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USING SIGNALS OF NAVIGATION SATELLITES IN THE MONITORING OF THE EARTH COVERS

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The features and capabilities of remote sensing of earth covers by means of signals of navigation satellites are presented. The methods of reflectometry of the surfaces of earth covers and radioscopy of forest canopy are described. The options for using the signals of GLONASS, GPS systems are considered. Test measurements of interference diagrams were carried out on 5 test platforms from heterogeneous soil surfaces: salt marshes and asphalt; water surfaces of saline and freshwater bodies in summer, including ice cover of small thickness in the period of autumn freeze-up. The method of radioscopy helped obtain the data on the spatial and temporal characteristics of attenuated signals of the GLONASS and GPS satellites in the pine forest. Estimates of the linear attenuation coefficients of the signals passing through a forest canopy with a coordinate reference were made. The results obtained are the basis for the development of methods and technologies for continuous monitoring of the characteristics and state of earth covers by means of signals of navigation satellites for solving a wide range of applied tasks.

Keywords: signals of navigation satellites, attenuation and reflection, remote sensing of the Earth, earth covers.

ИСПОЛЬЗОВАНИЕ СИГНАЛОВ НАВИГАЦИОННЫХ СПУТНИКОВ В МОНИТОРИНГЕ ЗЕМНЫХ ПОКРОВОВ

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Представлены особенности и возможности дистанционного зондирования земных покровов с помощью сигналов навигационных спутников. Описаны методы рефлектометрии поверхностей земных покровов и радиопросвечивания лесного полога. Рассмотрены варианты использования сигналов систем ГЛОНАСС, GPS. Проведены тестовые измерения интерференционных диаграмм на 5 тестовых площадках от гетерогенных почвенных поверхностей: солончаки и асфальт, водные поверхности соленых и пресных водоемов в летний период, включая ледовое покрытие малой толщины в период осеннего ледостава. Методом радиопросвечивания получены данные о пространственно-временных характеристиках ослабленных сигналов спутников ГЛОНАСС и GPS в сосновом лесу. Сделаны оценки значений коэффициентов погонного ослабления проходящих через лесной полог сигналов с координатной привязкой. Полученные результаты являются основой развития методов и технологий непрерывного мониторинга характеристик и состояния земных покровов с использованием сигналов навигационных спутников для решения широкого спектра прикладных задач.

Ключевые слова: сигналы навигационных спутников, ослабление и отражение, дистанционное зондирование Земли, земные покровы.

Introduction. Signals of the global navigation satellite systems (GNSS) are hi-tech and allow in a continuous wave mode to recover electrophysical parameters of environments which they interact with during propagation, along with coordinate measurements, almost in a real time. The GNSS have a significant resource for monitoring earth covers – the coherent and polarized pulse radio signals of multifrequencies passing the near-earth space of the ionosphere and atmosphere reflected and scattered by the surface of earth covers. The radiometry of changes of the signal characteristics transformed by environments allows recovering these environments' electrophysical characteristics significant for practice. They are coefficients of reflection from the boundary line of earth surfaces, phase delays and transmission coefficients of volume environments – ionosphere, atmosphere, vegetation, snow and ice covers [1–3].

Actually navigation satellite systems allow implementing the global radiometer at operating frequencies of the functioning and completely deployed GPS and GLONASS groupings. The periods of revolution of the GLONASS and GPS satellites make up to 11 h 16 min. and 11 h 57 min. accordingly. The receiving equipment registers about 10 scanning series of the signals transformed by the studied object within one hour. The frequency of registered changes of the parameters is 1 Hz [4]. The recovery of temporary changes of environment characteristics of earth covers is theoretically possible in time intervals with discreteness of 1 second. Space localization of these changes is limited by the accuracy of coordinate measurements of the functioning navigation systems.

The specifics of interaction of GNSS signals with the objects of sounding is defined by the parameters of probing radiation and electrophysical characteristics of earth covers. This fact requires the development of both special receivers and methods of processing of experimental data, and models of interaction of a pulse coherent radio emission with various environments of earth covers.

GNSS – reflectometry. The method works as a bistatic radar device: a system where a transmitter and a receiver are spaced-apart by a considerable distance. This definition can be expanded to a system where one receiver can monitor simultaneously the diversity of bistatically scattered signals from a set of different transmitting sources. The scheme of formation of an interferential signal is presented in fig. 1. The signals registered by the receiver from different devices with angular data of lateral angle φ and elevation angle above the horizon θ create an interferential field in the receiving point:

$$E^2 = E_0^2\left[1 + r^2 + 2r\cos\left(\frac{4\pi h \sin\theta}{\lambda}\right)\right], \qquad (1)$$

where h is the height of the antenna; θ is an arrival angle of the electromagnetic wave coming from the navigation satellite; r is a reflection coefficient (for linear and circular polarization).

The interferential field in the receiving point is created by forward signals from the navigation satellite transmitter and reflected from soil, water and snow-and-ice surfaces.

The information on a variation of characteristics of GNSS forward signals on the channel of the transmitter and receiver in an empty space, depending on the time, angle of altitude and azimuth is necessary for processing the primary data about scattered and reflected signals by the earth surface. The changes in the state of GNSS signals polarization and amplitude which occur during the interaction with environments surface and volume as well as considering the variations of forward signals characteristics allow to recover correctly effective values of a number of parameters, significant for monitoring. They are reflection coefficients of earth surfaces to determine the thickness and terrain of snow and ice covers, humidity of soil and grassland vegetation [2; 5–12].

Test measurements and platforms. A series of test measurements of the interferential diagrams (IDs) is carried out for earth covers: soils, saline and freshwater bodies, ice. There is a platform ("an antenna field") on the territory of the hospital of Krasnoyarsk Scientific Center (KSC) where the surface of the soil is with small variations of a terrain and sites with essential distinctions in composition and reflective characteristics of navigation satellites signals within the range of L1, fig. 2.

The scene of carrying out the measurements is presented in fig. 2, *a*. The use of GLONASS satellites demonstrated on the polar diagram of fig. 2, *b* would allow receiving IDs of the area of effective scanning with various sites: the soil with grassland vegetation, the soil covered with asphalt and the compacted motor road ground.

