Study on determination of an object material using the microwave doppler sensor

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Abstract. In this study, to consider a method for detecting the sediment portion of avalanches containing sediment using microwave Doppler sensors, we confirmed whether the signal processing obtained by the sensors can differentiate the objects. Since microwaves in this frequency band are not easily affected by rain and snowfall, these are being developed for use in dashboard camera and other applications. However, it is necessary to understand the attenuation of the microwave for the snow in order to apply this technology to detect the sediment in the avalanche. It is also necessary to know the rate of reflection of microwaves from the snow and sand. Therefore, it is necessary to verify whether the reflection of the microwave from the sediment is correctly measured or not. In this report, we discuss the results of the verification to see if the distance between the sensor and the object, which is known in advance, can be detected correctly.

1. Introduction
Avalanches involving sediment and snow are often treated in the fields of geotechnical engineering and geology that deal with slope disaster prevention as one of the sediment collapses with snow accumulation during the snowmelt season in Japan. In addition, it has been reported that the reach distance of collapsed sediment exceeds that of normal sediment due to the inclusion of snow [1]. On the other hand, there have been few reports focusing on avalanches containing sediment, and the phenomenon of avalanches reaching longer distances than usual has recently begun to attract attention in the field of glaciology, so the mechanical interpretation of the effect of sediment on avalanches has not progressed. A typical example is the avalanche that occurred in Tokamachi and Tsunan towns in Niigata Prefecture and Sakae town in Nagano Prefecture on March 12, 2011, which was the first reported case of heavy snowfall over 2 m due to the earthquake in northern Nagano Prefecture. After this case, there is a growing need to consider the simultaneous occurrence of landslides and avalanches [2]. In order to elucidate the motion mechanism of avalanches containing sediment, it is necessary to make experimental observations on how the shape of the avalanche changes during flow and how sediment is distributed in the avalanche during flow.

On the other hand, there is an example of analyzing the shape of an avalanche by measuring the avalanche's path and area of influence from monitoring images [3]. For the observation of the inside of avalanches, model slope experiments with artificial simulated avalanches in laboratory tests have been conducted to understand the internal structure of avalanches during flow from image data [4], and structures equipped with a number of monitoring instruments have been installed in advance on slopes
where avalanches are empirically predicted to occur [5]. However, there are still no sufficient reports for avalanches containing sediment. In this study, we have been developing an avalanche flow prediction method and have been conducting flow observation experiments of artificial avalanches using a small-scale model slope for the purpose of constructing an analytical model [6]. In this experiment, we are observing the basic flow of avalanches, especially changes in flow velocity and shape, to collect data that can be used to verify the accuracy of avalanche replication analysis, and to verify the effects of avalanche and snowpack incorporation during flow. In addition, experiments have been conducted in which sand and gravel, which are assumed to be sediment, are simultaneously flowed with snow to see how they affect the flow velocity. However, the process by which sediment contributes to avalanche motion is still unclear, and there are still issues such as how sediment is distributed and under what conditions it is fluidized over long distances in a downstream avalanche.

In this study, we focused on the microwave Doppler sensor, which has been used in the field of non-destructive inspection (e.g., [7] and [8]), in order to understand how much energy of the sediment is contributed to the avalanche flow by mixing the sediment with the snow. The purpose of this study is to observe how the distribution of sediment and snow inside the avalanche changes during the flow, and to differentiate the snow and sediment inside the avalanche by comparing the frequency characteristics of the electromagnetic waves obtained by the microwave Doppler sensor with the results observed visually. In this paper, as a preliminary step to differentiate between sediment and snow using microwave Doppler sensors, we discuss the results of organizing the frequency characteristics of sand and water as objects for measurement at the laboratory experimental.

2. Experimental system

2.1. Microwave Doppler sensor

In this study, the Microwave Doppler Sensor that can emit microwaves in the 24 GHz band was used (NJR-4262J: New Japan Radio). Figure 1 shows the Microwave Doppler Sensor used in this study. This sensor can detect the position of an object by using the fact that the frequencies of the transmitted and reflected waves are shifted by the Doppler effect when the radio wave is reflected from the object (e.g., [7] and [8]).

