

EMP 1.0

Electro Magnetic Processor

User manual

2019

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Purpose of the program

The **EMP** program is developed for quick processing and quality control of electromagnetic sounding data for various methods. The main purpose of the program is the conversion of the original time series of multi-channel recorders into the frequency spectra of the transfer functions of the geoelectrical section.

Version 1.0 is focused on data processing of the following methods:

- magnetotelluric soundings (MT);
- audiomagnetotelluric soundings (AMT);
- controlled-source audiomagnetotelluric soundings (CSAMT);
- radiomagnetotelluric soundings (RMT);
- controlled-source radiomagnetotelluric soundings (CSRMT).

The processing of MT and AMT sounding data is performed in the variant without a remote reference data (Single station).

The **EMP** program implements a multi-level data quality control system that takes into account the statistical parameters of the initial time series, the result of robust weighing of single realizations (windows) in the process of estimating the transfer functions of the geoelectric section and the characteristics of the transfer functions themselves.

Table 1 contains a list and description of the data formats supported by the **EMP** program.

Table 1. Data formats, supported by EMP 1.0 program.

Формат данных	Регистратор	Производитель
*.sbf (SM27)	AKF-4M	SPBU, "Mikrocor"
*.sbf (SM25)	RMT-F	SPBU, "Mikrocor"
*.sbf	ARMT-5	"Geodevice"
*.dat, *.log	VMTU-10	VEGA Geophysics
*.tbl, *.tbo, *.tsh, *.tsl, *.ts2, *.ts3, *.ts4, *.ts5	V8, MTU, MTU-A, RXU	Phoenix Geophysics
*.ats	ADU, TXB-07	Metronix geophysics

System requirements

The **EMP** program is вумудщзув to work on personal computers running Windows 7, 8, 10. For normal operation, the program requires at least 500 MB of RAM. The [Microsoft .NET Framework 4.6.1](#) library package must be installed on the computer for the **EMP** program to work.

Start screen

When you run **EMP**, the start screen appears (**Figure 2**).

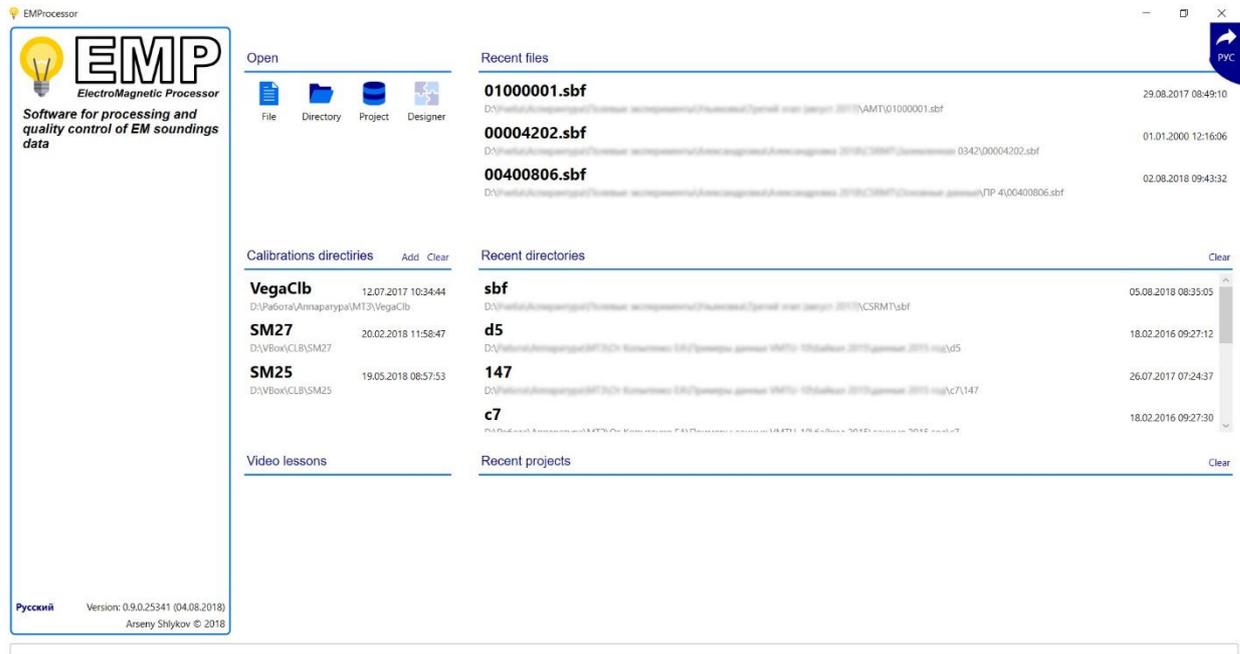


Figure 1. Start screen of the **EMP 1.0** program.

Main functions of the start screen are described below:

1. Change the user interface language between Russian and English. To change the language, use the hyperlink with the corresponding inscription in the lower left corner of the screen and a similar inscription on the blue pop up tongue in the upper right corner of the screen.
2. The “**Open**” section.
 - 2.1. Click on the “**File**” button opens standard open-file dialog. Current version this dialog allows to open ***.sbf** и ***.ats** files.
 - 2.2. Click on the “**Directory**” button opens standard open-directory dialog for select directory containing necessary data files. The search is conducted in both the selected directory and in all subdirectories. The search is performed on all available file formats with the appropriate grouping of data.
 - 2.3. Click on the “**Project**” button opens standard open-file dialog for selection **EMP** project file – internal binary format of **EMP** program.
 - 2.4. Click on the “**Designer**” button opens screen of manual designer unstructured data for loading and processing in the **EMP** program (will be done in the next versions).
3. Sections “**Recent files**”, “**Recent directories**”, “**Recent projects**” contain information about recently opened data. Double click on the line from the corresponding list opens the selected item (file, folder or project).
4. Section “**Calibrations directories**”. Here you have to add links to directories containing calibration files required for data processing. **Important:** The **EMP** program works only with text analogues of the original binary calibrations of various equipment manufacturers.
5. Section “**Video lessons**” contains links to online tutorials by using the **EMP** program.

If you have opened a file or directory and the data has been read without errors, you will see the data processing screen.

Data processing screen

Figure 2 illustrates the data processing screen. To go to the start screen, press the button in the form of a white rounded arrow located on the pop-up blue tongue in the upper left part of the data processing screen

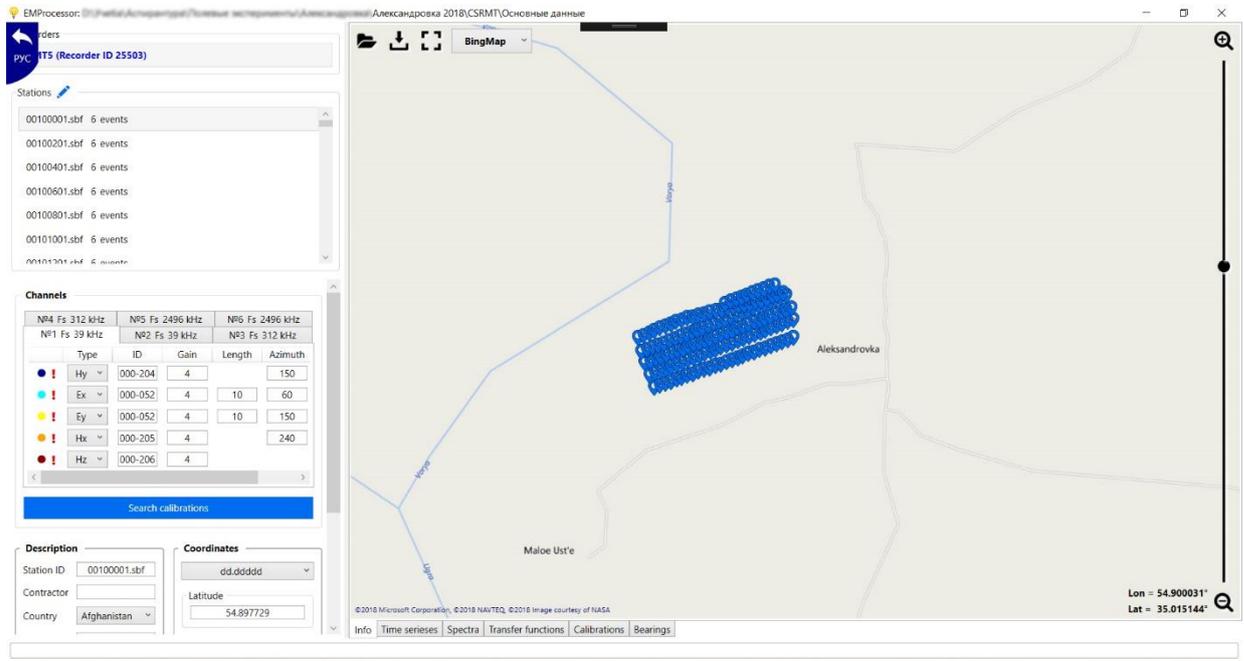


Figure 2. Screen for the view and correction of information about the sounding point, the Information tab.

The data processing screen has several tabs with various functionality.

