Theoretical Analysis and Experimental Verification of Microwave Radiation Features of Fractured Rock

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Abstract— Some researchers carried out the microwave detecting experiment of loaded rock, and found the microwave radiation changing significantly when the rock fractured, which indicates that the passive microwave is possible to detect the phenomenon of rock fracture and failure, including earthquakes. But it is unclear by now about the patterns and rules of microwave radiation variation in rock fractures, and the theoretical foundation is also unclear. In this paper we first analyze the microwave radiation characteristics and the influence factors of fractured rock based on the microwave radiation theory of layered medium, and the microwave radiation feature is compared with that of intact rock. Then the theoretical analysis results are verified by a series of passive microwave detecting experiment of fractured rocks.

1. INTRODUCTION

Rock fracture and failure is a common phenomenon in nature, many geological disasters including earthquake, landslide, collapse, ground subsidence, slope instability, rock burst, mine earthquake etc. are related to rock fracture and failure. Since the beginning of this century, many strong earthquakes have happened in the world, which caused serious disasters to mankind. In order to explore the abnormal phenomenon before earthquakes, many people analyzed the thermal infrared radiation variation before the earthquake based on the satellite remote sensing data and found some thermal infrared anomalies appearing before violent earthquakes [1–4]. But it is difficult to recognize the anomaly in cloudy conditions due to inability of infrared radiation to pass through clouds and arrive to the satellite. By contrastmicrowave is not only able to pass through clouds even small rain, but also pass through some-depth soil. Therefore microwave can availably explore the anomaly from the thermal and geology structure change due to earthquake action.

In order to validate the correctness of the above thought some microwave radiation observing experiment were carried out in rock loading process, and found that microwave radiation energy of rock significantly changed with the change of rock stress state, and most rock appeared abnormal precursory with sharp increase or decrease before failure of rock, further research also found that the radar wave reflection strength of rock changed with the change of pressure [5, 6]. In 2006, Maki et al. [7] found that rocks appeared microwave signal variation at 300 MHz, 2 GHz, 22 GHz when the rock failure in uniaxial compression loading. Based on the experimental results Takashi et al. [8] presented a data-restructuring algorithm and applied it to analyze the AMSR-E data for the earthquake of Wenchuan earthquake on May 12, 2008, and found definitive microwave signals around the epicenter one day after the main shock. In order to eliminate the stable influence of geography, terrain, cover sphere and seasons, as well as the random influence of weather Liu et al. [9] presented a two-step method to extract the seismic microwave radiation anomaly related with earthquake. Furthermore the two-step method was applied to analyze the anomaly of Wenchuan earthquake based on the data of AMSR-E. The result showed positive radiation anomaly appearing around the epicenter before and after the earthquake.

But it is unclear by now about the patterns and rules of microwave radiation variation in rock fracturing process. In this paper we firstly analyze the microwave radiation characteristics and the influence factors of fractured rock based on the microwave radiation theory of layered medium, and the microwave radiation feature is compared with that of intact rock. Then the theoretical analysis results are verified by a series of passive microwave detecting experiment of fractured rocks.

2. THEORETICAL ANALYSIS ON MICROWAVE RADIATION OF FRACTURED ROCK

Compared with the intact rock, fractured rock exist the non continuous surface in its internal, so the fractured rock has a layered structure. Therefore we can use the microwave radiation theory of layered medium to analyze the microwave radiation characteristics of fractured rock.

In order to understand easily the microwave radiation of layered rock we first calculate the microwave radiation of intact rock.

2.1. Microwave Radiation of Intact Rock

Because the intact rock is equivalent to the monolayer rock, the microwave radiation received by the radiometer is composed of three parts, as shown in Fig. 1. The first part is the radiation of rock itself, expressed by T_S. The second part is the radiation of back environment, expressed by T_{e2}. The third part is the reflection of rock on the front environment radiation, expressed by T_{e1}.