The sensor irradiates microwaves in the 24 GHz band to the measurement object and receives the reflected microwaves. The theoretical equation for the transmitted wave $T_s$ and the received wave $R_s$ is given as follows:

$$T_s(t) = A_s \cos(\omega_s t)$$

$$R_s(t) = A_r \cos(\omega_s + \omega_d) t + \phi)$$

where $A_s$ and $A_r$ are the respective amplitudes, $\omega_s$ is the angular velocity of the transmitted wave, $\omega_d$ is the Doppler angular velocity, $t$ is the time, and $\phi$ is the phase depending on the distance to the object. The microwave Doppler sensor used in this study is equipped with a function to output the frequency fluctuation components of mixing the transmitted and received waves as I and Q signals. The mixed signal is expressed by the following theoretical equation.

$$T_s(t)R_s(t) = A_s A_r \cos(\omega_s t) \cos(\omega_s + \omega_d) t + \phi)$$

$$= \frac{A_s A_r}{2} \{ \cos(\omega_d t + \phi) + \cos(2\omega_s + \omega_d) t + \phi) \}.$$  

(3)

The theoretical equation of the output I and Q signals after mixing is expressed by the following equation, in which only the term including the low frequency Doppler angular velocity is left out of equation (3), and the phase difference between the Q output and the I output is given by $\pi/2$. 

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In this case, the I-Q signal, which is the phase of the transmitted wave and the received wave, can be obtained from the sensor. This signal is detected when the target object is approached, the I output is \(+\pi/2\) greater than the Q output, and when the object is separated, the I output is detected \(-\pi/2\) greater than the Q output. This effect can be used to monitor the movement detection of an object.

If we define the phase \(\theta\) of the Lissajous waveform synthesized from the I and Q output signals as shown in Figure 2, the Doppler angular velocity \(\omega_d\) is the time derivative of the phase \(\theta\). In general, the displacement of the value of phase \(\theta\) is compared when the state of motion of an object is grasped using a microwave Doppler sensor, but it is said that it is possible to grasp the state of an object in more detail by tracking the change of Doppler angular velocity \(\omega_d\) [9].

In this study, we examine whether the Doppler angular velocity \(\omega_d\) in the I-Q signal obtained by the microwave Doppler sensor can be used to differentiate between objects. Mitani proposed the following approximate formula for the Doppler angular velocity to improve the efficiency of the calculation [9].

\[
\omega_d \approx \frac{(I - I_{\text{offset}}) \times \Delta Q - (Q - Q_{\text{offset}}) \times \Delta I}{(I - I_{\text{offset}})^2 + (Q - Q_{\text{offset}})^2} \tag{6}
\]

where \(\Delta I\) is the time variation of I output, \(\Delta Q\) is the time variation of Q output, and \(I_{\text{offset}}\) and \(Q_{\text{offset}}\) are the central values of I-Q Lissajous. In order to analyse the behaviour of I-Q Lissajous, we need the offset coordinates of I-Q, which is the center of the circular path. In order to analyse the behaviour of I-Q Lissajous, the offset coordinate of I-Q, which is the center of the circular path, must be calculated in accordance with the time variation of I-Q output, because this I-Q offset coordinate fluctuates with the movement of the object. In this study, we use the fact that the behaviours of the I-Q Lissajous is a circular path to estimate the I-Q offset at three points using the I-Q value of \(\pi/2\) and \(\pi\) periods ahead of the I-Q value based on the I-Q value at the time to be determined. The formula for estimating the I-Q offset is as follows.

\[
\begin{pmatrix}
I_{\text{offset}} \\
Q_{\text{offset}}
\end{pmatrix} = \frac{1}{2(\alpha \delta - \beta \gamma)} \times \begin{pmatrix}
\delta & -\beta \\
-\gamma & \alpha
\end{pmatrix} \begin{pmatrix}
|X_1|^2 - |X_2|^2 \\
|X_2|^2 - |X_3|^2
\end{pmatrix} \tag{7}
\]

![Figure 1. Microwave Doppler sensor.](image1)

![Figure 2. I-Q Lissajous waveform.](image2)
where

\[
\begin{pmatrix}
\delta \\
-\gamma \\
\alpha
\end{pmatrix} = \begin{pmatrix}
x_1 - x_2 & y_1 - y_2 \\
x_2 - x_3 & y_2 - y_3
\end{pmatrix}
\]  

(8)

\[|x_i|^2 = x_i^2 + y_i^2\]  

(9)

\(x\) is the value of I, and \(y\) is the value of Q.