“Information” tab

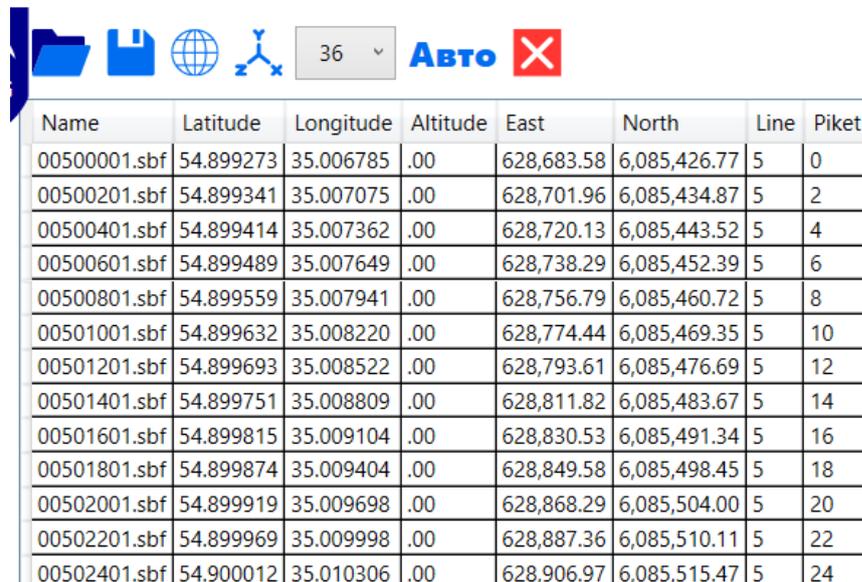
The information tab allows you to display, modify and supplement some information about the measurement system and individual measurement stations.

The left part of the “Information” tab contains:

1. List of recorders with which the data were collected;
2. List of measurement stations collected by the selected recorder;
3. The list of events and the parameters of the recording channels corresponding to these events;
4. Additional information about the sounding station (coordinates, profile and station number, description).

Stations and coordinate editor

The “Stations” section has a button with a pencil image, clicking on which opens the table for setting and correcting the coordinates of sounding stations (**Figure 3**).



Name	Latitude	Longitude	Altitude	East	North	Line	Piket
00500001.sbf	54.899273	35.006785	.00	628,683.58	6,085,426.77	5	0
00500201.sbf	54.899341	35.007075	.00	628,701.96	6,085,434.87	5	2
00500401.sbf	54.899414	35.007362	.00	628,720.13	6,085,443.52	5	4
00500601.sbf	54.899489	35.007649	.00	628,738.29	6,085,452.39	5	6
00500801.sbf	54.899559	35.007941	.00	628,756.79	6,085,460.72	5	8
00501001.sbf	54.899632	35.008220	.00	628,774.44	6,085,469.35	5	10
00501201.sbf	54.899693	35.008522	.00	628,793.61	6,085,476.69	5	12
00501401.sbf	54.899751	35.008809	.00	628,811.82	6,085,483.67	5	14
00501601.sbf	54.899815	35.009104	.00	628,830.53	6,085,491.34	5	16
00501801.sbf	54.899874	35.009404	.00	628,849.58	6,085,498.45	5	18
00502001.sbf	54.899919	35.009698	.00	628,868.29	6,085,504.00	5	20
00502201.sbf	54.899969	35.009998	.00	628,887.36	6,085,510.11	5	22
00502401.sbf	54.900012	35.010306	.00	628,906.97	6,085,515.47	5	24

Figure 3. Coordinates editor.

Table 2. Description of the purpose of the coordinate editor control buttons.

	Open file with coordinates. Supported formats *.txt, *.dat и *.gpx
	Save coordinates to *.txt file
	Update WGS84 coordinates by UTM coordinates and zone number
	Update UTM coordinates by WGS84 coordinates and zone number
	Manual zone number selection
	Automatic selection of the zone number by WGS84 coordinates
	Close the coordinate editor

Coordinate files with the extension *.txt and *.dat, which have to be opened in the EMP program, must have the following format (Figure 4):

name	lat	lon	z	East	North	Profil	Piket
1000	54.897729	35.007632	0	628742.8	6085256.6	1	0
1002	54.897790	35.007928	0	628761.6	6085263.9	1	2
1004	54.897851	35.008224	0	628780.4	6085271.2	1	4
1006	54.897912	35.008521	0	628799.2	6085278.5	1	6
1008	54.897973	35.008817	0	628818.0	6085285.9	1	8
1010	54.898035	35.009113	0	628836.8	6085293.3	1	10

Figure 4. The structure of the text file with coordinates.

In this case, the register of the name of the columns, as well as their order and completeness of the presence in the file does not matter.

Important! When forming the name of the sounding station in the file with coordinates, you must follow the following rule. The name of the sounding station in the file with coordinates must fully or partially contains the name of the sounding station in the EMP program and vice versa. This means following. If in the EMP program the sounding station is called, for example, **001002.sbf**, then in the file with coordinates the line corresponding to this sounding station must be named **1002**, or **1002.sbf**, or **001002**, or **001002.sbf**.

When opening files with coordinates, it is possible to select several files at the same time.

Recording channels

Section "Channels" has the following form (Figure 5).

Channels

№1 Fs 39 kHz
№2 Fs 312 kHz
№3 Fs 2496 kHz

	Type	ID	Gain	Length	Azimuth	Reverse
● !	Hy	000-501	4		0	<input type="checkbox"/>
● !	Ex	000-515	4	5	90	<input type="checkbox"/>
● !	Ey	000-515	4	5	0	<input type="checkbox"/>
● !	Hx	000-502	4		90	<input type="checkbox"/>
● !	Hz	000-505	4			<input type="checkbox"/>

Figure 5. Recorder channels information editor.

Each tab of the “Channels” section corresponds to one logging event — a set of synchronous time series recorded at one sampling rate. Event tabs contain information about the sequence number of the event and the sampling rate.

Table 3. Description of column assignment of the recorder channel information editor.

Column	Description	Level of connectedness
Type	Chanel type: Ex, Ey, ..., Hz	Changes here lead to changes in all events of all measurement points that involve this channel of this recorder.
ID	Sensor serial number	Changes here lead to changes in all events of all measurement points that involve this channel of this recorder.
Gain	Used gain	Unique for each channel of each event.
Length	Electric antenna length	Unique for each channel of each event.
Azimuth	The direction of the sensor relative to the North. For electric antennas this direction is from minus to plus. For induction magnetic sensors, this is the direction from the connector.	Unique for each channel of each event.
Reverse	If this option is selected, the result of the Fourier transform for this channel is multiplied by -1. Sometimes this is required to correct the quadrant of the transfer function phase.	Unique for each channel of each event. The button  applies the operator to access all channels with the same type and serial number, if their direction coincides with the direction of the current channel $\pm 45^\circ$

The button “Search calibrations” repeats the search for calibrations, for example, the field of correction of serial numbers.

Description and summary of the sounding station

The description section of the sounding station is as follows (**Figure 6**):

Description		Coordinates	
Station ID	<input type="text" value="23500101.sbf"/>	<input type="text" value="dd.ddddd"/>	
Contractor	<input type="text" value="Shlykov"/>	Latitude	<input type="text" value="54.535426"/>
Country	<input type="text" value="Russian Federation"/>	Longitude	<input type="text" value="36.166992"/>
State	<input type="text" value="Alexandrovka"/>	Altitude	<input type="text" value="165.00"/>
		Line	<input type="text" value="5"/>
		Piket	<input type="text" value="7"/>

Summary
Good weather

Figure 6. Sounding station information editor.

The information entered here is transferred to an EDI or PLT file. To start processing data, go to any of the following tabs on the data processing screen:

1. Time series
2. Spectra
3. Transfer functions
4. Calibration
5. Bearings

«Time series» tab

The tab "Time series" has the following form: (Figure 7):

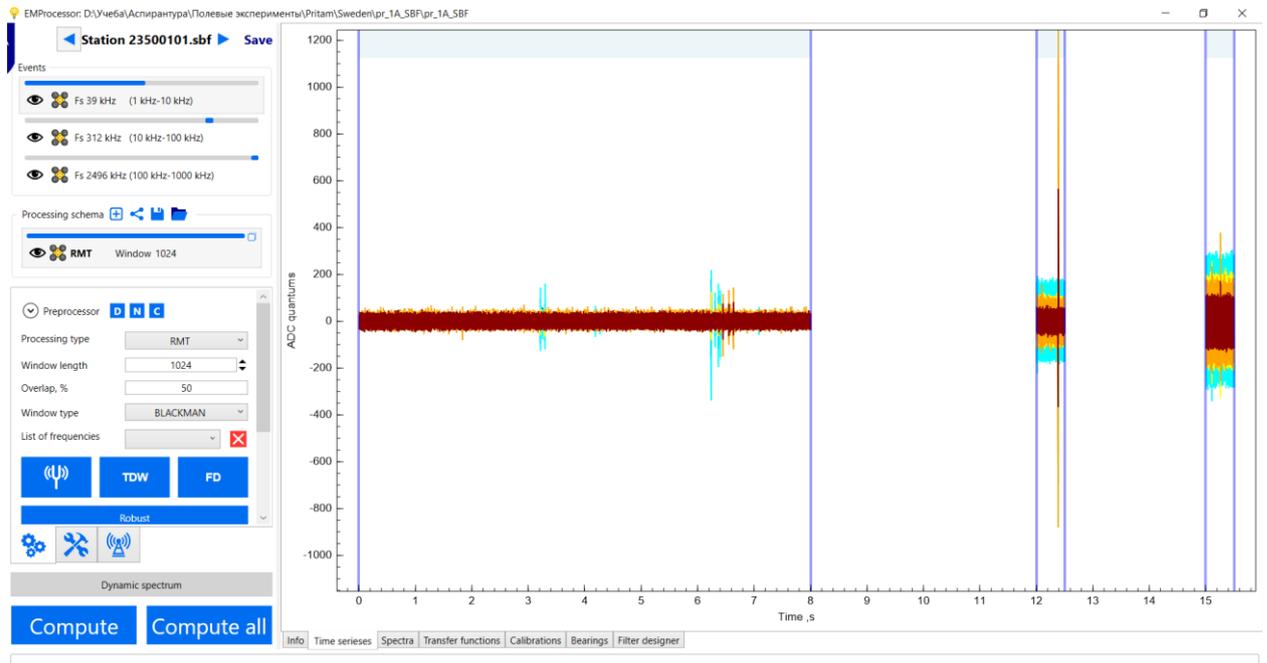


Figure 7. General view of the Time Series tab.