2.1.1. The Calculation of T_S

In Fig. 1, T_s is the any thin layer of rock, its contribution to the radiometer is composed of two parts: one part is the upward radiation T_{s1}, it upward radiates to the above interface of rock with the angle θ_2, then transmits to the radiometer with the angle θ_1 or is reflected repeatedly by the two interface and transmits to the radiometer at last, as shown by the red line of Fig. 1. The other part is the downward radiation T_{s1}. It downward radiate to the lower interface with the angle θ_2, then is reflected by the lower interface and finally transmit to the radiometer with the angle θ_1, as shown by the black line of Fig. 1. According to the microwave radiation theory of layered medium, we can get following formulas,

$$\begin{aligned} T_{s1} &= T_A \cdot (1-\Gamma_1) + T_A \cdot (1-\Gamma_1) \cdot \frac{\Gamma_1 \cdot \Gamma_2}{L^2} + T_A \cdot (1-\Gamma_1) \cdot \left(\frac{\Gamma_1 \cdot \Gamma_2}{L^2}\right)^2 + \ldots \\ &= T_A \cdot (1-\Gamma_1) / \left(1 - \Gamma_1 \cdot \Gamma_2 / L^2\right) \end{aligned} \quad (1)$$

$$\begin{aligned} T_{s2} &= T_A \cdot (1-\Gamma_1) \cdot \frac{\Gamma_2}{L} + T_A \cdot (1-\Gamma_1) \cdot \frac{\Gamma_2}{L} \cdot \frac{\Gamma_1 \cdot \Gamma_2}{L^2} + T_A \cdot (1-\Gamma_1) \cdot \frac{\Gamma_2}{L} \cdot \left(\frac{\Gamma_1 \cdot \Gamma_2}{L^2}\right)^2 + \ldots \\ &= T_A \cdot (1-\Gamma_1) \cdot \Gamma_2 / \left[L \cdot \left(1 - \Gamma_1 \cdot \Gamma_2 / L^2\right)\right] \end{aligned} \quad (2)$$

Γ_1 is the reflectivity of the above interface, Γ_2 is the reflectivity of the lower interface, T_A is the total radiation energy from the rock to the above interface, expressed by following formula:

$$T_A = \int_0^d dT_A(\theta_2, \xi) = T_2 \cdot \left(1 - \frac{1}{L}\right) \qquad L = \exp\left(k_e \cdot d \cdot \sec(\theta_2)\right) \quad (3)$$

T_2 is the thermodynamic temperature of the rock, k_e is the extinction coefficient of the rock, d is the thickness of the rock.

2.1.2. The Calculation of T_{e2}

T_{e2} in Fig. 1 is the radiation of the back environment of rock, which can be considered as a semi-infinite medium, and only exist upward radiation, as shown by the green line of the Fig. 1. It firstly transmits into the rock, then is reflected repeatedly by two interface, finally transmit to the radiometer. According to the microwave radiation theory of layered medium we can get following formula,

$$\begin{aligned} T_{e2} = {} & T_3 \cdot \Gamma_e \cdot \frac{(1-\Gamma_2) \cdot (1-\Gamma_1)}{L} + T_3 \cdot \Gamma_e \cdot \frac{(1-\Gamma_2) \cdot (1-\Gamma_1)}{L} \cdot \frac{\Gamma_1 \cdot \Gamma_2}{L^2} + T_3 \cdot \Gamma_e \cdot \frac{(1-\Gamma_2) \cdot (1-\Gamma_1)}{L} \\ & \cdot \left(\frac{\Gamma_1 \cdot \Gamma_2}{L^2}\right)^2 + \ldots = T_3 \cdot \Gamma_e \cdot (1-\Gamma_1) \cdot (1-\Gamma_2) / \left[L \cdot \left(1 - \Gamma_1 \cdot \Gamma_2 / L^2\right)\right] \end{aligned} \quad (4)$$

T_3 is the thermodynamic temperature of back environment. Γ_e is the emissivity of back environment.

