Justification of electromagnetic scanning of oil-filled formation using downhole matrix antenna arrays

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Abstract. An overview of methods for mapping disturbances in a rock mass is given on the example of determining hydraulic fracture systems in an oil-filled formation. Methods of passive and active microseismic monitoring, as well as electromagnetic examining of rock masses for the presence of inhomogeneities in it are considered. A promising option for the development of hydraulic fracture mapping systems is proposed - creation of downhole logging probes representing ground penetrating radars that implement the mode of electrical scanning of the rock mass under study. The calculation of downhole antenna array based on the Butler matrix is performed. The calculated parameters of a phased antenna array with a Butler matrix can be used to design a downhole logging probe for mapping hydraulic fractures, as well as for surveying engineering structures, for example, foundations of buildings.

1. Introduction
Worldwide energy consumption is expected to grow 50% from current levels by the end of 2030. This growth can be achieved both from renewable resources and from hydrocarbons. Primary and secondary oil production methods usually yield only 15-30% of the original oil, depending on the compressibility of fluids and initial reservoir pressure [1].

Hydraulic fracturing is used to increase the productivity of a well by injecting pressurized fluid into a selected zone of the formation. High pressure causes the formation of new fractures or increasing in size of existing ones in this zone. To prevent their complete closure, proppant is usually placed in fractures before stopping fluid injection. Thus, proppant keeps fractures open creating a porous permeable path, which is open for fluid flow from the reservoir to the wellbore. Recoverable fluids such as oil, gas or water are then pumped through the well to the surface.

Despite a long history of hydraulic fracturing, fracture growth with time is not sufficiently studied. Information about the geometry of the created hydraulic fracture system in the reservoir is essential for production management: for designing future wells, choosing the type and calculating the amount of proppant, etc. Thus, there is a need for accurate fracture mapping. Methods commonly used include pressure and temperature analysis, seismic sensor observation analysis, microseismic monitoring of fracture formation during hydraulic fracturing. Each of these methods has advantages and disadvantages.

2. Theory and calculation of downhole antenna array
For mapping induced fractures in typical hydraulic fracturing systems, microseismic receiver arrays are positioned at the surface or downhole (Figure 1) and configured to record the “pops” that occur...
when induced shear fractures intersect with existing natural fractures. Energy release associated with shocks or seismic events is recorded through the propagation of elastic waves to an array of geophones (e.g. receivers) that are used to triangulate the location of event or hypocenter. Seismic data are collected and computations are made to locate the source of seismic activity. There is a high degree of uncertainty in measuring microseismic activity due to the impossibility of knowing a priori when a failure event will occur. This approach to seismic monitoring is known as passive microseismic monitoring, in which the term “passive” refers to the absence of controlled energy input. Since there is no controlled input of energy, the timing of the shift event is unknown. Thus, more unknowns appear in the system of equations, and the problem of its solution becomes more complicated.

![Image 1](image1.png)

**Figure 1.** Measurements of microseismic vibrations during hydraulic fracturing of oil and gas wells: 1–well, 2–hydraulic fracture, 3–surface geophones, 4–monitoring well, 5–downhole geophones, 6–concentrator, 7–data processing equipment.

A method for measuring microseismic vibrations using active radiating elements during hydraulic fracturing of oil and gas wells to assess the geometry of the induced fracture is also known (Figure 2). Various sensor arrays are available for measuring microseismic events in wells. Microseismic vibrations caused by hydraulic fracturing are typically monitored by: surface sensor arrays with a natural frequency of 4.5 Hz, downhole sensor arrays with a natural frequency of 10–15 Hz, 3-component fiber-optic distributed acoustic sensor cables, etc. (2–4).

![Image 2](image2.png)

**Figure 2.** Active method for measuring microseismic vibrations: 1–well, 2–packer, 3–fracture, 4–radiating element, 5–proppant.

Improving the quality of sensors and increasing their number is positively useful for determining the characteristics and geometry of a hydraulic fracture. More accurate results can be obtained under
the following conditions: location of geophones closer to seismic events, decrease in background noise level, increase in the number of sensors for summarizing measured microseismic events; increasing the signal-to-noise ratio of the receiving equipment, etc. [5] There are many algorithms to filter noise and record microseismic events in real time during hydraulic fracturing. However, these methods are still limited and cannot display the configuration and spatial orientation of the propped fracture with a high degree of confidence [6].

A common disadvantage of these methods is complex decompilation of the obtained data, dependence on uncertain parameters, measuring the shape of fractures during formation (and not after closure or during production), mapping fractures that may not have an exit to the wellbore, acoustic “noise” from hydraulic fracturing procedures and inability to distinguish seismic events caused by fracture formation and other processes.

Another method for monitoring hydraulic fractures involves the placement of sensitive dipmeters serving as a level to measure the movement of the Earth’s surface due to expansion and displacement of underground formations caused by injection of pressurized fluid and the resulting network of artificial fractures.