The test registration of IDs was carried out on this platform for the purpose of identification of selective opportunities of the GNSS-scatterometry method in diagnostics of characteristics of surface soil and vegetation state. The receiving dipolar antenna focused vertically was located at a distance of 6 meters from the asphalt platform and a traffic-compacted motor road. The elevation of the antenna phase center was 4.2 m. The coordinates of the receiving antenna were 54°29'36.1" N, 90°08'29.8" E, the absolute altitude (the Baltic Sea level altitude) was 398 m. The registration was carried out by MRK-32 receiver. The session duration was 2 h. 23 min. Moderate rain was registered within 20 minutes at the closing stage.

The IDs, created by GLONASS navigation satellites 9, 10 and 11 are presented in fig. 3. These IDs contain the characteristic sites connected with reflection from the horizontal asphalt platform, the traffic-compacted road and a natural soil with grassland vegetation. The rehabilitation of the soil humidity and its characteristics are possible on the basis of specialized dielectric models.

Amplitude characteristics are registered on IDs with a frequency of 1 Hz and are followed by the record of angular coordinates of the navigation satellite. These data allow determining coordinates of the platform which reflects a signal and local reflective characteristics of the soil surface. The values of reflection coefficients are connected with granulometric and mineral composition of the soil, humidity and existence of vegetation.

There was held a registration session of IDs of salt Lake Shira surface and waterside soil. The antenna was located on the shore in the vicinity of the water surface. The lakeshore has a flat terrain with a grade of about 10°, with rare grassland and shrub vegetation. The soil type is saline. The registration scene of IDs and the polar diagram of satellites trajectories of sequential scanning of water and soil surface are presented in fig. 4.

The dipolar antenna focused vertically was used. It was located at the distance of 3.2 meters from the border of the water surface. The elevation of the antenna phase center was 4.5 m from water level. The coordinates of the receiving antenna were 54°30'22.9" N, 90°08'55.9" E, the absolute altitude was 338 m. The registration was carried out by MRK-32 receiver. The session duration was 3 h. 10 min. Fig. 5 presents IDs containing characteristic sites connected with the reflection from the surface of water and waterside soil.

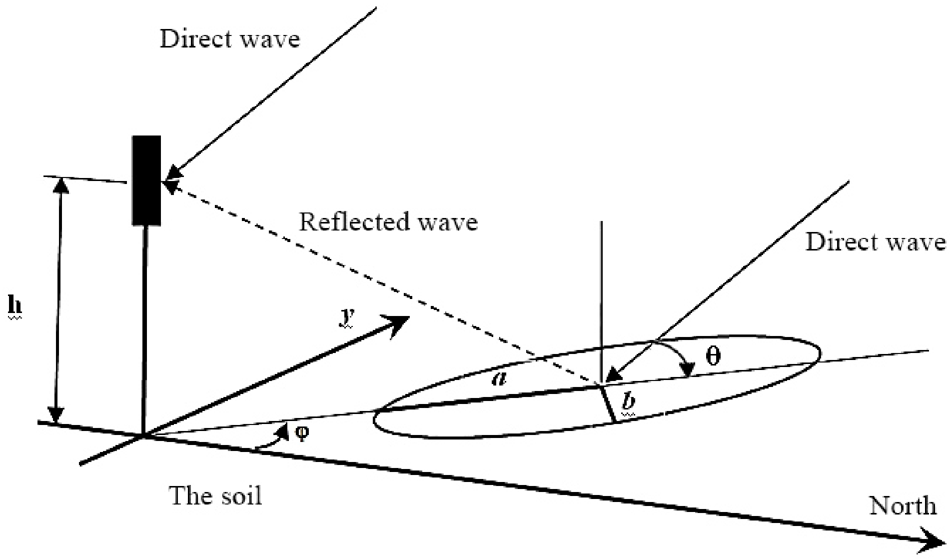
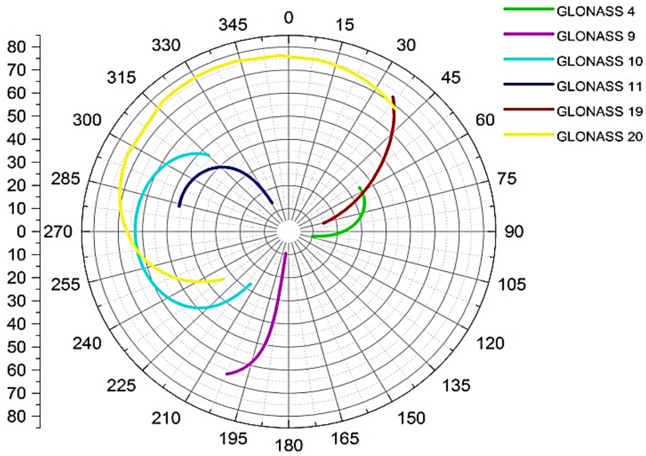


Fig. 1. The scheme of formation of the interferential signal at the receiving antenna

Рис. 1. Схема формирования интерференционного сигнала на приемной антенне



a *b*

Fig. 2. Experimental platform of "antenna field":
a – is an Interferential diagrams (ID) measuring scene on the test platform of the soil of the KSC hospital; *b* – is a polar diagram of the angular coordinates of effective scanning satellites of the "antenna field" test platform

Рис. 2. Экспериментальная площадка «антенное поле»:
а – сцена измерений интерференционной диаграммы (ИД) на тестовой площадке почвы стационара ФИЦ КНЦ; *б* – полярная диаграмма угловых координат спутников эффективного сканирования тестовой площадки «антенное поле»