2.1.3. The Calculation of T_{e1}

In Fig. 1 T_{e1} expresses the radiation contribution of front environment. It includes two parts: one part is the reflection of rock surface to the radiometer, and the other part firstly transmits into the rock then is reflected by the lower interface to above interface, and finally transmits to the radiometer.

In order to calculate T_{e1}, we first calculate the summary of T_{s1}, T_{s2} and T_{e2},

$$T'_{int} = T_{s1} + T_{s2} + T_{e2} \quad (5)$$

Then the effective reflectivity Γ_{eff} of rock and back environment is obtained,

$$\Gamma_{eff} = 1 - T'_{int} / T_2 \quad (6)$$

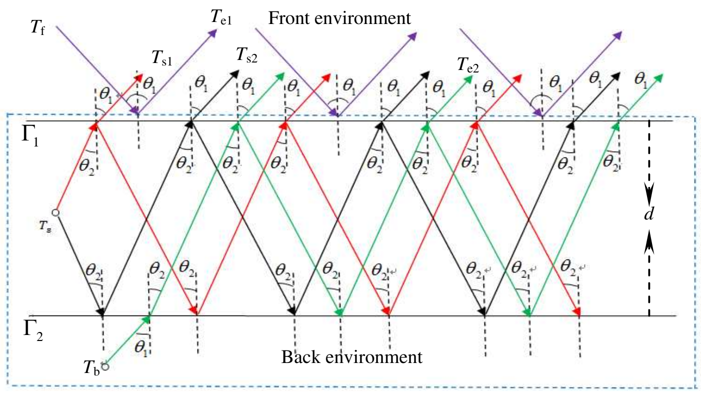


Figure 1: Schematic diagram of microwave radiation of intact rock.

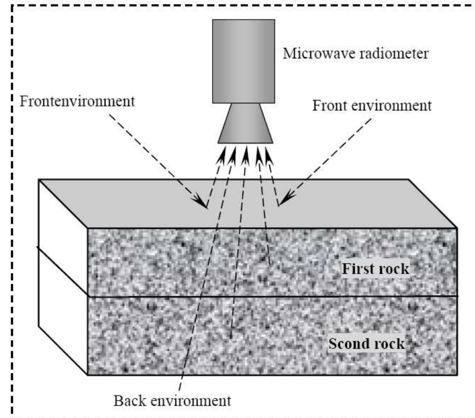


Figure 2: Microwave radiation of two-layer rock.

Therefore, T_{e1} can be calculated by the following formula,

$$T_{e1} = T_f \cdot \Gamma_{eff} \tag{7}$$

T_f is the microwave brightness temperature of front environment. Thus the microwave radiation of intact rock is obtained,

$$T_{lay1} = T_{s1} + T_{s2} + T_{e2} + T_{e1} \tag{8}$$

2.2. Microwave Radiation of Two-layer Rock

When the rock is composed of two layers of medium, the microwave radiation received by the radiometer consists of four parts, as shown in Fig. 2. The first part is the radiation from the first layer of rock; the second part is the radiation form the second layers of rock; the third part is the radiation from the back environment; the fourth part is the reflection of front environment.

2.2.1. Brightness Temperature Contribution of the First Layer of Rock

The brightness temperature contribution of the first layer of rock includes T_{AU1}, T_{AD1} and T_{A12}, as shown in Fig. 3(a). They are calculated by the following formulas:

$$T_{AU1} = T_{A1} \cdot (1-\Gamma_1)/(1-\Gamma_1 \cdot \Gamma_2/L_1^2) \tag{9}$$

$$T_{AD1} = T_{A1} \cdot (1-\Gamma_1) \cdot \Gamma_2/\left[L_1 \cdot \left(1-\Gamma_1 \cdot \Gamma_2/L_1^2\right)\right] \tag{10}$$