One more method assumes the addition of radioactive isotopes to hydraulic fracturing fluid and subsequent monitoring using gamma spectrometry. However, this approach introduces additional potentially hazardous substances into the soil. The US patent no. 7705294 describes a device that measures X-rays scattered backward from the internal layers of a wellbore in selected radial directions, while missing segment data are filled by moving the device through the wellbore. The device allows generating the data for two-dimensional workover of a well or wellbore. The US patent no. 4415805 proposes a method for evaluating a multi-stage hydraulic fracturing by injecting various radioactive tracers at each stage of hydraulic fracturing.

A promising direction in the development of hydraulic fracture mapping systems is the creation of downhole logging probes for ground penetrating radar survey of the rock mass, both at the time and after hydraulic fracturing. The GPR method is widely used in engineering geology to study rock masses, as well as in mining for geophysical support of methods for determining stresses in rock masses [7].

The direction of scanning can be controlled by antenna arrays - antennas containing a set of radiating elements arranged in a certain order, oriented and excited in such a way as to obtain a required directional pattern.

There are two ways to provide scanning with an antenna array. In the first case, the movement of the beam is provided by mechanical movement of parts of the antenna array, changing the direction of the main maximum in space or the shape of directional pattern. This is achieved by changing the geometric shape of the exciting radio waveguide or by rotating the entire antenna array. Such systems are very complex both for construction, taking into account the well geometry, and for operation.

The second method includes electrical control of the amplitude-phase distribution of currents or fields on the radiating elements. This way of controlling the position of the directional pattern is called electrical scanning, and the antenna system is called a phased antenna array.

The structural diagram of a multi-beam antenna includes a radiating part (an array of radiators or antenna aperture), a beamformer – the main element of a functional circuit that creates the required fields in the radiating part, and antenna inputs in the form of cross-sections of a transmission line with a single propagating wave type.

Currently, a large number of practical circuits of matrix antenna arrays are known. The most common are antenna arrays based on parallel (Butler matrix) and sequential (Blass matrix) beamforming systems.

In this paper, the calculation of downhole antenna array based on the Butler matrix is performed [8-10].

The circuit of a parallel-fed beamforming system based on the Butler matrix connects 2n of array elements with an equal number of beam ports. The main elements of the system are alternating rows of hybrid junctions and fixed phase shifters. The classic Butler circuit is shown in Figure 3.
In fact, the Butler matrix is the equivalent of fast Fourier transform analog circuit; therefore, the beamformer has a minimum number of components and minimum electric lengths [11, 12].

The main element of the Butler matrix is a quarter-wave stripline directional coupler (Figure 4).

Let us calculate the parameters of a stripline directional coupler. Transmission lines are formed on both sides of the initially double-sided foil-clad dielectric film. The values of operating frequency and attenuation parameters are accepted with regard to the results presented in [14].

Initial data:
- \( f_0 = 1 \text{ GHz} \)—operating frequency;
- \( \rho_0 = 50 \text{ Ohm} \)—characteristic impedance of transmission lines;
- \( S_{21} = 3 \text{ dB} \)—transient attenuation of a directional coupler.

The main material for work was foil-clad fluoroplastic (FAF-4D) with parameters:
- \( t = 0.035 \text{ mm} \)—foil thickness;
- \( \alpha = 1.43 \text{ mm} \)—insulating dielectric thickness;
- \( s \)—film thickness;
- \( \varepsilon = 2.5 \)—substrate dielectric permeability.

Directional coupler sizes were calculated according to [12].

Distance between the frame plates:
- \( b = (2.965 + s) \text{ mm} \).

At film thickness of 0.33 mm, the distance between the frame plates is 3.295 mm.

Wavelength \( \lambda = \frac{c}{f_0} = 0.30 \text{ m} \), where \( c \)—speed of light in vacuum.

Directional coupler strip length \( l = \frac{\lambda}{4\sqrt{\varepsilon}} = 0.0236 \text{ m} \).

Directional coupler strip width \( w = 0.44b = 0.0026 \text{ m} \).

Transmission line width \( w_0 = 0.81b = 0.0048 \text{ m} \).

Minimum distance between the frame and closest line
D_{\text{min}} = 2b = 0.0118 \text{ mm}.

Output contacts of the Butler matrix for connecting with radiating elements should be placed at a
distance of half a wavelength in air:

\[ l_{\text{out}} = \frac{\lambda}{2} = 0.0188 \text{ m}. \]

3. Conclusions

The calculated parameters of a 4-beam phased antenna array with a Butler matrix can be used to
design a downhole probe for mapping hydraulic fractures in oil-filled formations and to examine rock
masses and engineering structures for detecting hidden defects - fractures, decompactification zones
and areas with discontinuities.

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