Time series are displayed for all events contained in the selected observation point.

Events

The "Events" section displays a list of events at the sounding station (Figure 8).

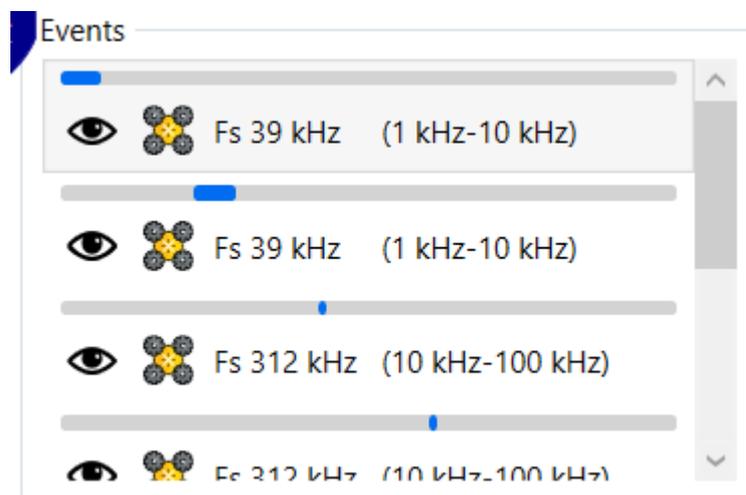


Figure 8. List of events.

Each item in this list has the following controls (**Figure 9**).

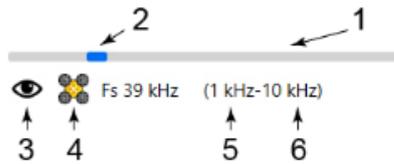


Figure 9. Event controls. **1** - Relative timeline of the sounding station. **2** - position of the time of measurement during the current event on a common timeline **3** - flag for visibility of events on the plots. **4** - flag of the inclusion of events in the processing. **5** and **6** - the lower and upper limits of the frequency range (changes after the left mouse button double-clicking on the element).

Important! If it is necessary to use very long Fourier transform windows (of the order of a million or more), the problem of memory allocation for computations may arise. This problem can be solved by narrowing the target frequency range with tools 5-6 on Figure 9, if it is possible.

Each element of the event list has a context menu (**Figure 10**), called up by right-clicking.

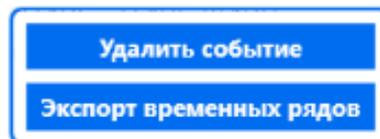


Figure 10. Event context menu.

Export time series is available in two formats: text and binary. In text form, the file has a simple table structure (**Figure 11**). Values are saved for each channel in Volts. Columns are separated by tabs. Time values are not saved in the file

Hy	Ex	Ey	Hx	Hz
-6.50720019E-003	2.13808008E-002	1.42096011E-002	1.01260003E-002	1.48404008E-002
-5.51120052E-003	2.15800013E-002	1.54712005E-002	1.08896010E-002	1.38112009E-002
-7.50320032E-003	2.16132011E-002	1.30144004E-002	1.77620016E-002	1.19520007E-002
-6.24160049E-003	2.09824014E-002	1.62016004E-002	1.14208004E-002	1.27488002E-002
-5.94280055E-003	2.15800013E-002	1.31804002E-002	1.13876006E-002	1.30144004E-002
-4.84720012E-003	2.14472003E-002	1.66332014E-002	6.44080015E-003	1.39440009E-002
-5.37840044E-003	2.13808008E-002	1.22508006E-002	9.59480088E-003	1.37448004E-002

Figure 11. Structure of exported time series text file.

Binary file has following format:

Int32 – number of channels

Int64 – number of samples

Next data are voltages for each time, for each channel:

Float – voltage in Volts

Event processing schema

Each event has its own processing schema, which is configured using the corresponding section on the left side of the processing screen. (Figure 12).

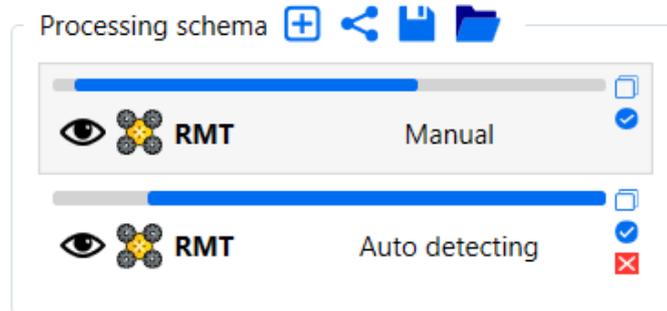


Figure 12. The section for setting up the event processing schema.

Table 4. Controls of processing schema.

	Create new processor
	Apply a processing scheme to similar events
	Save processing schema
	Open processing schema

Each row of the “Processing schema” list corresponds to processor with its independent processing settings (Figure 13).

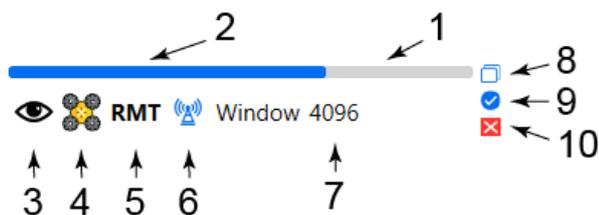


Figure 13. Processor’s controls. 1 – Relative time line of event. 2 – Location of processable fragment of time series on the event’s time line. 3 – Visibility flag for processor and its processing results on plots. 4 – Processing flag for application or not application the processor. 5 – Type of processor. 6 – Symbol of use defined frequency list. 7 – Changeable name. 8 – Button for copying data about processor to clipboard. 9 – Button for selecting current processor as single for event. 10 – Button for removing processor.

Each processor has its own set of processing settings. General view of the processing settings editor depending on the type of processing is shown in Figure 14.

Processing type: MT, Window length: 1024, Overlap, %: 50, Window type: BLACKMAN

Processing type: RMT, Window length: 16384, Overlap, %: 50, Window type: SLEPIAN

Processing type: CSEM, Window length: 8192, Overlap, %: 50, Window type: BARTLETT

List of frequencies: D1, D2-all

Buttons: Robust, Decimate, Log

Type	Threshold
<input checked="" type="checkbox"/> Coherency \geq	0.8
<input type="checkbox"/> Coherency of inputs \leq	0.2
<input checked="" type="checkbox"/> Coherency of outputs \leq	0.2
<input type="checkbox"/> Partial coherency 1 \geq	0.8
<input type="checkbox"/> Partial coherency 2 \leq	0.2
<input type="checkbox"/> Multiple coherency \geq	0.8
<input type="checkbox"/> Polarization E	0
<input type="checkbox"/> Polarization H	0
<input type="checkbox"/> Orthogonality \pm°	10

Figure 14. Different processing settings depending on the type of data processing: MT - on the left, RMT - in the center and CSEM - on the right.

A description of each of the data processing parameters is given in Data processing [Ошибка! Источник ссылки не найден.](#)

The data processing schema is designed to solve two main problems:

1. selection of optimal processing parameters,
2. applying different settings to different segments of the time series.

The selection of optimal processing parameters is done by the user by creating various processors and comparing the results of processing in the graphical data representation window (spectra, transfer functions, etc.). The **EMP** program allows to display the results of processing all created handlers on a single plot with the ability to hide / show individual ones for interactive data comparison.

Applying different processing settings to different segments of a time series can be applied in the following case. Suppose that a signal of a controlled source (transmitter) was recorded at different frequencies in one continuous file. At the same time, the transmitter operated according to a schedule (automatically) with specified durations of generation of individual frequencies. But for some reason, the recorder does not allow to automatically record each frequency of the transmitter in a separate time series file. In this case, the user has the opportunity to create a separate processor for each fragment of time corresponding to the time of generating any transmitter frequency. In the settings of the processor, you can specify your own realization length or Fourier window, list of frequencies and other settings.

The processing schema can be saved to a file for later use for other events and / or measurement points. Saving the processing scheme is possible both for a single event and for a measuring point with many events. When applying a previously saved measurement scheme, the following features of the **EMP** program must be kept in mind.

1. The saved processing schema contains information about the relative time to start processing (from the beginning of the event) and the duration of the fragment to be processed.

2. If the user saves the processing schema for a measurement point containing several events, then this processing scheme should be applied only for measurement points with a same-type event structure — the same sampling rates, the same order of events and their recording duration.

Time series tools

On the **Figure 15** a set of time series management tools is shown. In the upper part are the controls for the visibility of individual channels. A summary of all events of the selected measurement point is displayed here.

The “Remove mean” button controls the display of time series either in its original form when the flag is removed (gray background of the button), or as original data minus the expected value for the entire time series with the flag set (blue background of the button).

The "Border of segments" button shows or hides the borders of the segments of the time series if the recorder with time series are segmented in time. For example, Phoenix receivers of RMT-F.

The following is a summary of data quality assessment in the time domain: the total number of realizations in the time series of the selected event and the first of the decimation levels, taking into account the current window settings, the percentage of rejected realization, and an overall assessment of the data quality in the range of 0-5. Rejected realization have weight equal to zero. Quality assessment is performed according to the following formula:

$$Q = 5 \cdot \frac{\sum_{i=0}^N w_i}{N} \cdot \frac{1 - \max(0; 60 - N)}{60}$$

Here N – is the number of realizations whose weights are greater than zero, the number 60 is the conditional minimum of the number of realizations for the representative estimation of transfer functions.

