Study on Position Determination of Space Debris Impact via Microwave

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Abstract

This paper describes the detection of the position of a space debris impact on a space structure via microwave. Microwaves are received by two antennas. We estimate the arrival direction by the delay time on the basis of a cross correlation between the received signals. The experimental result shows that it is possible to estimate the delay time. The delay time is 5.3 nsec, which agrees well with the delay value calculated from the geometry of the experimental set-up.

1. INTRODUCTION

The space debris impacts on a spacecraft lead to a hypervelocity impact, which is 10 km/sec on average [1]. There are two kinds of methods to detect the space debris; the measurement of flying debris to avoid the impact to the spacecraft with a radar and a telescope [2] and the measurement of the impact with the on-board detector in the spacecraft [3]. The minimum size in detection of debris in LEO with radars and those in GEO with telescopes is 10 cm, and 1m, respectively [4]. We, therefore, have to consider the impacts with the debris less than 10 cm for safe space activities.

Recently, we have successfully detected the microwave emission due to a hypervelocity impact between a metal target and a projectile using an accelerator [5]. The debris detection system was proposed based on this microwave generation [6].

The microwave is an extremely-short pulse with a few nano seconds in cycle observed in the hypervelocity impact experiment using the accelerator. The light emission is a continuous wave, but the microwave emission is a intermittent wave in the hypervelocity impact. The microwave emission become large with increasing the impact velocity. However, the observation waveform is different among each experiment. The mechanism of the microwave emission has not been revealed yet. We assume that the microwave is emitted spatially-uniform or homogeneously.

In the case of previous detection system, the debris impact was detected but the impact position was not determined [6]. The goal in our study is the establishment of the method for the detection of the position of a space debris impact on a International Space Station via microwave. The position detection needs an arrival detection and a distance estimation. This paper examines only a direction-of-arrival estimation, the position is decided with the angle of two microwave.

From Section 2 to 3, we consider the detection method of the impact position of a space debris via correlation of two waveforms received with two antennas from a theoretical aspect. We proposed an experimental methodology using an accelerator.

In Section 4 and 5, we present a hypervelocity impact experiment with an accelerator and calculate cross-correlation function of the received waveform. We confirm the principles of the arrival time interval of two waveforms can be obtained.

In Section 6, we compare the arrival time intervals among experimental results and a theoretical value, considering errors in receiving system circuits.

2. THE DETECTION METHOD OF A SPACE DEBRIS IMPACT POSITION WITH CORRELATION

We set two antennas to detect the microwave from the hypervelocity impact point (Fig. 1). The equation (1) is obtained when the microwaves detected with the antenna #1 and #2 is assumed as plane waves.

$$d \cdot \sin\theta = c \cdot \tau \qquad (1)$$

$$\Delta\theta = \frac{c}{d}\Delta\tau \qquad (2)$$

τ is the arrival time interval, c is the light speed, d is the distance between antenna #1 and #2 and θ is the arrival angle. Equation (2) is available when θ is small enough. $\Delta\tau$ is the measurement error in experiments and $\Delta\theta$ is the determination error.

The arrival direction is calculated with Eq. (2) when τ is obtained. When the arrival wave is a spherical one , the arrival angle is also calculated from the phase difference calculated with the arrival time interval.

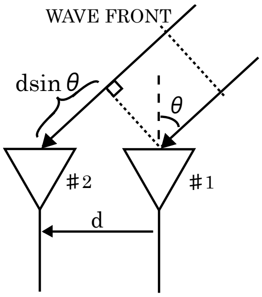


Fig. 1: The schematic draw of the arrival wave detection with two antennas

There are two kinds of methods to decide the arrival time interval: using a single pulse wave(method I) and using correlation among all pulse waves (method II). The advantages of the method I are an early detection of debris impact and avoidance of multipath effect. However, the detected single pulse is possibly the pulse from noises. On the other hand, the advantages of the method II is high precision of arrival time because this method decides the arrival time interval using the average timing on all pulses. However, the multipath effect makes it difficult to acquire the real impact timing. In the method II, τ is calculated from the maximum timing in

$$\phi_{12}(\tau)=\lim_{T\to\infty}\frac{1}{2T}\int_{-T}^{T} f_1(t)f_2(t+\tau)dt\,, \qquad (3)$$

where $f_1(t)$ is the signal detected with the antenna #1 and $f_2(t)$ is that with the antenna #2.

3. IMPACT EXPERIMENT AND MICROWAVE RECEIVING SYSTEM

Figure 2 shows the ground experimental system for detecting the microwave emission due to a hypervelocity impact. An electromagnetic accelerator, or a rail-gun is used as an accelerator to reach the hypervelocity. A thin zigzag-shape wire with 5 mm width is located in front of a target. The distance between the target and the wire is about 27 cm. A trigger signal is generated when the projectile cuts the wire. The velocity of the projectile is measured at two points with an X-ray. The target is located in a vacuum chamber. The microwave receiving antennas are located near a chamber window.