$$T'_{A12} = T_{A1} \cdot (1-\Gamma_1)/\left(1-\Gamma_1 \cdot \Gamma_2/L_1^2\right) + T_{A1} \cdot (1-\Gamma_2) \cdot \Gamma_1/\left[L_1 \cdot \left(1-\Gamma_1 \cdot \Gamma_2/L_1^2\right)\right] \tag{11}$$

$$T''_{A12} = T'_{A12} \cdot \frac{\Gamma_3}{L_2^2} \cdot (1-\Gamma_2)^2/\left(1-\Gamma_2 \cdot \Gamma_3/L_2^2\right)] \tag{12}$$

$$T_{A12} = T''_{A12} \cdot (1-\Gamma_1) \cdot (1-\Gamma_2)/\left[L_1 \cdot \left(1-\Gamma_1 \cdot \Gamma_2/L_2^2\right)\right] \tag{13}$$

Therefore, the radiation B_1 of the firstlayer rock is

$$B_1 = T_{AU1} + T_{AD1} + T_{A12} \tag{14}$$

2.2.2. Brightness Temperature Contribution of the Second Layer of Rock

The calculation of the brightness temperature contribution of the second layer of rock is divided into two steps, as shown in Fig. 3(b). The first step is to calculate the radiation of second layer of rock to the bottom surface of the first layer of rock, which is consists of the upward radiation T_{AU2} and the downward radiation T_{AD2},

$$T_{AU2} = T_{A2} \cdot (1-\Gamma_2)/(1-\Gamma_2 \cdot \Gamma_3/L_2^2) \quad T_{AD2} = T_{A2} \cdot (1-\Gamma_2) \cdot \Gamma_3/\left[L_2 \cdot \left(1-\Gamma_2 \cdot \Gamma_3/L_2^2\right)\right] \tag{15}$$

So the radiation T'_{A2} of second-layer rock to the bottom surface of the first-layer rock is

$$T'_{A2} = T_{AU2} + T_{AD2} \tag{16}$$

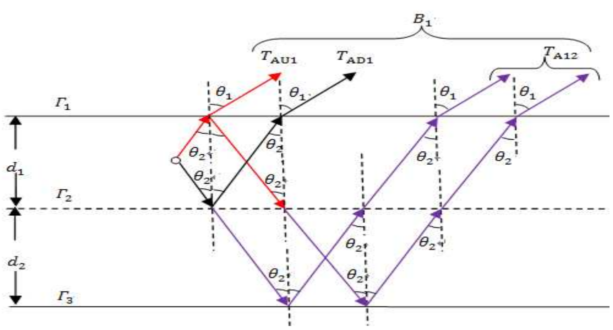
The second step is to calculate the attenuation and reflection of the radiation T'_{A2} when it passes into the first-layer rock, thus B_2 can be obtained,

$$B_2 = T'_{A2} \cdot (1-\Gamma_2) \cdot (1-\Gamma_1)/[L_1 \cdot (1-\Gamma_1 \cdot \Gamma_2/L_1^2)] \tag{17}$$

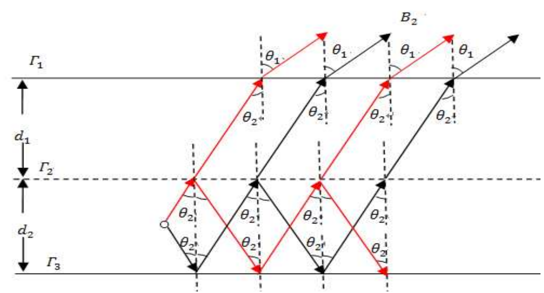
2.2.3. Brightness Temperature Contribution of the Back Environment

The calculation of the brightness temperature contribution of the back environment can divided into two steps, as shown in Fig. 3(c). The first step is to calculate the radiation attenuation when it passes into the second-layer rock, the second step is to calculate the radiation attenuation when it passes into the first-layer rock.