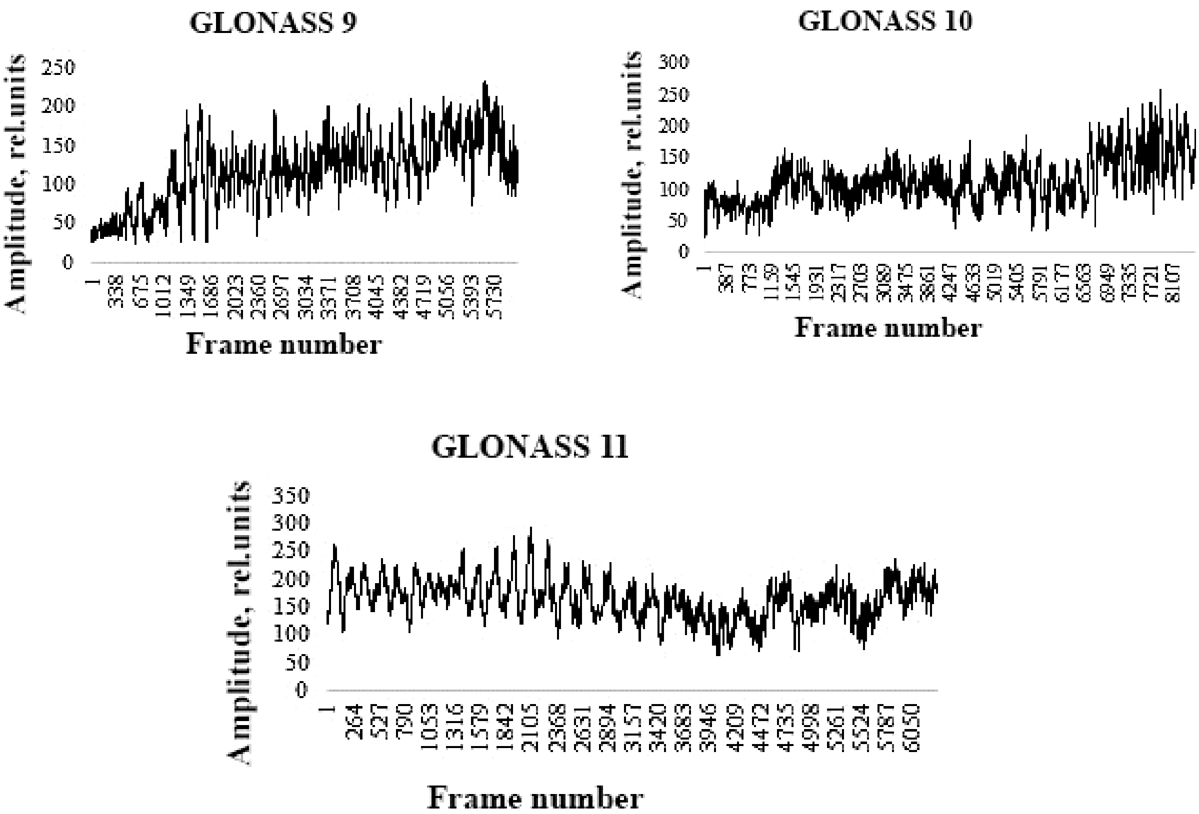
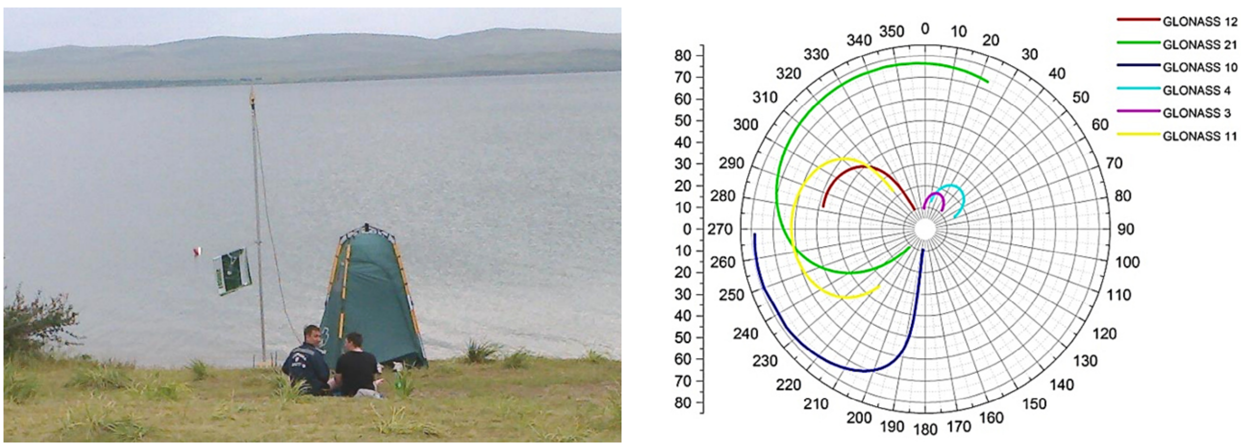


Fig. 3. ID of the test soil platform, soil sites:
GLONASS 9 – mostly horizontal asphalt platform; GLONASS 10 – mostly grassy soil with a rough terrain;
GLONASS 11 – equivalent parts of the road and soil with a rough terrain

Рис. 3. ИД тестовой площадки почвы, участки почвы:
ГЛОНАСС 9 – преимущественно горизонтальная асфальтовая площадка; ГЛОНАСС 10 – преимущественно травянистая почва с шероховатым рельефом; ГЛОНАСС 11 – эквивалентные части дороги и почвы с шероховатым рельефом



a *b*

Fig. 4. Test platform “Lake Shira”:
a – is a registration scene of IDs on the shore of salt Lake Shira; *b* – is a polar diagram of the angular coordinates of GLONASS satellites of the test platform of “Lake Shira”

Рис. 4. Тестовая площадка «оз. Шира»:
а – сцена регистрации ИД на берегу соленого озера Шира; *б* – полярная диаграмма угловых координат спутников ГЛОНАСС тестовой площадки «оз. Шира»