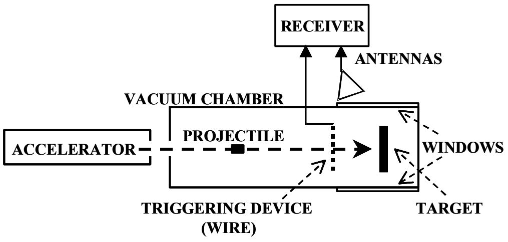


Fig. 2: The experimental system.

4. THE RECEIVING SYSTEMS AND THE PARAMETERS FOR EXPERIMENTS

Figure 3 shows the receiving system in 2 GHz band. The receiving systems, #1 and #2, have the same condition, such as the same apparatus and the same cables in length, to minimize the errors in these two systems. The antenna is selected the half-wave dipole antenna aligned without any directional characteristics to the arrival waves. Low-noise amplifiers (LNAs) are applied in the all receivers to detect the small signals. The characteristics of the receivers are listed in Table 1; the observed frequency (RF) bands, the intermediate frequency (IF) bands and the gains. The microwave signals are recorded using a digital storagescope with 4 GHz sampling frequency and 1 msec observation period.

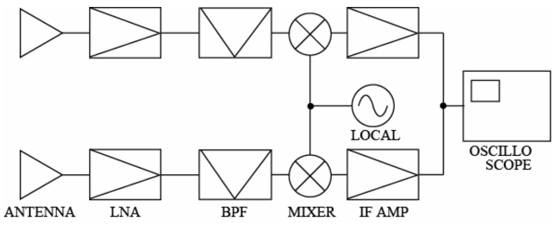


Fig. 3: The receiving system in 2 GHz band.

TABLE 1: THE CHARACTERISTICS OF THE RECEIVERS

frequency band [Hz]	RF band [MHz]	IF bande [MHz]	gain [dB]
2G-No1	1850-2250	0 – 120	54.15
2G-No2	1820-2230	0 – 120	54.15

The receiving system parameters, the distance between the antennas d and the arrival angle θ, should be decided to increase the receiving precision. The high receiving precision is decided by a large arrival time interval, which is realized by a large distance between the antennas and a large arrival angle. In addition, the simple setup is recommended to reduce the arrival angle error caused by the setup misalignment. These parameters are decided as shown in Table2, considering the special limitation in the experimental environment and the characteristics of arrival waves, which is explained later. The experimental setup is shown in Fig. 4. Though the arrival angle should be 90 degree, the antenna #1 shields the signals before the antenna #2. We set 1 degree arrival angle difference between antenna #1 and #2 .

TABLE 2:. THE RECEIVING SYSTEM PARAMETERS

the distance between antennas d [m]	arrival angle θ [°]
1.5	90

The microwave emitted by the impact propagates the space as a spherical wave. The wave becomes a plane wave when it fulfils the condition Eq.4.

$$R > 2d^2/\lambda\,, \qquad (4)$$

where R is the distance between the target and the antenna, λ is the wavelength of the emitted microwave. The microwave is assumed as a plain wave with R > 30 m. R is 515 m between the target and the antenna #1. Therefore, the wave is a plane wave. The difference between a plane wave and a spherical wave can be reduced with 90 degree in arrival angle.

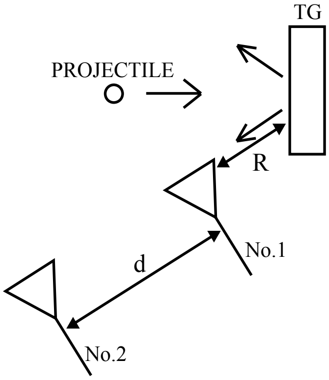
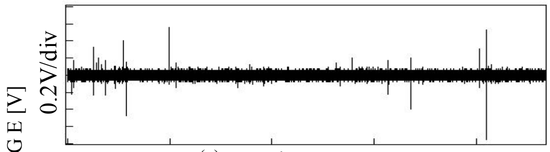


Fig. 4: The experimental setup.

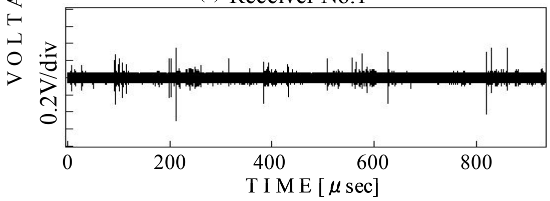
5. EXPERIMENTAL RESULTS

The projectile is the cylindrical polycarbonate with the weight of about 1 gram, and the target is an aluminium plate with the diameter of 130 mm and the thickness of 20 mm. The impact velocity is 4.1 km/sec. We insert an attenuator between antenna and low-noise amplifier in each system to avoid saturation of received waveform as the receiving system properties. The receiving system in No.1 has a 10 dB attenuators and that in No.2 has a 3 dB one.