2.2. Measurement System

In this study, we used Arduino uno to realize a simple measurement system. Arduino uno is one of the general-purpose microcontroller boards. In addition, the microwave Doppler sensor used in this study is an analog output type. Therefore, we used an AD converter to get the digital data. An overall diagram of the measurement system is shown in figure 3. The sampling rate of the measurement data was set to 50 Hz.

![Measurement system](image)

**Figure 3.** Measurement system.

3. Experimental conditions

In this experiment, sand and water were placed in a 500 ml glass beaker, and the beaker and the object were moved by means of the elevating machine that operated at a constant speed. The beaker was filled with four cases: (1) empty, (2) only water, (3) only sand and (4) water with sand. Table 1 shows experimental condition of this study. These objects were irradiated with microwaves from the top of the beaker to detect the signals. Figure 4 shows an overall view of the experimental system. The displacement speed of the elevating machine is 0.01 m/s. The object used in the experiments is shown in figure 5. The object filled with sand in the beaker was prepared in two cases in amount of 150 ml and 300 ml of sand. The distance between the sensor and the top plate of the elevating machine is 16 cm, and the distance from the position where the content of the beaker is 500 ml to the sensor is 7 cm, and the distance from the position where the content of the beaker is 300 ml to the sensor is 10 cm. Each object was measured by repeating move up and down 3 times.
Table 1. Experimental conditions.

| Sample | Case1 | Case2 | Case3 | Case4 | Case5 | Case6 |
|--------|-------|-------|-------|-------|-------|-------|
|        | None  | Sand 150 ml | Sand 300 ml | Water | Sand 150 ml with water | Sand 300 ml with water |
| **H**  | 15.0  | 15.0  | 15.0  | 15.0  | 15.0  | 15.0  |
| **D₁** | 14.5  | 12.0  | 10.0  | 14.5  | 12.0  | 10.0  |
| **D₂** | -     | -     | -     | 7.00  | 7.00  | 7.00  |

Unit: cm

Figure 4. Overall view of the experimental system.

Figure 5. The object used in the experiments.
4. Experimental results and discussion

4.1. Time variation of I and Q signals

Figure 6 and figure 7 show the output results of the I and Q signals and the resultant value of the I and Q signals obtained in the experiment. In figures, red shows the I signal, blue shows the Q signal, and green shows the resultant value of the I signal and the Q signal. The resultant value of the IQ signal is defined by the following equation,

\[
V_{IQ} = \sqrt{V_I^2 + V_Q^2}.
\]  

(10)

**Figure 6.** I-Q signal without water.
It is known that the amplitude of the signal obtained from the microwave Doppler sensor varies with the presence of the object. In the result of the measurement, we found three points where the amplitude oscillated greatly. In addition, each point was symmetrical and the time of the large amplitude oscillation was about 3 seconds. In this experiment, the raising and lowering of the elevating machine was done in 3 seconds each in all the experiments. It can be seen that the three points where the waveform changed greatly in all the measurements responded to the movement of the elevating machine. In other words, we can see that this measurement system is able to detect the movement of the object.

![Figure 7. I-Q signal with water.](image)

In the next section, we analyse the results of the measurement with the object containing sand only in the beaker. It can be seen that there is a difference in the amplitude of the waveform obtained by the movement of the elevating machine between the case with and without the sand. The difference in amplitude is smaller when the sand is as little as 150ml than when the sand is empty, and larger when the sand is 300ml. Accordingly, it can be seen that the difference in amplitude is dependent on the type
of moving object and also on the distance to the sensor. However, the voltage obtained from the first step-up cycle to the second and third cycle was different from the initial value.