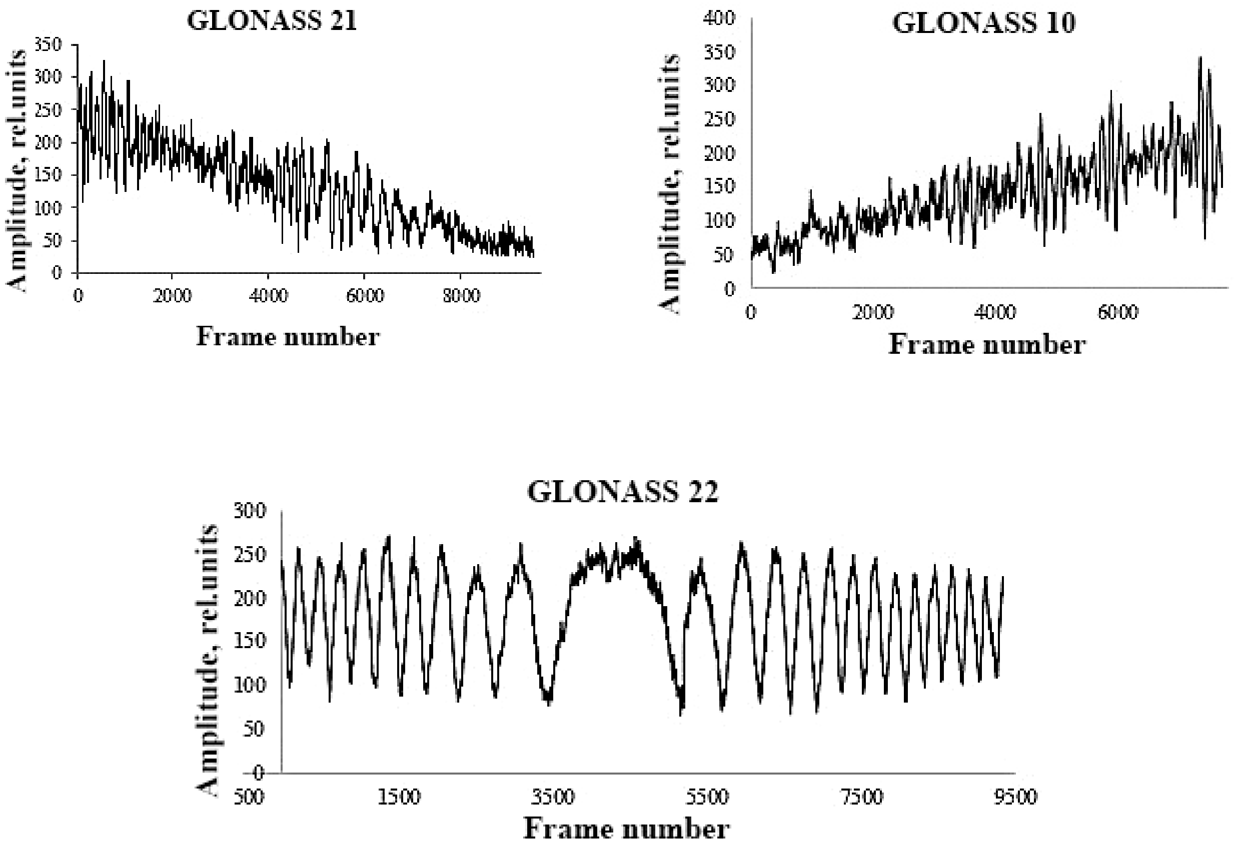


Fig. 5. IDs of the test platform:
GLONASS 21 – water site and shore; GLONASS 22 – mainly water surface;
GLONASS 10 – soil with a rough terrain and reasonable gradient

Рис. 5. ИД тестовой площадки:
ГЛОНАСС 21 – участок воды и берег; ГЛОНАСС 22 – преимущественно водная поверхность;
ГЛОНАСС 10 – почва с шероховатым рельефом и умеренным уклоном

The nature of spatiotemporal dependence of IDs is caused by significant difference of reflection coefficients and the terrain of the surficial reflecting water and soil layer.

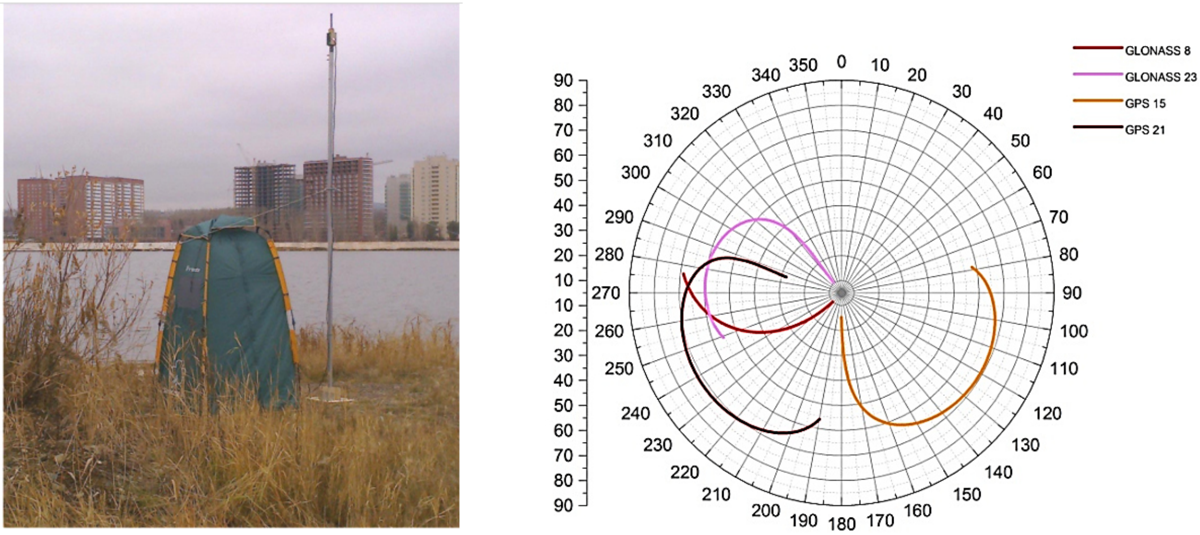
The registration session of a surface of a fresh lake in the vicinity of Krasnoyarsk was held. The dipolar antenna focused vertically was located at the distance of 7 meters from the border of the water surface. The elevation of the antenna phase center was 4.4 m from water level. The coordinates of the receiving antenna were 56°03'49.9" N, 92°43'46.0" E, the absolute altitude was 170 m. The registration was carried out by MRK-32 receiver. The session duration was 3 h. 13 min. The registration scene of IDs and the polar diagram of satellites trajectories of sequential scanning of water and soil surface are presented in fig. 6, 7.