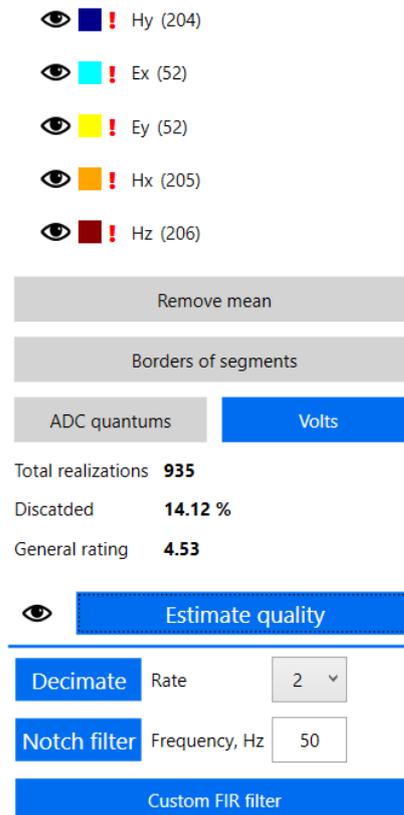


Figure 15. Time series tools.

The button "Estimate quality" starts the process of quality estimation in the time domain, taking into account the specified window settings.

Next tools are time domain preprocessing tools. In the current version, the **EMP** program provides three tools: decimator, notch filter and custom filter with a finite impulse response. This section of tools is intended for preliminary selection of the processing graph. Therefore, after applying any of the tools, an event copy is created, added to the events of the current sounding point. This allows you to keep the original data unchanged and get the opportunity to visually compare both the time series and the processing results before and after applying the processing tools in the time domain on the plots. All filters used for processing in the time domain have finite impulse response (FIR). After applying a filter, its transfer function is stored in the parameters of the resulting event for subsequent spectrum correction ensuring the accuracy of the obtained spectrum values in the passband.

Decimator

The "Decimator" tool allows you to reduce the sampling rate of time series by an integer factor, corresponding to the decimation factor selected from the drop-down list next to the "Times" text. The limitations on the decimation factor are as follows:

- Decimation factor is only integer value
- The maximum decimation factor is equals to 1000
- The maximum decimation factor for the current event is determined from the consideration that the resulting sampling rate after decimation should also remain an integer.

In the process of decimation, low-frequency filtering is performed in accordance with the selected decimation factor and the subsequent down sampling of the time series. The decimation process is started by pressing the “Decimate” button. As a result, a new event is created with a sampling rate equal to the initial sampling rate divided by the decimation factor.

Notch filter

The “Notch filter” tool allows you to suppress signals with a specified frequency. The frequency of suppression is set in Hertz in the field near to the inscription "Frequency, Hz". The band of suppression is chosen equal to 10% of the value of the frequency of suppression.

Important! When suppressing industrial noise signals, it is necessary to take into account that the “Notch filter” tool suppresses only the specified frequency without harmonics. Therefore, if it is necessary to suppress harmonics of industrial frequency signals, it is necessary to use a notch filter several times for the corresponding frequencies separately or use a pre-designed filter using the “Custom FIR filter” tool.

Custom FIR filter

The “Custom FIR filter” tool allows you to apply a pre-designed digital filter with finite impulse response. The filter can be designed in third-party programs or in the “Filter Designer” tab of the **EMP** program. By clicking on the "Custom FIR filter" button, you are invited to select a text file containing the filter impulse response recorded in the column (**Figure 16**).

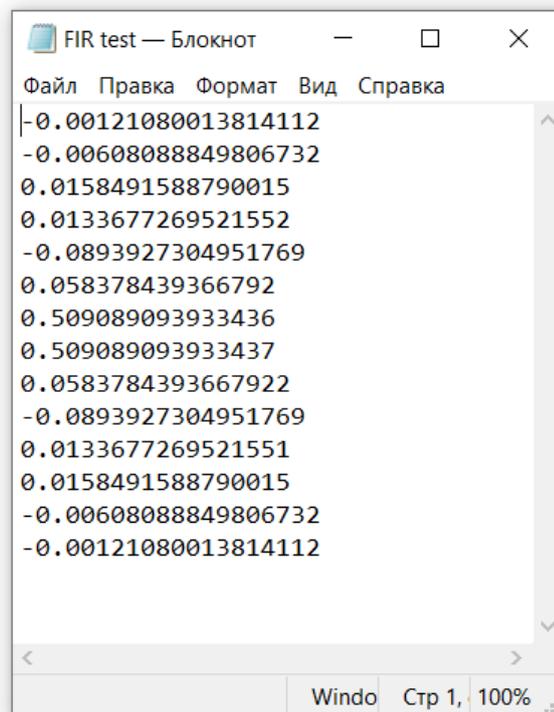


Figure 16. Sample file with impulse response of custom FIR filter.

Filter designer

The “Filter designer” tab provides tools for calculating the filter impulse response with “arbitrary” transfer function (**Figure 17**).

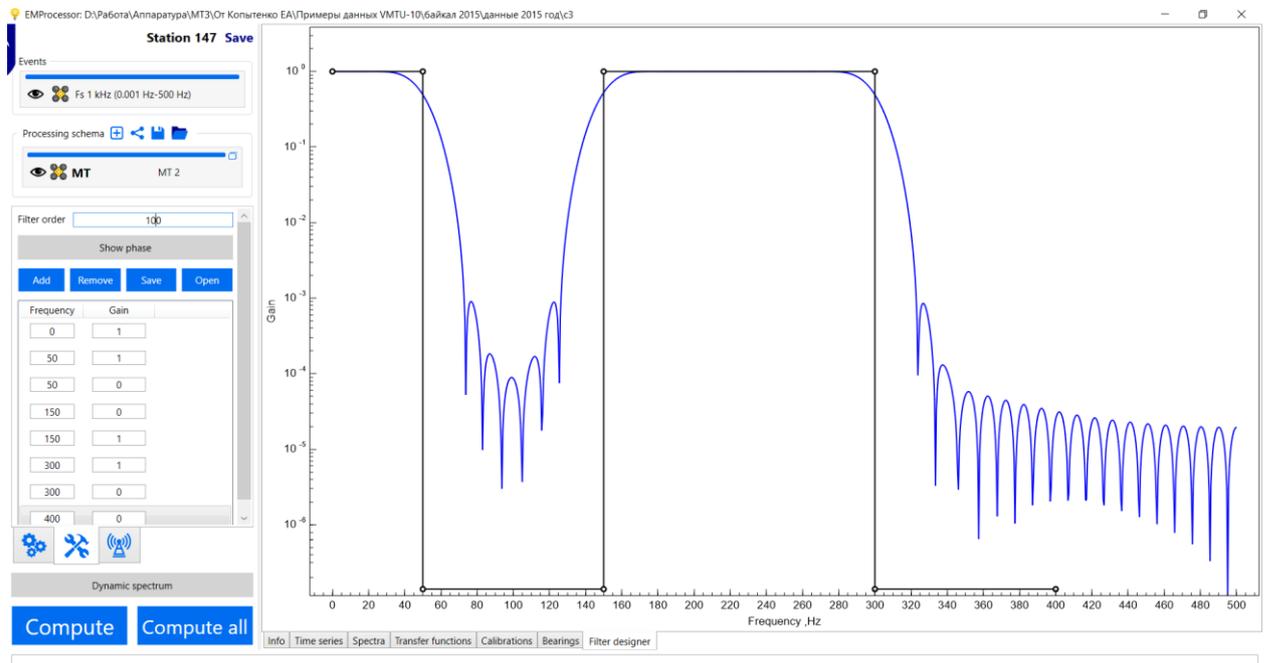


Figure 17. The «Filter designer” tab.

The toolbar sets the order of the filter and its target transfer function in a table form. The transfer function is set by frequency-gain value pairs. A gain less than 10^{-4} is considered as zero. On the plot, the required transfer function is duplicated by a black line with circles in the nodes. If you hover the mouse over one of the nodes and clamp the left mouse button, you can change the gain by moving the mouse along the vertical axis. By holding the left mouse button in the vicinity of the flat portion of the transfer function series by moving the mouse, you can change the gain for the nearest nodes to the left and right of the mouse cursor. Left-clicking on the plot adds a new node to the transfer function at the frequency corresponding to the current mouse coordinate. You can also add a node by clicking the “Add” button on the toolbar. If any of the nodes is selected in the transfer function node table, it can be deleted by clicking the “Delete” button on the toolbar.

The blue line shows the actual transfer function of the resulting filter, calculated using the Fourier transform.

The "Save" button on the toolbar allows you to save the results of the calculations of three options:

1. Base points or a table of nodes of the required transfer function in the form of a “frequency-gain” text table;
2. Impulse response as a column of calculated filter coefficients;
3. The spectrum of the final transfer function in the form of a text table "frequency-gain-phase shift".

By clicking on the “Open” button, you can load a previously saved table with the base point of the transfer function of the filter.

Adding the time domain preprocessing steps to a processing graph

At the top of the “Settings” tab there is a drop-down list of necessary time domain preprocessing stages for the current event. (**Figure 18**). The “D” button, short for “Decimator”, opens the dialog for selecting the decimation factor for the decimator to be added. The “N” button, short for “Notch filter”, opens the notch filter settings dialog. In this dialogue there is a flag “With odd harmonics”. Setting this flag to the selected position (blue background) gives the command to create a conveyor notch filter containing all the odd subharmonics of a given suppression frequency up to the upper frequency in the spectrum of the current event. Also in this dialog you can adjust the absolute width of the suppression band. The “C” button, abbreviated from “Custom filter”, opens the dialog for specifying the path to a file with a custom filter.