Figure 8. The results of the I-Q Lissajous waveforms.
Then, the object filled with water up to 500 ml scale is analyzed. The first thing that can be confirmed from these results is that the voltages obtained by all the I and Q signals returned around the initial values after three cycles. This indicates that the signals obtained tend to be stabilized when water is included in the object. In addition, the amplitude that responds to the movement of the elevating machine is larger in the case of water only than in the case of an empty object. This indicates that the sensor used in this experiment is affected by water. On the other hand, in the case of the object containing sand and water, the difference in amplitude of the waveform obtained is different as in the case of the object containing sand only.

4.2. Comparison of Doppler angular velocities calculated from I-Q Lissajous waveforms

Figure 8 shows the results of the I-Q Lissajous waveforms obtained in each case. The broken line in blue shows the trajectory for all the times when the ascent and descent were repeated three times, and the broken line in red shows only the first ascent part. In Cases 1 to 3 without water, the shape of the Lissajous waveform becomes larger as the amount of sand in the object increases.

On the other hand, in Case 4 to Case 6 where water is added, as the amount of sand increases, the shape of the Lissajous waveform increases as in the case without water, indicating that the waveform starts differently from the case without water. These mean that the I-Q Lissajous obtained by changing the object are different, and it is confirmed that the results are largely related to the differentiation of the object. In the case with water, the circular path fluctuation is less than the case without water, which raises the possibility that the water absorbs the noise contained in the I-Q signal.

Figure 9. The time variation of the Doppler angular velocity obtained from Case 1 to Case 3.
Next, figure 9 shows the time variation of the Doppler angular velocity obtained from Case 1 to Case 3 where no water is added, and figure 10 shows the time variation of the Doppler angular velocity obtained from Case 4 to Case 6 where water is added. Note that the graphs shown below each figure represent an enlarged view of the first moving part where the elevating machine is raised. The results without water show not much difference in the variation of the Doppler angular velocity, but the results with water show that the Doppler angular velocity fluctuates with a fine period in proportion to the amount of sand. These results suggest that it may be possible to differentiate the objects by comparing the results with the changes in the I-Q Lissajous waveform.

5. Conclusion
In order to understand whether the microwave Doppler sensor is effective as a method to confirm the structure inside the avalanche including sediment in a non-contact way, we verified the basic analysis method to differentiate the material of the object from the detection signal of the moving object obtained by the microwave Doppler sensor. In addition, a simple material of water and sand were used for the basic verification of whether the microwave Doppler sensor can differentiate the object. Furthermore, we used an inexpensive and simple microcomputer board as a system to measure the signals obtained from the microwave Doppler sensor, assuming the measurement at the field level.

In the measurement of object detection, the object was moved by an elevating machine that can maintain a constant speed moving environment, and the movement of the object was detected by the
microwave Doppler sensor. The object was prepared as a specimen in a beaker with water or sand. In this measurement, the I-Q signal output by the microwave Doppler sensor was obtained even in an environment where the microcomputer board was used as the measurement system, and it was confirmed that the movement detection of the object was approximately correct.

We also analysed whether the material of the object can be differentiated from the I-Q signal obtained from the microwave Doppler sensor. In this analysis, the I-Q Lissajous waveform and the Doppler angular velocity were calculated from the obtained I-Q signals, and it was confirmed that the magnitude of the I-Q Lissajous waveform and the period of the Doppler angular velocity changed depending on the condition of the object. In particular, it was found that the waveform and the magnitude of the period were different when with and without water in the object. This suggests that the method of comparing I-Q Lissajous waveform and Doppler angular velocity may be effective as a method to differentiate the material of the object.

On the other hand, in order to understand the internal structure of avalanches, which is the purpose of this study, it is necessary to confirm the detection of snow and ice objects. In the future, we will investigate the possibility of understanding the internal structure of avalanches by confirming the signals obtained when snow, ice and sand are used as objects.

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