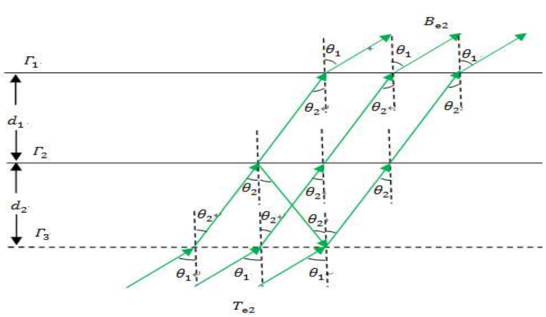
$$T'_{e2} = T_{e2}\cdot(1-\Gamma_3)\cdot(1-\Gamma_2)/[L_2\cdot(1-\Gamma_2\cdot\Gamma_3/L_2^2)]; \quad B_{e2} = T_{e2}\cdot(1-\Gamma_2)\cdot(1-\Gamma_1)/[L_1\cdot(1-\Gamma_1\cdot\Gamma_2/L_1^2)] \tag{18}$$



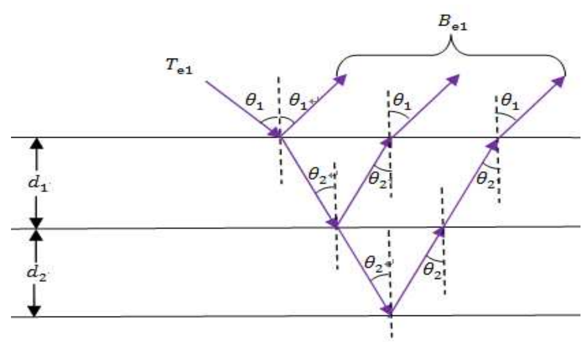
(a) Microwave radiation of the first layer rock



(b) Microwave radiation of second layer rock



(c) Microwave radiation of back environment



(d) Microwave radiation of front environment

Figure 3: Microwave radiation composition of two-layer rock.

2.2.4. Brightness Temperature Contribution of the Front Environment

In order to simplify the process, we can calculate the effective reflectance of rock,

$$\Gamma_{\mathit{eff}} = 1 - (B_1 + B_2 + B_{e2})/T_2 \tag{19}$$

So the brightness temperature contribution B_{e1} can be obtained,

$$B_{e1} = T_{e1}\cdot\Gamma_{\mathit{eff}} \tag{20}$$

Through the above analysis, the total radiation contribution of the two-layer rock to the radiometer is expressed by the following formula:

$$T_{lay2} = B_1 + B_2 + B_{e1} + B_{e2} = B_1 + B_2 + T_{e1}\cdot\left(1 - \frac{B_1 + B_2 + B_{e2}}{T_2}\right) + B_{e2} \tag{21}$$

3. EXPERIMENTAL VERIFICATION OF THE THEORETICAL MODEL

3.1. Microwave Radiation Comparison of Layered Rock and Intact Rock

Assuming the observation is taken under the condition of horizontal polarization and cold sky background. The observation angle is 40°. The thickness of intact rock is 10 cm. The total thickness of two-layer rock is also 10 cm, and the thickness of first layer is 3 cm, the thickness of second layer is 7 cm. According to the above theory model, the brightness temperature of intact rock can be calculated to be 278 K, but the brightness temperature of two-layer rock is only 262.8 K, which is lower than the intact rock.

Figure 4 shows the microwave observation result of intact rock and fractured rock by a C-band radiometer under cold sky background and horizontal polarization. The rock type and the thickness of intact rock and fractured rock are the same. Fig. 4 shows that the microwave brightness temperature of intact rock is higher than the fractured rock at any observation angles, and the difference between them is 4–8 K, which indicates that when rock is fractured the microwave brightness temperature will decreases.

