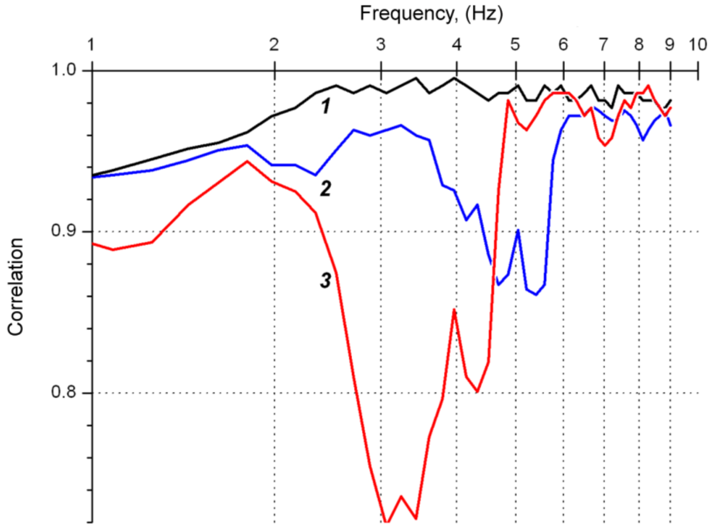

Fig. 5: Cross correlation of registered signals from the two collated seismic modules for different measurement conditions: 1 is the seismic modules placed on asolid base at the lab; 2 is the seismic modules placed in the freezing chamber; 3 is the seismic modules placed in the pit on the Kola peninsula

The control measurements have revealed a pretty good reciprocal identity of the modules, which justifies their subsequent use in putting the equipment to cooling tests by collation methods.

Laboratory tests at T=-55°C

To perform the test at ultralow temperatures, the module inside the freezing chamber was exposed to cooling. The positions of the modules corresponded to their placement in the previous control measurements.

At the initial startup of the freezing chamber its compressor begins to intensively run in forced mode. After some time the target in-chamber temperature of -55°C is reached.Then the plant enters temperature stabilization mode, when the compressor switches on from time to time only for short spans to maintain the target temperature. To provide the stationary thermal state of the whole module and each of its elements, the system was left in the given condition for 24 hours. Then, microseismic background recordings were made for the tested modules.

It is necessary to take into account that the compressor runs with pretty strong vibration interferences of about 56 dB. In this case the analysis of microseismic signals makes sense only when the compressor is off. Statistical processing requires a fairly long data array. The minimum interval between compressor starts is 15 minutes. In this case, more than a hundred windows can be processed for a Fourier transformation span of six seconds. The respective array of data is quite enough for exposing the signal to statistical appraisal.

The nature of the produced signals and the results of their processing do not essentially differ from the earlier control measurements and generally comply with the earlier correlation estimate (Fig. 5, curve 2).The numerical correlation estimate does not drop below 0.86 either.

Final control measurements at the lab under normal conditions

The cooling tests ended with additional repeated control measurements at a normal temperature of 20°C. The modules were left in their previous position, the freezing chamber was switched off, and it took 24 hours to attain the thermal balance with the ambient medium at the lab.

The repeated control measurements have shown a good reproducibility of the attained collation evaluations, which is yet another proof of their correctness.

On the whole, the low-temperature test results have shown that the seismic modules remain operable at an ambient temperature drop from 20 to -55°C. The measurements in such extreme conditions have not caused any major changes in the nature and spectrum of the recorded microseismic background. The reliability of the correlation evaluation results does not drop below 0.86, which is quite an allowable level for prospecting and exploration.

II.iv. Tests In The Actual Arctic Microseismic Noise Environment

As already said, the principal aim of this development is to provide operability to the equipment in question at ultralow climatic temperatures. At the same time, however, the equipment must be sensitive to extremely weak signals. This requirement stems from the passive nature of seismoacoustic methods.

Unfortunately, the cooling testing conditions did not allow evaluating the seismic module sensibility limit. This was because the technogenic background at the laboratory was pretty intensive and reached about 10^{-4} $(m/s)^2/Hz$ at a frequency of 1 Hz (Fig.6, curve 1). This level is far above the limits of natural microseismic noise according to the classical Peterson model (Fig. 6, curve NHNM) [II]. Therefore, the sensitivity limit evaluation required additional testing in a weak microseismic background.

The tests were performed on the Kola peninsula in the Arctic region known for its specific tectonic geology showing in increased seismic activity against very weak general microseismic background noises (Fig.6, curve 2). The area for installing the seismic sensors was chosen near the location of the Northern corrosion research station of the IPCE RAS (http://www.phyche.ac.ru/index.php/explore/2019-03-25-12-44-52/korrozionnye-stantsii). The point, where the seismic sensors were installed, was located further inland, several kilometres away from the shore of the Far Zelenets Gulf of the Barents Sea. The nearest source of potential technogenic noise was the Teriber HPP Cascade found at more than 30 km further away. Taking into account that the tests at ultralow temperatures had already been conducted, the tests at this stage were conducted under natural climatic weather conditions, actually registered on the test day (T~0°C).