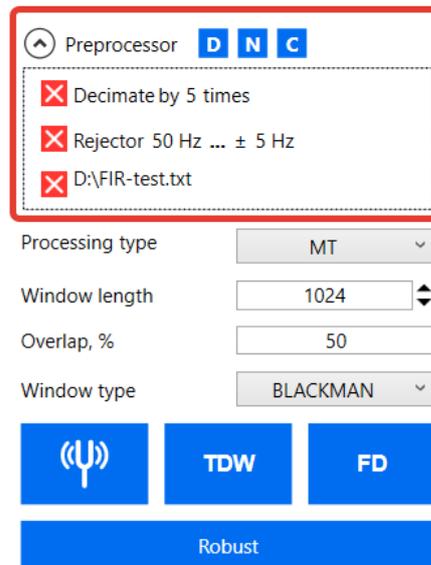


Figure 18. Setting the time domain preprocessing graph in the Settings panel.

The order of operations corresponds to the order of their application to time series. You can edit the order by deleting and re-creating elements.

“Spectra” tab

The general view of the “Spectra” tab is shown in **Figure 19**. This tab has plots of the amplitude spectra for each of the channels and some of the parameters calculated from the cross-spectral estimates: coherence, amplitude and phase of the cross-spectrum. The plot show the values averaged over the entire ensemble of realizations of the corresponding event.

In **Figure 20** shows a set of tools to control the plotting of spectra. In the upper part, as in the case of the Time Series tab, there are controls for the visibility of the spectra of various channels. This is followed by a set of tools to control the upper black graph, which displays the selected parameter, calculated from cross-spectral estimates. The drop-down lists “Channel 1”, “Channel 2” and “Channel 3” allow you to select the channels for which the parameter is calculated. Near the “Channel 3” drop-down list there is a button for resetting the third channel for calculating a given parameter using only two selected channels.

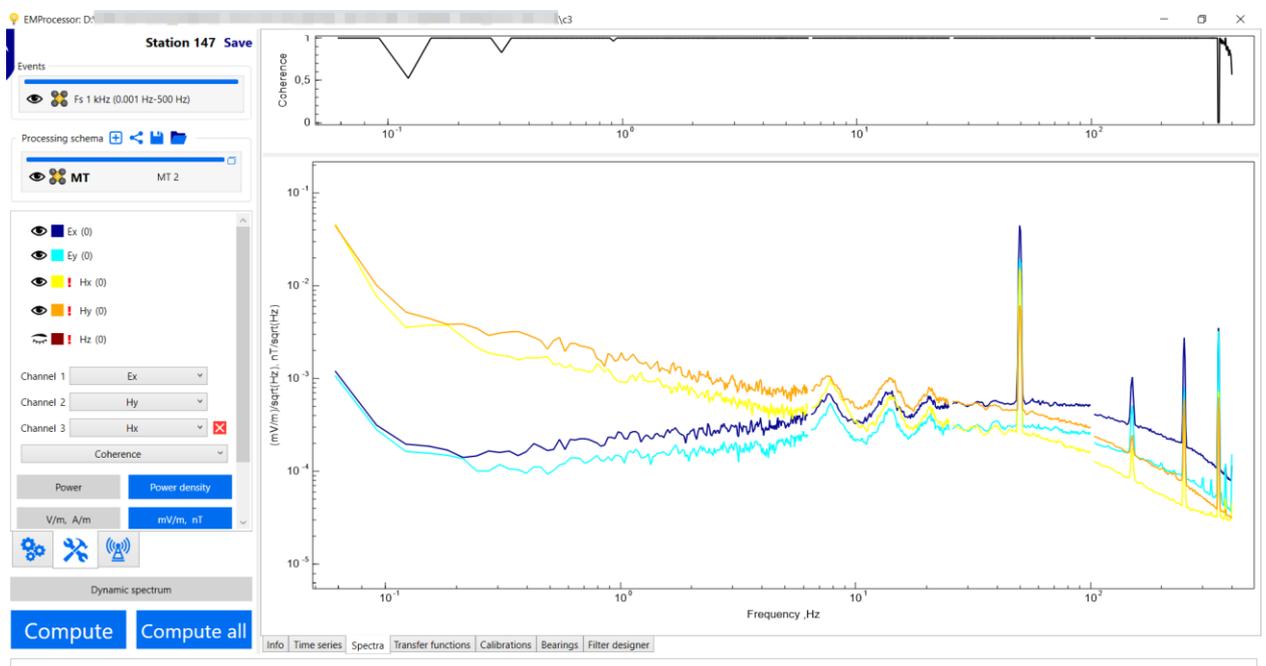


Figure 19. General view of «Spectra» tab.

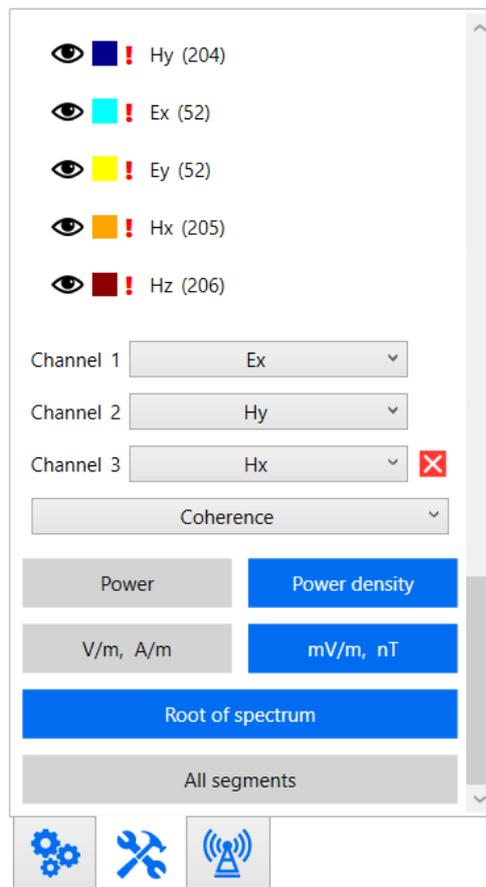


Figure 20. Spectra tools.

Three parameters are available for selection: coherence, cross-spectrum amplitude and cross-spectrum phase. For the two-channel case, these parameters are calculated using the following formulas:

$$Coherency = \frac{|S_{12}|^2}{|S_{11}||S_{22}|}$$

$$CrossMagnitude = |S_{12}|$$

$$PhaseShift = atan\left(\frac{ImS_{12}}{ReS_{12}}\right)$$

Here S_{11} is the auto spectrum of the first channel, S_{22} is the auto spectrum of the second channel, S_{12} is the cross spectrum between the first and second channels. In the case of a three-channel estimate, these parameters are calculated using the following formulas:

$$Coherency = \frac{|S_{12/3}|^2}{|S_{11/3}||S_{22/3}|}$$

$$S_{ij/k} = S_{ij} - \frac{S_{kj} \cdot S_{ik}}{S_{kk}}$$

$$\text{CrossMagnitude} = |S_{12/3}|$$

$$\text{PhaseShift} = \text{atan}\left(\frac{\text{Im}S_{12/3}}{\text{Re}S_{12/3}}\right)$$

Here $S_{ij/k}$ – “clean” spectrum [Semenov, 1985], or estimation of cross spectrum between channel i and channel j without influence of channel k.

This is followed by the flags for controlling the dimension of the spectra and the type of normalization of the spectra. The “Power” type of normalization implies normalization by the square of the sum of weighting window coefficients. The “Power density” normalization type implies normalization by the product of the sampling frequency of the time series and the sum of the squares of the weighting window coefficients. The set flag “All segments” shows on the graphs the spectra for all segments of the time series, into which it was divided in the course of processing for comparison with the total final estimate. The graphs for each of the segments are shown in a semitransparent color (**Figure 21**).

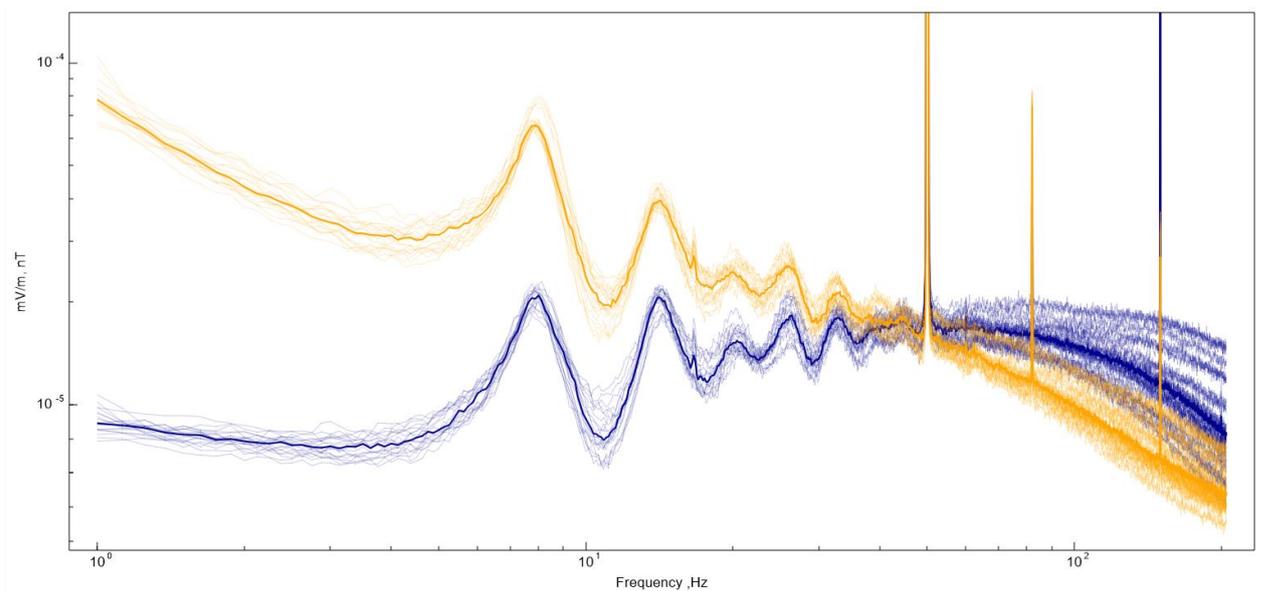


Figure 21. Spectra plots for each of the processing segments overlapped the plots of the final spectra estimation for each of the channels.