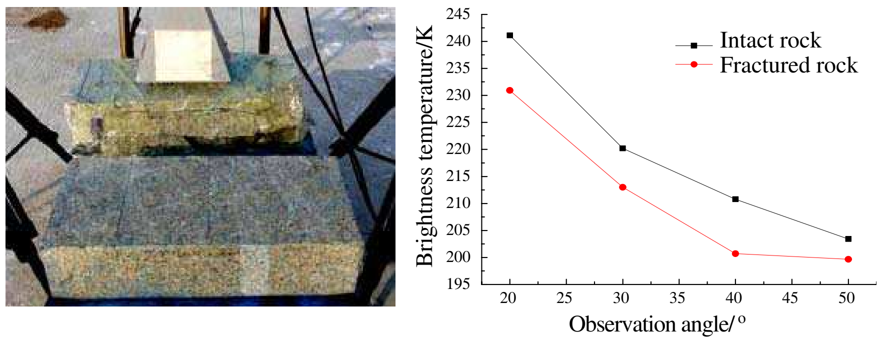


Figure 4: C-band microwave observation of intact rock and fractured rock under cold sky background and horizontal polarization.

3.2. Effect of the Front Environment on the Microwave Observation

Assuming the microwave observation is taken at horizontal polarization, the observation angle is 50°, and the observation frequency 18.7 GHz. The thickness of an intact rock is 15 cm, and the total thickness of a two-layer of rock is also 15 cm. The other observation conditions and parameters are shown in Table 1. Table 2 shows the theoretical calculation results at different front environment.

It can be found from Table 2 that the brightness temperature both intact rock and layered rock increase with the increase of the temperature of the front environment. When the observation is taken in an indoor environment the brightness temperature difference between intact rock and layered rock is very little, only 0.06 K. But when the observation is taken in cold sky background the brightness temperature difference is larger, up to 8.9 K, which indicates the rock fracturing phenomena is easy to be detected. So the microwave observation of the rock fracturing phenomena should be chosen in outdoor and cold sky background.

Table 1: Experimental condition and parameters of microwave observation.

Temperature of rock	Temperature of back environment	Real part of electric constant	Imaginary part of electric constant	Relative permeability	Magnetic susceptibility	Thickness of the first layer	Thickness of second layer
300 K	300 K	2	0.07	1	0.0001	5 cm	10 cm

To verify the influence of the front environment on the microwave radiation, we carried out the microwave observation test respectively in indoor and outdoor environment for intact and fractured rock. The result is shown in Table 3. Table 3 shows the difference of observation in different conditions. The microwave brightness temperature difference between intact and fractured rock is very small in indoor environment, less than 3 K. In contrast, in the cold sky background the difference is up to 10.61 K (C-band, sandstone). The experimental result is similar to the theoretical calculation results, which indicates that the front environment has an important impact on the microwave observation.

3.3. Effect of the Observation Angles on the Microwave Radiation

Assuming the microwave observation is taken at horizontal polarization and cold sky background. The thicknesses of the first layer and second layer of rock are respectively 1.5 cm and 2.5 cm. We analyze the effect of observation angles on the microwave observation. Fig. 5(a) shows the theoretical simulation result. From the diagram we can see the brightness temperature of layered

Table 2: Effect of the front environment on the microwave radiation received by the radiometer.

Temperature of front environment/K	Brightness temperature for intact rock/K	Brightness temperature for layered rock/K	Brightness temperature difference between intact rock and Stratified rock/K
298 K (Indoor)	299.82	299.76	0.06
78 K (Liquid nitrogen background)	280.19	273.38	6.81
10 K (Cold sky background)	274.12	265.22	8.9

Table 3: Microwave brightness temperature contrast for intact and fractured rock at vertical observation and in different environment.