The nature of spatiotemporal dependence of IDs is caused by significant difference of reflection coefficients and the terrain of the surficial reflecting water and soil layer. Unlike the registration session on Lake Shira, the waterside of the fresh lake had flatter terrain and a layer of grassland and shrub vegetation.

There was held a registration session of an ice surface on the fresh lake in the vicinity of Krasnoyarsk with ice 4 cm thick. The registration scene and the polar diagram of angular coordinates of navigation satellites with the trajectories of effective scanning are presented in fig. 8.

The dipolar antenna focused vertically was located at the distance of 9 meters from the border of the water surface. The elevation of the antenna phase center was 4.4 m from water level. The coordinates of the receiving antenna were 56°03'50.0" N, 92°43'45.9" E, the absolute altitude was 170 m. The registration was carried out by MRK-32 receiver. The session duration was 2 h. 55 min.

Real part of complex dielectric capacity of fresh water at frequencies of 1–2 GHz and temperatures near zero is about 80, the one of ice is about 3. The presence of an ice layer essentially reduces the reflection coefficient of navigation satellites radio signals from the border of air-ice and additionally results in the interferential effect of a multilayer structure of the borders of air-ice and ice-water [12]. The IDs, created by GLONASS navigation satellites 18, 24 and GPS navigation satellite 21 are presented in fig. 9.



a *b*

Fig. 6. Sequential scanning of water and soil surfaces:
a – is the registration scene of IDs on the shore of a freshwater lake in the vicinity of Krasnoyarsk;
b – is a polar diagram of the angular coordinates of GLONASS satellites of the test platform on the shore of a freshwater lake in the vicinity of Krasnoyarsk

Рис. 6. Последовательное сканирование водной и почвенной поверхностей:
а – сцена регистрации ИД на берегу пресного озера в окрестности г. Красноярска; *б* – полярная диаграмма угловых координат спутников ГЛОНАСС тестовой площадки на берегу пресного озера в окрестности г. Красноярска

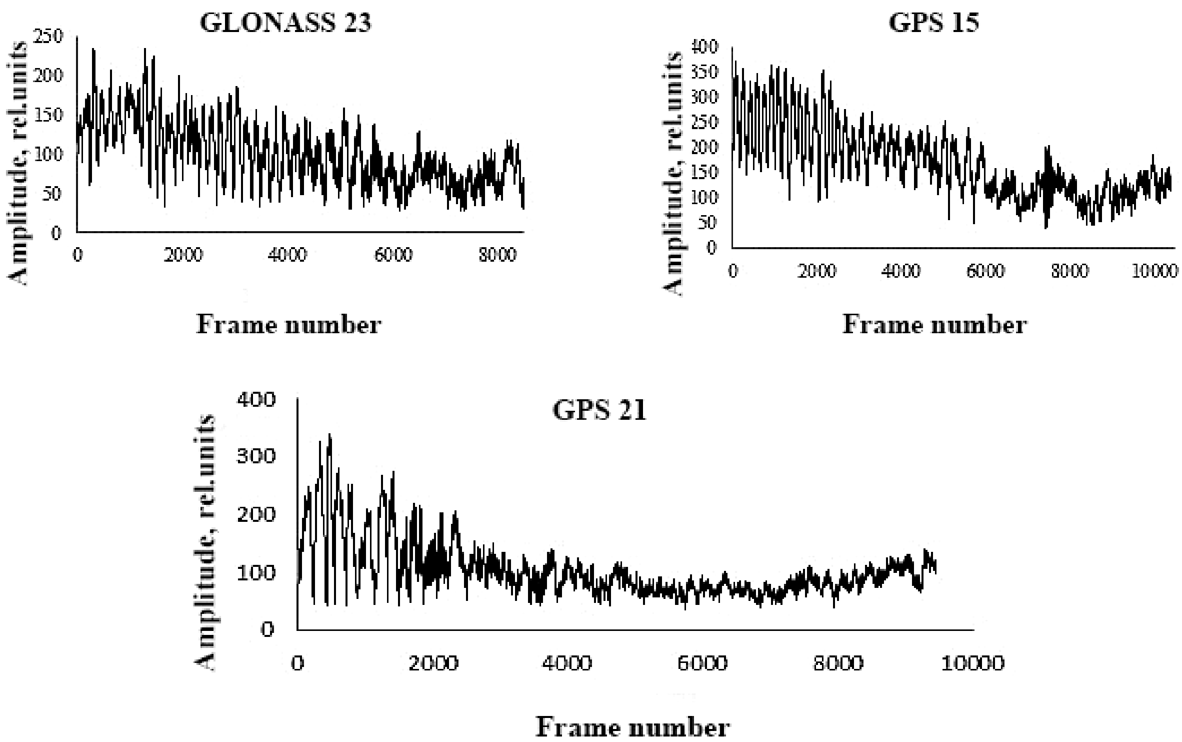
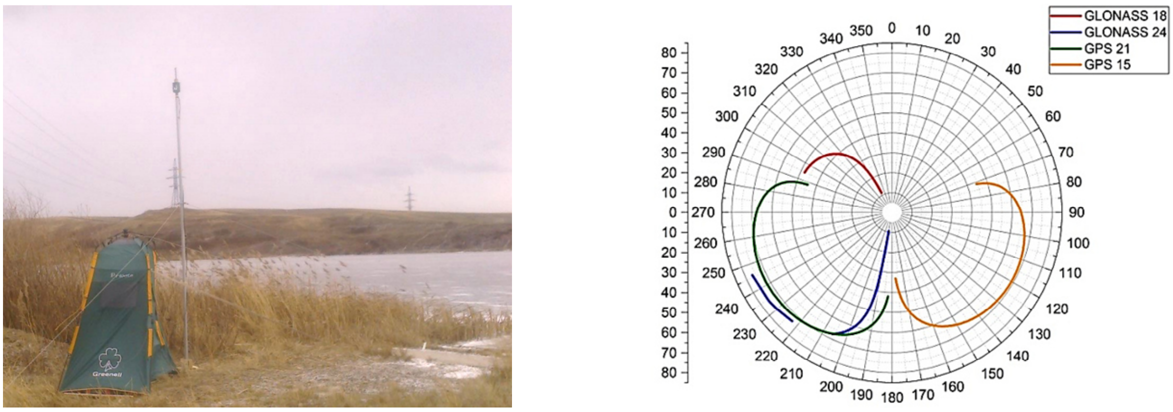