“Transfer function” tab

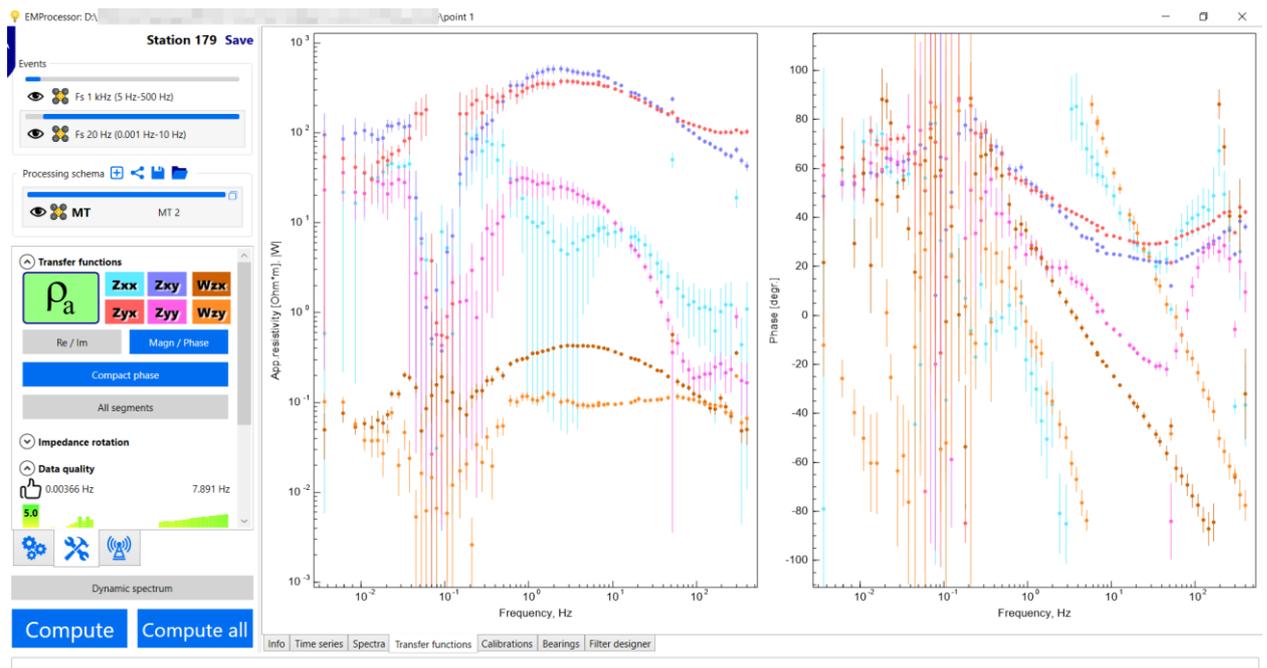


Figure 22. General view of “Transfer functions” tab.

Data processing

This section provides general information about the data processing algorithms used and describes the purpose of the various settings of parameters that control the data processing.

Tuning the data processing graph

Once again we give an example of settings for all types of data processing (**Figure 23**).

Figure 23 displays three panels of data processing settings for different processing types: MT (left), RMT (center), and CSEM (right).

MT Settings:

- Processing type: MT
- Window length: 1024
- Overlap, %: 50
- Window type: BLACKMAN
- List of frequencies: D1
- Selection criteria: Coherency \geq 0.8, Coherency of outputs \leq 0.2, Partial coherency 1 \geq 0.8, Partial coherency 2 \leq 0.2, Multiple coherency \geq 0.8, Polarization E 0, Polarization H 0, Orthogonality \pm° 10.

RMT Settings:

- Processing type: RMT
- Window length: 16384
- Overlap, %: 50
- Window type: SLEPIAN
- List of frequencies: D1
- Selection criteria: Coherency \geq 0.8, Bearing H \leq 30, Elliptivity E \leq 0.3.

CSEM Settings:

- Processing type: CSEM
- Window length: 8192
- Overlap, %: 50
- Window type: BARTLETT
- List of frequencies: D2-all
- Selection criteria: Coherency \geq 0.8, Bearing H \leq 30, Elliptivity E \leq 0.3.

Figure 23. Different processing settings depending on the type of data processing: MT - on the left, RMT - in the center and CSEM - on the right.

Window (realization) length

The “window length” parameter sets the number of consecutive samples of the **continuous** part of the time series, which is used to calculate the Fourier transform coefficients using the fast transform algorithm (FFT). Sometimes, when considering random processes, the term “realization” is used. In this case, it’s the same things.

As is known, the upper frequency of the spectrum is determined by the sampling rate of the ADC:

$$f_{max} = f_N = 0.5f_s, \quad (1)$$

here f_N – Nyquist frequency, f_s – ADC sampling rate. In this case, it is a constant value. The frequency resolution, or the minimum non-zero frequency that can be obtained from the Fourier transform, depends on the window length:

$$f_{min} = f_s / \text{winLen}, \quad (2)$$

here *winLen* – number of samples in the window.

The longer the time interval over which the FFT is calculated, the more detailed spectrum can be estimated.

Usually, when calculating the spectra of a magnetotelluric field, small windows are used in hundreds, the first thousand samples. This allows for a smoother distribution of signal power over frequencies.

In the case of processing narrow-band signals of artificial origin (controlled source, broadcasting radio transmitters), it makes sense to use longer windows to obtain better frequency resolution.

The value of the “window length” parameter can be any positive integer. This does not have to be a power of two, as in usual signal processing. For example, if a receiver writes time series in short segments of 2400 counts, it is desirable to use this value or less, corresponding to integer dividers (1200, 600, etc.).

In the text box, you can specify an arbitrary window length. The up / down arrows allow you to select a value equal to an integer power of two.

Important: Often, when processing signals of a monitored source, for example, CSEM data, processing is carried out in a window equal to the period of the fundamental frequency of the transmitter. This allows you to get significant advantages when dealing with random noise. However, when calculating the spectrum of such a length, the Fourier transform window is not enough. The FFT algorithm implies working only with windows whose duration is equal to an integer power of two (32, 64, 128, etc.). It almost never happens that this value corresponds to the number of samples in the period of the transmitter. Therefore, a formal increase in the length of the window before calculating to the nearest integer power of two by zeros will distort the resulting frequency grid, but will not add information and real frequency resolution. Therefore, when calculating the spectrum of the signal of the controlled source for only one period, it will lead to significant errors in the estimates of the transfer functions. Use at least 3-5 periods.

Overlap

The window overlap parameter sets the length of the overlap interval of adjacent windows of the continuous part of the time series as a percentage of the window length. If this parameter is zero, then the first count of the next window is the count following the last count of the current window. At overlap of 50%, the first sample of the next window is the middle sample of the current window (adjusted for even window length). Window overlap allows to increase the count of spectrum estimates and to increase the temporal resolution.

Window type

The “window type” parameter sets the weighting function. Weighting functions are used to control the spectrum leakage and frequency resolution.

The Gauss window function is calculated with the parameter $\alpha = 2.5$.

The Slepian’s weighting function is calculated with the bandwidth parameter 4.0. In normal single-window processing, the first of the functions is used. In the current version of the **EMP** program multi-window processing (multitaper) is not available.

Using calibrations

Flag button with symbol  controls the use of hardware calibrations of sensors and recorders. If the background of the button is blue, calibrations will be applied. If the background is gray - no calibration will be applied. Often, calibrations are supplied by the hardware manufacturer as separate files with names containing the serial numbers of the sensors or recorders.

Important: **EMP** works only with textual variants of third-party calibration files (Phornix, Metronix, etc.). Exceptions are the calibrations given in the Metronix XML files.

In the process of reading the data file, a search is made for suitable files with calibrations in the folders indicated on the start screen of the **EMP** program. If some calibrations are not found, the program will display a warning in the form of a red exclamation mark next to the number of the sensor and / or recorder in the list of channels or recorders in the “Information” tab (**Figure 24**).

Channels

N°4 Fs 312 kHz		N°5 Fs 2496 kHz		N°6 Fs 2496 kHz		
N°1 Fs 39 kHz		N°2 Fs 39 kHz		N°3 Fs 312 kHz		
	Type	ID	Gain	Length	Azimuth	Reverse
● !	Hy	204	4		150	<input type="checkbox"/> 
● !	Ex	52	4	10	60	<input type="checkbox"/> 
● !	Ey	52	4	10	150	<input type="checkbox"/> 
● !	Hx	205	4		240	<input type="checkbox"/> 
● !	Hz	206	4			<input type="checkbox"/> 

Search calibrations

Channels

N°4 Fs 312 kHz		N°5 Fs 2496 kHz		N°6 Fs 2496 kHz		
N°1 Fs 39 kHz		N°2 Fs 39 kHz		N°3 Fs 312 kHz		
	Type	ID	Gain	Length	Azimuth	Reverse
● !	Hy	204	4		150	<input type="checkbox"/> 
●						<input type="checkbox"/> 
●						<input type="checkbox"/> 
●						<input type="checkbox"/> 
●						<input type="checkbox"/> 
●						<input type="checkbox"/> 

Search calibrations

No calibrations for channel Hy, ID=204, gain 1, band D3
 No calibrations for channel Hy, ID=204, gain 4, band D3
 No calibrations for channel Hy, ID=204, gain 16, band D3
 No calibrations for channel Hy, ID=204, gain 64, band D1
 No calibrations for channel Hy, ID=204, gain 64, band D2
 No calibrations for channel Hy, ID=204, gain 64, band D3
 No calibrations for channel Hy, ID=204, gain 64, band D4

Figure 24. Missing calibrations warning.