Similar to the low-temperature tests, the testing at this stage was also carried out by comparison with the help of two modules. However, unlike in the above described tests, both modules were placed in identical thermal conditions. The measured signal intensity was pretty weak and could be compared with natural equipment noises. These equipment's noises restrict the opportunities for measuring weak microseismic signals. In this case, the two synchronous modules in use allow excluding uncorrelated equipment noises and distinguishing the effective signal component corresponding to microseismic oscillations.

The seismic modules under testing were placed in a specially dug rectangular shot pit of about 30 to 50 cm in depth and oriented in space strictly along the geographic axes of reference. Then the pit with the modules was backfilled with the excavated soil. The microseism recording process was launched a few hours after the necessary stabilization of the system’s overall state.In that case, steps were taken to rule out any technogenic or anthropogenic interferences in the immediate vicinity within a radius of about one kilometer. The recording was made for several hours for making it possible to analyze the dynamics of the microseismic processes, statistically process the random signals, and somehow reproduce short-term monitoring mode.

For the results of the correlationprocessing of the recorded microseismic background see Fig. 5 (curve 3). It is seen that the correlation curve remains at the previous high level, with a certain drop to 0.75 observed at 2.5÷4.5 Hz. The observed decline in correlation is probably determined by the manifestation of equipment flicker noises rising as 1/F.At lower frequencies below 2 Hz the microseismic background sharply intensifies according to the Peterson model and, possibly, suppresses the equipment noises. In such a case the correlation rises to the previous value of 0.9. The exposed correlation analysis allows making the conclusion about the validity of the taken weak microseismic background measurement

For the measured background level estimate see Fig. 6 (curve 3). It is seen that, on the whole, the spectrum complies with the Peterson model. The background intensity in a range of 1÷10 Hz is approximated to the bottom NLNM limit. Moreover, the resulting level is a hundredfold lower than the one measured at the seismic station on the Frantz Joseph Archipelago using a CMG-6TD precision sensor [VII] (Fig. 6, curve 2). It is seen that the detected signal is pretty weak and can be compared with limit natural noises 0.1 nm/s √Hz typical of classical primary electrodynamic sensors [VII].

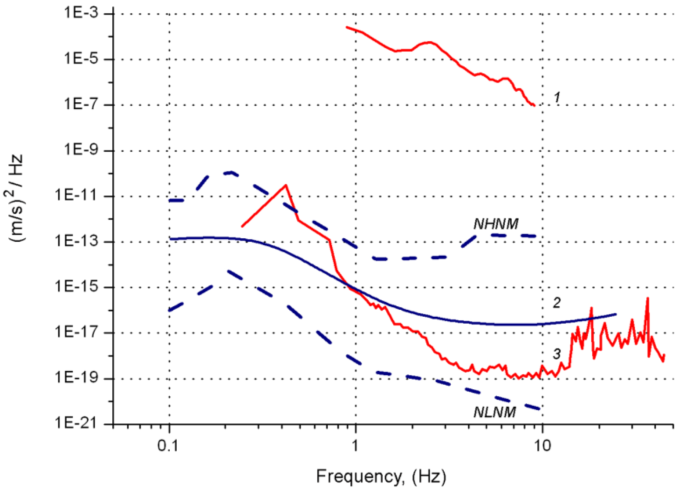

Fig. 6: Microseismic background spectra

NLNM and NHNM are the limits of the Peterson model; 1 is the background noise registered using the developed seismic module in the laboratory environment and 3 is the background noise registered in the actual setting on the Kola peninsula; 2 is the typical background noise at the seismic station on the Frantz Joseph Archipelago [VII].

The conclusion it is possible to derive from the results of the tests conducted in the realsetting with weak microseismic background noises is that the developed equipment meets the precision requirements and is capable of detecting extremely weak microseismic signals.

III.Conclusions

The basic criteria of developing seismic instruments and each component unit for operation in the expedition at ultralow climatic temperatures are formulated.

A seismic module testing procedure is developed, including the collation method and the correlation evaluation of measurements for validity.

A seismic module is created for exploring petroleum and gas in the climate of the Arctic by passive seismoacoustic methods.

The tests of the seismic modules performed at the lab at an ultralow temperature of -55°C have confirmed their operability.

The tests performed in the actual weak microseismic background setting of the Arctic have confirmed that signal measurements are possible at the level close to the bottom limit of the classical Peterson model.

The considered approach to developing the seismic module and the procedure of testing it can be useful in creating special-purpose geophysical equipment for operation at ultralow climatic temperatures, which will favor the general exploration of the Arctic.

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