Fig.7. IDs of the test platform:
GLONASS 23 – shore site with natural soil; GPS 15 – mainly water surface; GPS 21 – shore and water surface

Рис. 7. ИД тестовой площадки:
ГЛОНАСС 23 – участок берега с естественной почвой; GPS 15 – преимущественно водная поверхность; GPS 21 – берег и водная поверхность



a *b*

Fig. 8. Sequential scanning of ice and soil surfaces:
a – is a registration scene of the IDs on the shore of the freshwater lake with ice cover; *b* – is a polar diagram of the angular coordinates of GLONASS and GPS satellites of the test platform on the shore of freshwater lake with ice cover

Рис. 8. Последовательное сканирование ледовой и почвенной поверхностей:
а – сцена регистрации ИД на берегу пресного озера с ледовым покрытием; *б* – полярная диаграмма угловых координат спутников ГЛОНАСС и GPS тестовой площадки на берегу пресного озера с ледовым покрытием

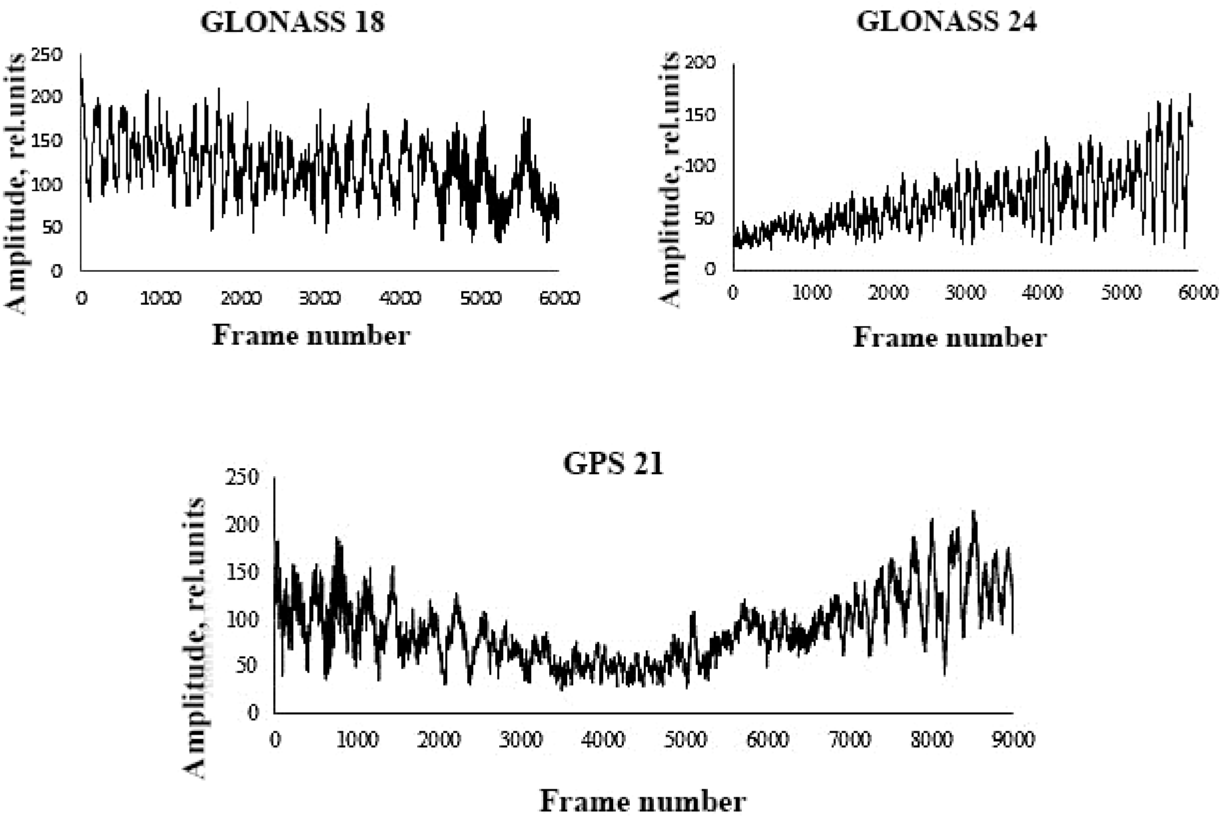


Fig. 9. IDs of the test platform:
GLONASS 18 – the shore site covered with snow; GLONASS 24 – mainly ice;
GPS 21 – the site of ice and shore covered with snow

Рис. 9. ИД тестовой площадки:
ГЛОНАСС 18 – участок берега, покрытый снегом; ГЛОНАСС 24 – преимущественно лёд;
GPS 21 – участок льда и берега, покрытого снегом

Interferential effects of a multilayer structure of water-ice are shown the most contrasting in the experimental data given above. The boundary lines of water-ice and ice-air are geometrically almost ideal, dielectric capacity of both environments are known. Direct measurements of thickness of an ice cover are available. There is a real perspective for development of an operational method and tool for remote measurement of thickness of an ice cover and its uniformity during the period from a freeze-up till spring destruction.

Radioscopy of the forest. There are many factors influencing radiowave propagation in a forest cover, they are caused by structural features of a forest crop and separate trees, a variety and seasonal changes of their electrophysical characteristics depending on the frequency range of radio waves [13–18]. The main reasons of characteristics changes of an electromagnetic field of GNSS signals in a reception point are:

1. Processes of attenuation due to losses of energy in stems, branches, needles and leaves;
2. Processes of diffraction on structure elements of trees that results in fluctuations of a radio signal amplitude and phase, change of its spectrum during wind loads on trees;
3. The resultant electromagnetic field in a reception point that represents an interferential field which constituents are:

– field components disseminated after diffraction;

– arising additional (for example, orthogonal) components of an electromagnetic field resulting in cross-polarization of the received signal;

– field reflection from the geological substrate of the forest resulting in additional fluctuations of a radio signal;

– change of forest density with seasonal changes resulting in change of a specific attenuation coefficient;

– change of forest humidity with the change of weather conditions;

– change of position of tree elements depending on a wind load resulting in field fluctuations;

Forests in terms of distribution and reflection of radio waves are heterogeneous environments which have electrodynamic parameters depending on the factors given above.