If, after opening the file, it turned out that there is no link to the desired folder, or correction of serial numbers and / or sensor types is required, then after making the necessary corrections, click the “Search calibration” button in order for the missing calibrations to be loaded into the program.

The list and plots of the loaded calibrations can be viewed in the “Calibrations” tab. (**Figure 25**).

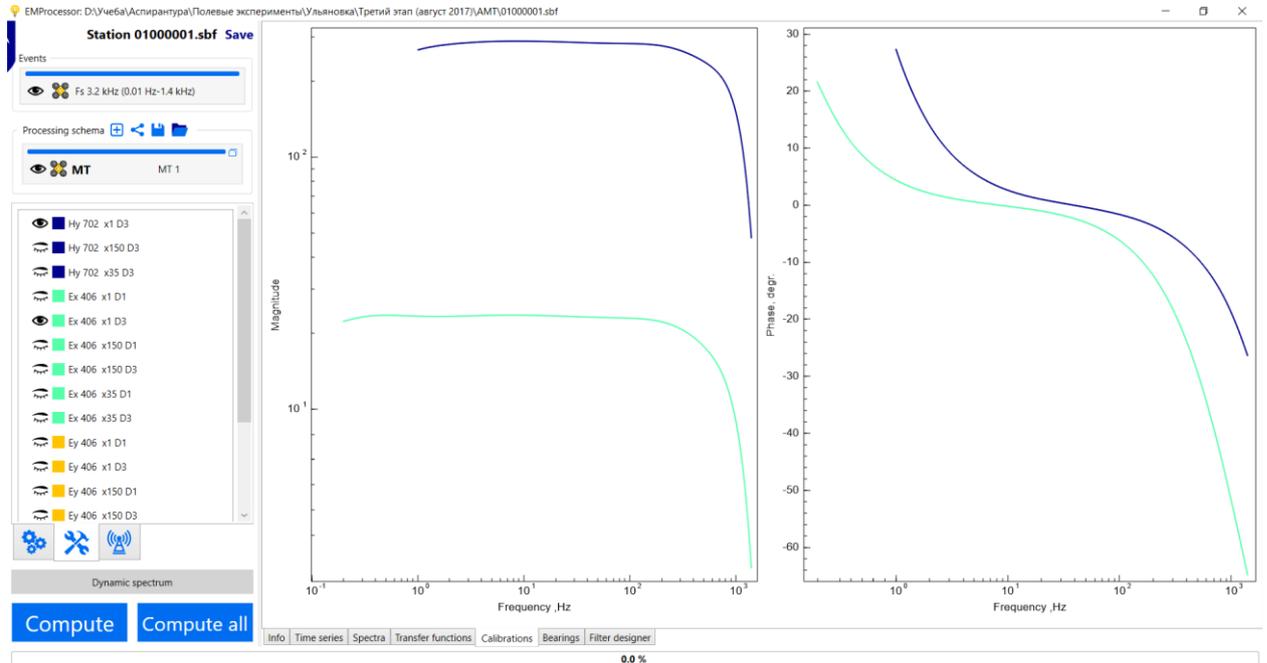


Figure 25. List and plots of available calibrations.

If there is no calibration in some part of the frequency range (in the upper or in the lower part), then the spectra and transfer function at the corresponding frequencies will also be absent. For example, in the above case (**Figure 25**), electric sensor calibrations are available up to a frequency of 0.2 Hz, and for magnetic sensors only up to 1 Hz. Thus, when applying calibrations, the spectra of magnetic channels and transfer functions at frequencies below 1 Hz will be absent.

Usage of weights of realizations (windows) obtained in time domain

Flag-button with symbol  (Time Domain Weights) controls the use of weights of realizations calculated in the time domain at the initial stage of processing. If the background of the button is blue, the quality estimation in the time domain will be performed and the weights will be applied. If the background is gray - no.

The quality of data estimated in time domain following algorithm described in [Moskovskaya, 2007]. It is important to note that this algorithm sets the weight close to one, to those windows whose energy and correlation characteristics are close to some average over the ensemble. Conversely, the weight is set close to zero if the characteristics of the window are far from some average over the ensemble. If noisy data prevails in the record, then the use of this algorithm eliminates not the noisy segments of the record, but good ones, since the ensemble average will characterize the noise. **Figure 26** demonstrates the operation of the data quality estimation algorithm and the rejection of noisy recording sections.

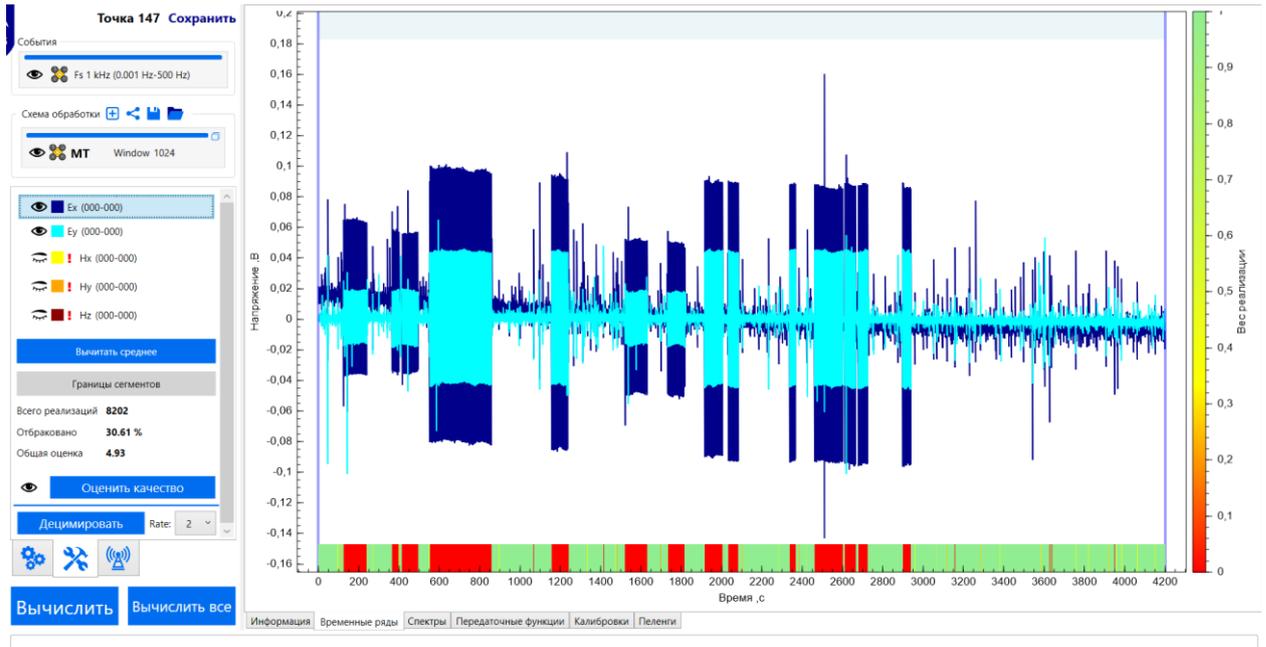


Figure 26. Eliminate noisy recording fragments using quality estimation in the time domain. Red shows the window (realizations), the contribution of which will be completely excluded during the evaluation of transfer functions.

When using this algorithm, it is also worth keep in mind that weights are given to each window, and not to a section of arbitrary length. Thus, the excluded section of the recording, containing a short impulse noise, may also contain some useful information.

Important: The algorithm estimates the weight of realizations only by visible channels. If a channel should be excluded from this assessment, make it invisible.

Prewhitening of spectrum

Flag-button with symbol  (First Difference) manages the use of the spectrum prewhitening algorithm - making the distribution to the Gaussian one. If the button background is blue, prewhitening and the corresponding spectrum corrections will be performed. If the background is gray - no.

In the **EMP** software, prewhitening is performed by the simplest algorithms of the first difference (first difference):

$$y_j = x_{j+1} - x_j, \quad (3)$$

where $\{x\}$ – initial time series, $\{y\}$ – the result of applying a prewhitening filter. In the case of applying a prewhitening filter, the resulting values of the Fourier coefficients are normalized as follows:

$$X(f) = \frac{Y(f)}{\exp\left(\frac{2\pi i f}{f_S}\right) - 1}. \quad (4)$$

Here i – imaginary one. The use of prewhitening is advisable when processing low-frequency signals (less than approximately 10 Hz).

List of frequencies

When choosing a RMT or CSEM processing method, a tool is available to specify a list of frequencies at which you want to calculate transfer functions (**Figure 27**).



Figure 27. Select the list of frequencies. Drop-down list of available frequency lists and a button to cancel using the frequency list.

Frequency lists are discussed in more detail in the appropriate section.

Robust estimation

A flag- button labeled “Robust” controls the type of transfer function estimation. If the button background is blue, a robust estimation is performed. If the background is gray – non-robust.