Waveband	Rock type	Cold sky background		Indoor environment	
		Fractured rock	Intact rock	Fractured rock	Intact rock
band C	Granite	264.23	281.31	292.22	292.97
	Sandstone	262.1	272.72	286.16	287.09
Band K	Granite	277.7	287.52	297.15	300.14
	Sandstone	268.88	276.7	292.66	293.87

rock decrease with the increase of the observation angle. Fig. 5(b) and Fig. 5(c) are the experimental observation result of Kband radiometer at horizontal polarization, which is the similar to the theoretical simulation results.

(a) Theoretical simulation result (b) Experimental scene (c) Experimental result

Figure 5: Effect of the observation angles on the microwave radiation.

Assuming the observation is taken at horizontal polarization and frequency 18.7 GHz, the other observation conditions and parameters are shown in the Table 1. Table 4 show the observation result of intact and layered rock under different observation angles. It can be found that the brightness temperature difference of intact rock and layered rock increases gradually with the increase of the observation angles. When the observation angle increases from 35° to 60°, the brightness temperature difference of the intact rock and layered rock increases from 6.14 K to 11.73 K, which indicates that microwave detection on rock fracture phenomenon should choose large observation angle. In practice the observation angle of satellite microwave remote sensing is mostly 55°, which is larger and suitable to detect the crystal rock fracture phenomenon, such as the earthquake.

3.4. Effects of Observation Frequency on Microwave Radiation

Assuming the observation at horizontal polarization and the cold sky background with temperature 10 K, the observation angle is 40° and the other observation conditions and parameters are same as Table 1. Table 5 is the theoretical simulation result of brightness temperature of intact rock and layered rock at different frequencies.

It can be found from Table 5 that the brightness temperature difference of intact rock and layered rock decreases with the increase of frequency. When the frequency increases from 6.6 GHz (band C) to 31.68 GHz (band Ka) the brightness temperature difference of intact rock and layered

Table 4: The microwave observation result of intact and layered rock at different observation angles.

Observation angles/°	Brightness temperature of intact rock/K	Brightness temperature of layered rock/K	Difference of Brightness temperature between intact and layered rock/K
35	285.34	279.20	6.14
40	282.69	275.82	6.87
45	279.08	271.30	7.78
50	274.12	265.22	8.9
55	267.22	257.00	10.22
60	257.54	245.81	11.73

Table 5: Theoretical simulation result of brightness temperature of rocks at different observation frequencies.

Frequencies/GHz	Brightness temperature of intact rock/K	Brightness temperature of layered rock/K	Brightness temperature difference of intact rock and layered rock/K
6.6	281.19	263.83	17.36
13.9	282.59	272.77	9.82
18.7	282.69	275.82	6.87
31.68	282.71	279.92	2.79

rock decreases from 17.36 K to 2.79 K. The experimental results indicated that the low-frequency radiometer is easier to detect the fracture phenomenon of crust rock.

4. CONCLUSION

In this paper, the microwave radiation characteristics and the influence factors of fractured rock is analyzed based on the microwave radiation theory of layered medium, and the microwave radiation feature of fractured rock is compared with that of intact rock. Then some theoretical analysis results are verified by the passive microwave detecting experiment. The main results are: (1) the microwave brightness temperature of layered rock is smaller than that of intact rock under same conditions; (2) the environmental radiation have an important influence to brightness temperature of layered rock, and the brightness temperature increase with the increase of environmental temperature in the front of rock; (3) the brightness temperature of layered rock decrease with the increase of the observing angle; (4) the brightness temperature of layered rock increase with the increase of the microwave frequency.

The experiment results indicated that it is possible to use the microwave remote sensing to monitor the fracturing of rock masses, including earthquakes.

ACKNOWLEDGMENT

This work is supported by the National Important Basic Research Project (No. 2011CB707102), the National Natural Science Foundations of China (No. 41074127) and the Specialized Research Fund for the Doctoral Program of Higher Education (No. 20120042110029).

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