Currently, there is no uniform classification of forests. Different countries of the world classify forests by different characteristics.

There are some variants of the forests classification by geographic location (southeast, northwest forests), climate (tropical, subtropical, continental), type of prevailing vegetation (coniferous, broad-leaved, mixed), land configuration. Other forest classifications use the combination of morphological and seasonal characteristics (e.g. the evergreen coniferous or broad-leaved deciduous forests).

Depending on growth conditions (in open terrain or in forests), trees have the following features:

– trees, growing in open terrain, have branches practically all over the trunk, forming their crowns extended along the whole trunk height, with a different-scale set of structural elements: trunks, branches, needles, leaves;

– trees growing in forests, as a rule, have vertical direct trunks, their crowns have fewer branches which are placed closer to the top, in comparison with trees growing in open terrain [13].

Electrophysical characteristics of forests have a significant variable parameter – humidity. The amount of water in the wood of a growing tree varies from 30 to 100 % and is the indicator of a tree physiological state. A significant amount of atmospheric moisture in the forest area is held by tree crowns.

The general dielectric model of forests of different types and ages is a heterogeneous layered environment. The layer of trunks and the layer of crowns contain various elements: trunks, branches, needles, leaves. The layer of trunks as a set of vertically oriented trunks has a vertical extent equal approximately to the average height of a tree of the selected platform of a forest crop. The crown layer extent is determined from the tree top to the lower layer of alive branches. As a rule, both layers intercross, forming a structurally mixed environment.

The particularity of GNSS signals is a limited frequency range which wave lengths of radiation are comparable to the characteristic sizes of trunks and parts of branches, but much more than the sizes of needles and leaves. The two-layer dielectric model of the forest area allows calculating an effective dielectric capacity (EDC) separately for the layer of crowns and the layer of trunks. Wood substance of trunks and branches has anisotropic dielectric capacity [19]. Considering the anisotropy of the dielectric capacity of wood substance gives opportunity to structure a forest canopy on statistically isotropic layer of crowns and an anisotropic layer of trunks.

Spatiotemporal coordinates of navigation satellites position in combination with coordinates of location of the antenna and the border of the forest area allow determining precisely the trajectory of the signal trace through a forest canopy and the movements of the scattering volume of a forest canopy. This circumstance makes it possible to determine the coefficient of a linear attenuation with a coordinate referencing and to recover EDC connected with the biomass and humidity of a forest crop.

The antenna location was chosen near the forest border with a field of grassland vegetation with coordinates 55°59'27.7" N, 92°45'42.6" E. The standard antenna of the MRK-32 equipment was used. The elevation of the antenna over the soil level was 2.8 m. The axis of the antenna directional pattern was set up vertically. The antenna was located at the distance of ~ 1 m from forest crop border. The duration of continuous registration was 3 hours.

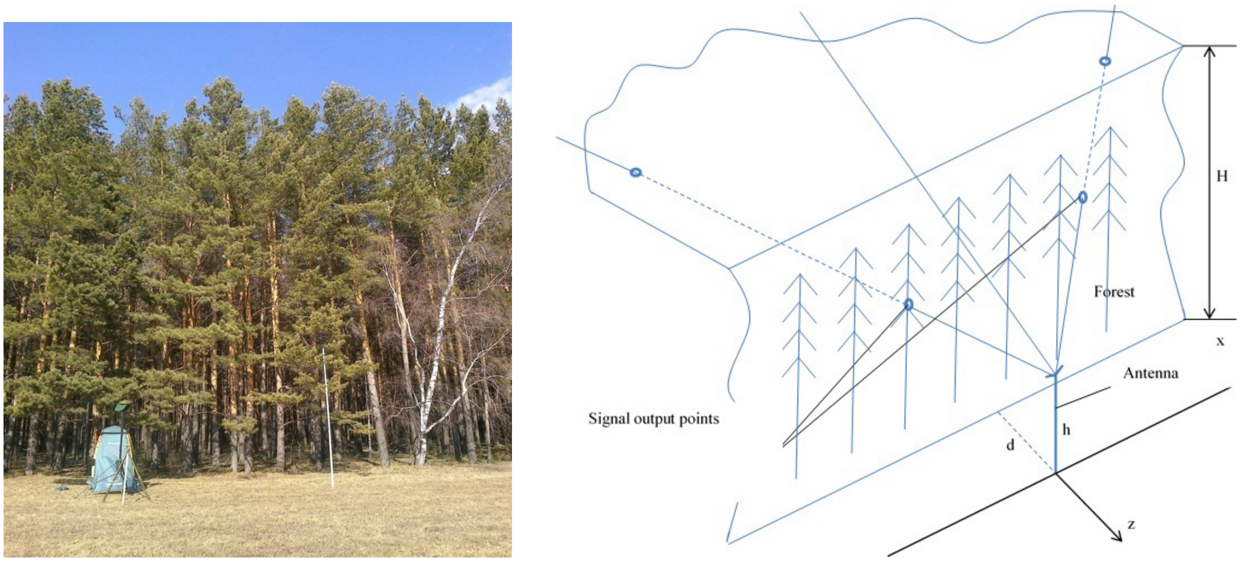
The scene and the scheme of measurements are presented in fig. 10.

The site of pine plantings of the forest belt is located near the Institute of physics, Siberian Branch of the Russian Academy of Science. The age of plantings is about 60 years old. Its category is a dense forest. The average values of tree parameters are: height of trees is 22 m, extent of crowns is 6 m, diameter is 0.26 m, distance between trees is 3.5 m. The trees are planted in lines, distance between lines is 3–4 m, the trees are not arranged inside a line, distances variance is from 1 to 10 m. Vertical extent of crowns inside the forest area is within 25 % of a tree height. There is no shrub layer. The direction azimuth of lines and borders of the forest belt is 47°.