We will use the following notation:

1. $\{x\}_j^k$ – an array of consecutive samples of the time series on channel j for realization k .
2. S_j^k – “instantaneous” spectrum of channel j for realization k .
3. $S_{ij}^k = S_i^{k*} \cdot S_j^k$ – “instantaneous” cross spectrum of channels i and j for realization k . Asterisk sign * means complex conjugate.
4. $[S_{ij}] = \frac{\sum_k (w_k \cdot S_{ij}^k)}{\sum_k w_k}$ – weighted average “accumulated” cross-spectrum of channels i and j . w_k – weight of realization.

Graph of non-robust transfer functions estimation:

1. If necessary, time domain weights are calculated for the entire time series.
2. Calculation of instantaneous spectra and cross spectra for each realization and accumulation of the result without saving intermediate data (dynamic spectrum)

$$S_j^k = FFT(\{x\}_j) \quad j = E_x, E_y, \dots, H_z$$

If the use of time domain weights is specified and the weight of some realization is zero, the calculation for this realization is not performed.

3. Calculation of weighted average “accumulated” cross spectra using weights calculated in the time domain or without them.
4. Calculation of transfer functions. In this case, the transfer functions variance is calculated using simplified statistical relations based on the Fisher distribution. [Weckmann et al., 2005].

Graph of robust transfer functions estimation:

1. If necessary, pre-processing is performed in the time domain (decimation, filtering).
2. If necessary, time domain weights are calculated for the entire time series.
3. Time series splitting into approximately 20 segments. The exact number of segments depends on the length of the time series and on the amount of available memory for calculations. Those implementations whose weight is zero by the estimate in the time domain (if this check is specified) are skipped.
4. For each segment of the time series, the full dynamic spectrum is calculated: a set of instantaneous spectra for each realization.
5. For each segment, the median power spectra and cross spectra are calculated (used for visualization in the "Spectra" tab).
6. If required, some realizations are rejected according to a given set of criteria (coherence, polarization, etc.).
7. For each segment, a robust estimate of the transfer functions is performed with the successive use of the Huber and Thompson (exponential) loss functions. In this case, the transfer functions variance is calculated using the jackknife algorithm. [Chave, Thomsom, 1989].
8. The final result of processing is the median for all segments. In future versions this procedure will be more flexible and interactive.

Decimation

When choosing the type of MT processing, the option of cascade decimation is available during processing (the flag-button with the inscription "Decimate").

Cascade decimation consists of applying a low-pass filter with a finite impulse response and thinning the resulting time series with a 4-fold decrease in the sampling rate. Decimation continues until there are at least 20 realizations in the remaining time series. Decimation can help extend the frequency range of the evaluation of transfer functions towards low frequencies without increasing the window length. In addition, sequential high-pass filtering can also help improve the transfer function estimates at low frequencies.

Frequencies step

When choosing the type of MT processing, a choice of frequency steps is available for estimating the transfer functions. When choosing the logarithmic frequency step (Log), the frequencies are chosen so that 16 frequencies are placed per decade with a uniform step on a logarithmic scale, starting from the upper available frequency.

When using the linear frequency step (Lin), the transfer functions are calculated at all frequencies obtained after the Fourier transform taking into account the specified frequency limits of the selected event (see **Figure 9**).

Selection criteria

При выборе типа обработки МТ или RMT доступен выбор критериев отбраковки «плохих реализаций» перед началом оценки передаточных функций.

Consider working with selection criteria on the example of the criteria for the RMT processing type (**Figure 28**). The "Type" column contains the name of the criterion and the flag of its use in processing. Also, each criterion has a tooltip with an explanation. The columns "Minimum" and "Maximum" define the boundaries of the range that you want to skip or not skip to further processing. The last column determines how the selection criteria are applied. If the "Include" flag is checked, then implementations or windows that have the values of the selected parameter within the specified range will be included in the processing. Otherwise they will be excluded. For example, on **Figure 28** for the criterion "Signal / noise" range [0; 10] is marked as exclusive. This means that all implementations with a signal-to-noise ratio from zero to ten will be excluded from processing. Here, according to the "Coherence" criterion, only those windows will be included in the processing, the coherence in which lies in the interval [0.80; 1.0].

Selection criteria			
Type	Minimum	Maximum	
<input type="checkbox"/> Signal/noise	0	10	<input type="checkbox"/> Include
<input checked="" type="checkbox"/> Coherency	0.8	1	<input checked="" type="checkbox"/> Include
<input checked="" type="checkbox"/> Bearing H	0	30	<input checked="" type="checkbox"/> Include
<input type="checkbox"/> Elliptivity H	0	0.3	<input checked="" type="checkbox"/> Include

Figure 28. Selection criteria for PMT type of processing.

Criteria for RMT processing type

The criterion "**Signal / noise**" is defined as follows. The calculated power spectrum, namely the square root of the auto spectrum, is filtered for each channel by a median filter with a window of about 50-100 FFT frequencies to get an estimate of the noise level. Then, for each frequency, the ratio of the power spectrum value to the resulting noise estimate at each frequency is calculated. A signal is considered suitable by the "**Signal / Noise**" criterion if, at least one of the two channels (Ex / Hy, Ey / Hx, Hz / Hy, Hz / Hx), the signal-to-noise ratio thus obtained satisfies the on or off interval.

The criterion "**Coherence**" is defined as the square of two-channel coherence:

$$Coh_{ij}^2 = \frac{|S_{ij}|^2}{S_{ii}S_{jj}} \quad (5)$$

The criterion "**Bearing H**" determines the azimuth (bearing) to the source of the EM field relative to the receiving antenna of the recorder, calculated from the horizontal magnetic field. When using linearly polarized signals, such as radio transmitters signals, only those signals should be included in the processing, the polarization direction of which is close to the orientation of the receiving antennas.

The criterion "**Ellipticity H**" determines the ratio of the small axis of the polarization ellipse of the horizontal magnetic field to its major axis. Zero ellipticity corresponds to linear polarization. Ellipticity unit - circular polarization. This criterion is useful when rejecting non-linearly polarized signals.

Important: The criteria "Bearing" and "Ellipticity" work well when processing signals from radio transmitters, since most of them are vertical electric dipoles. The normal field of a vertical electric dipole is linearly polarized in the horizontal plane. However, this is not always the case for a horizontal electric dipole. This should be borne in mind when working, for example, with a controlled source.

Criteria for MT processing type

A complete list of selection criteria for the type of MT treatment is given in **Рисунок 29**. Each criterion has a detailed description in a tooltip (**Figure 30**).

Type	Minimum	Maximum	
<input checked="" type="checkbox"/> Coherency	0.8	0.99	<input checked="" type="checkbox"/> Include
<input type="checkbox"/> Coherency of inputs	0.01	0.2	<input checked="" type="checkbox"/> Include
<input checked="" type="checkbox"/> Coherency of outputs	0.01	0.2	<input checked="" type="checkbox"/> Include
<input type="checkbox"/> Partial coherency 1	0.8	0.99	<input checked="" type="checkbox"/> Include
<input type="checkbox"/> Partial coherency 2	0.01	0.2	<input checked="" type="checkbox"/> Include
<input checked="" type="checkbox"/> Multiple coherency	0.8	0.99	<input checked="" type="checkbox"/> Include
<input type="checkbox"/> Polarization E, °	-180	180	<input checked="" type="checkbox"/> Include
<input type="checkbox"/> Polarization H, °	-180	180	<input checked="" type="checkbox"/> Include
<input type="checkbox"/> Orthogonality ±°	80	100	<input checked="" type="checkbox"/> Include

Рисунок 29. Критерии выбора для типа обработки МТ.

Type	Minimum	Maximum	
<input checked="" type="checkbox"/> Coherency	0.8	0.99	<input checked="" type="checkbox"/> Include
<input type="checkbox"/> Coherency of inputs	0.01	0.2	<input checked="" type="checkbox"/> Include
<input checked="" type="checkbox"/> Coherency of outputs	0.01	0.2	<input checked="" type="checkbox"/> Include
<input type="checkbox"/> Partial coh			clude
<input type="checkbox"/> Partial coh			clude
<input checked="" type="checkbox"/> Multiple co			clude
<input type="checkbox"/> Polarizati			clude
<input type="checkbox"/> Polarizati			clude
<input type="checkbox"/> Orthogona			clude

Univariate coherency between orthogonal outputs. For example, for impedance this is coherence between E_x and E_y .

$$Coh_{E_x E_y}^2 = \frac{|[E_x^* E_y]|^2}{[E_x^* E_x][E_y^* E_y]}$$

Figure 30. Tooltip describing selection criteria.

For the case of the MT processing type, the list of available criteria depends on which channels are available in the event. For example, in the case of a three-channel measurement (E_x , H_y , H_x) the criteria **“Coherence of outputs”**, **“Partial coherence 2”**, **“Polarization E”** and **“Orthogonality”** will not be available due to the absence of the E_y channel.

To be continued ☺

References

1. Moskovskaya L.F. Impedance-admittance regression analysis of magnetotelluric fields. *Izvestiya, Physics of Solid Earth*, February 2007, Vol. 43, #2, pp. 148-160.
2. Semenov V.Ju. Magnetotelluric data processing. Moscow, "Nedra", 1985. 133 p.
3. Weckmann, U., Magunia, A., Ritter, O. (2005): Effective noise separation for magnetotelluric single site data processing using a frequency domain selection scheme. *Geophysical Journal International*, 161, 3, pp. 635—652.
4. Chave A.D., Thomson D.J. Some comments on magnetotelluric response function estimation. *Journal of Geophysical Research*, Vol. 94, no. B10, pages 14,215-14,225, October 10, 1989