The spatiotemporal dependences of the amplitude of the GNSS signals on time are given in fig. 11. The signal which passed through a forest canopy (wood) is drawn in red colour, the signal which passed through an empty space is drawn in black colour.

The change of signal amplitude differs considerably on signal traces through a forest and an empty space. The characteristic "grass" of the amplitude in an empty space is connected with the generator and receiver noise as well as with fluctuations of dielectric capacity of atmosphere and ionosphere.

When entering a forest canopy the signal attenuates on large-scale heterogeneity (tree trunks, large volumes of snow on branches, difference of their distribution in space) and is partially absorbed by small-scale elements of trees (thin branches, needles, leaves).



a *b*

Fig. 10. Scene and scheme of measurements:
a – is a scene of radioscopy of the forest; *b* – is a scheme of radioscopy of the forest with the antenna location near the forest crop border

Рис. 10. Сцена и схема измерений:
а – сцена радиопросвечивания леса; *б* – схема радиопросвечивания леса с расположением антенны у границы древостоя

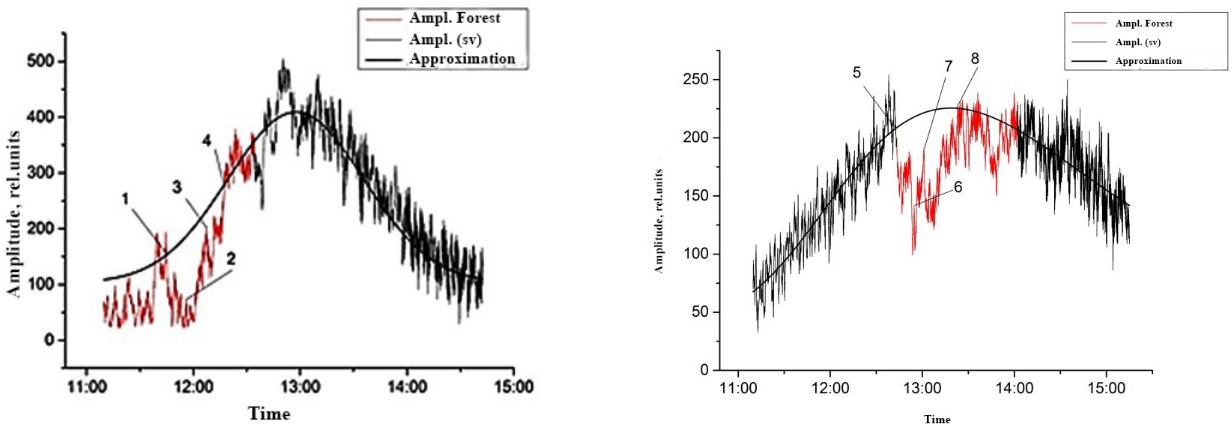


Fig. 11. The dependence of the amplitude of the GNSS signals on time.
1–8 are points of calculation of the coefficient of linear attenuation (table)

Рис. 11. Зависимости амплитуды сигналов ГНСС от времени.
1–8 точки расчета коэффициента погонного ослабления (см. таблицу)

Coefficient of linear attenuation in a forest crop

Point number	1	2	3	4	5	6	7	8
Azimuth (α), degrees	307.98	302.74	293.1	278.74	230.55	237.80	243.76	313.97
Angle of altitude (φ), degrees	59.06	64.69	69.78	73.24	66.69	72.75	76.11	84.75
L, m	19.47	17.64	15.73	13.44	20.54	11.13	12.58	13.83
– γ, dB/m	0.007	0.533	0.085	0.008	0.006	0.391	0.122	0.004

Spatiotemporal coordinates of navigation satellites position in combination with coordinates of location of the antenna and the border of the forest area allow determining precisely the trajectory of the signal trace through a forest canopy and the movements of the scattering volume of a forest canopy. This circumstance makes it possible to receive electrophysical characteristics of the forest and to recover humidity and biomass of a forest canopy with a coordinate referencing. Length of the trace (L) which the signal passed in the forest is calculated by the formula:

$$L = \frac{(H-h)\cos(\alpha) - d\mathrm{tg}(\varphi)}{\cos(\alpha)\sin(\varphi)}, \quad (2)$$

where H is the average height of trees; h is the elevation of the antenna location; d is the distance from the antenna to the forest edge; α is a satellite azimuth; φ is a satellite elevation angle.

We approximate the signal which passed through an empty space taking into account the shape of the total curve received earlier for each satellite in the database of forward signals characteristics of the GLONASS and GPS groupings [8; 9]. Further, taking into account the position of the amplitude maximum at the elevation angle maximum value, we extrapolate the function for amplitude dependence of a forward signal from time by the time of a signal transmission through the forest. We determine signal amplitudes and corresponding to them traces lengths in the forest, we calculate coefficient values of linear attenuation γ for the selected points (frames) in fig. 11:

$$\gamma = -\frac{10 Ln \frac{P}{P_0}}{L}, \quad (3)$$

where P is the amplitude of a signal which passed through the forest; P_0 is the signal amplitude of an empty space. The results of calculation of linear attenuation coefficient for points 1–8 are given in table.

Variations of attenuation coefficients values are connected with spatial heterogeneity of distribution of trees elements throughout the forest canopy. It is possible to form a speckle pattern of a radio field of GNSS coherent signals scattered by the forest.

Conclusion. There were carried out test measurements of interferential diagrams from heterogeneous soil surfaces (salt marshes, asphalt), water surfaces of saline and freshwater bodies in summer period as well as at temperatures of an autumn freeze-up, including an ice covering of small thickness (4 cm).

The method of determination of local coefficient of linear attenuation of navigation satellites signals in a forest canopy was developed and approved along with the method of radioscopy of a forest area. The calibration variant was used according to a continuous consecutive writing of forward and analytical signals. Measurements of the linear attenuation coefficients of navigation satellites signals were made in the pinetum forest crop.

The received results are the basis for development of methods and technologies of continuous monitoring of earth covers characteristics and condition with the help of navigation satellites signals to solve a wide range of applied tasks.

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