Figure 5 shows the microwave signals after the destruction due to the hyper velocity impact. The abscissa indicates the time and the ordinate indicates the voltage. The impact time is 0 sec. The projectile penetrates through the target and debris impact a rear chamber wall.



(a) Receiver No.1



(b) Receiver No.2

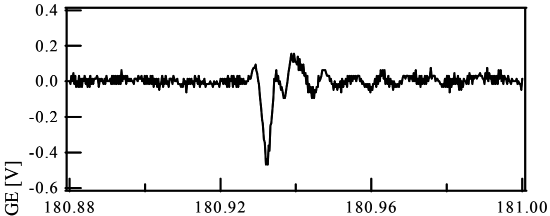
Fig. 5: The observed signals.

The intermittent pulse signals are measured in Fig. 5. The signal in the receiving system No.1 is earlier than that in the receiving system No.2 when the timing of the signals are similar, because the receiving system No.1 is closer to the impact point than the receiving system No.2. However, several signals were not detected in both receiving systems due to the pulse-like-noises and the multipath effects. The amplitudes of signals were also different. The mechanism of the microwave emission has not been revealed yet about signal level difference.

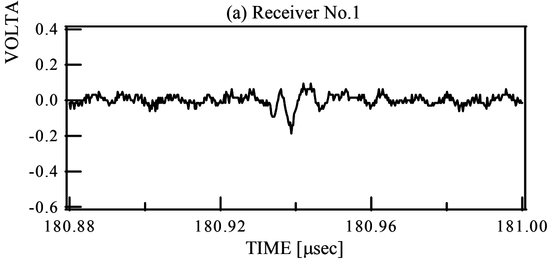
6. THE COMPARISON ABOUT TIME INTERVALS BETWEEN THEORY AND EXPERIMENT

A. Arrival time in the single pulse method

The arrival direction was assumed based on the observation results in our experiments. The arrival time interval should be discussed among the 5 pulses just after the impact due to the multipath effect and the target fragment reflection to the chamber wall. The arrival time between in two receiving systems were compared in Fig. 6. The averaged arrival time interval was calculated with Eq. (2), resulting in τ = 7.5 nsec.



(a) Receiver No.1



(b) Receiver No.2

Fig. 6: The expansion of signal.

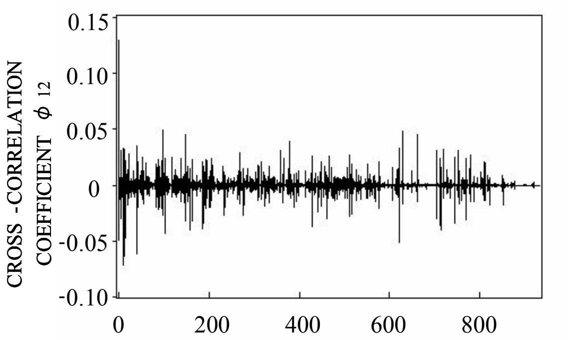
B. Arrival time in the pulse correlation method

The arrival direction was also assumed using this method based on the observation results in our experiments. The signal in this experiment was not continuous. The Eq. (3) should be redefined with discrete parameters.

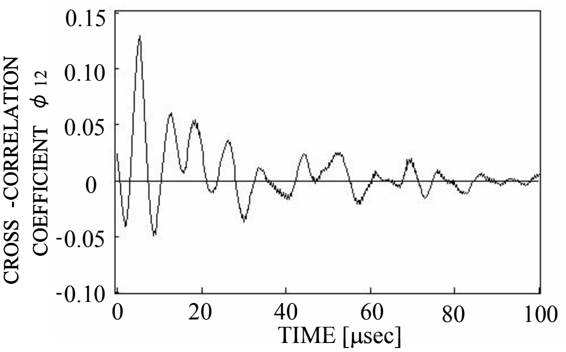
$$\phi_{12}[\tau] = \sum_{k=1}^{N} f_1[t] f_2[t+\tau] \Big/ \sqrt{\sum_{k=1}^{N} f_1^{\,2}[0]}\sqrt{\sum_{k=1}^{N} f_2^{\,2}[0]} \qquad (5)$$

N was data points, normalized data using autocorrelation function in both receiving systems. We removed the thermal noises from the signals before the calculation with Eq. (5) to obtain the real correlation in both receiving systems. The pulses from -80 mV to 80 mV were cut in this experiment. The correlation function $\theta_{12}(\tau)$ was calculated and plotted in Fig. 7.

The arrival time interval at the peak was detectable in Fig. 7. The coefficient of cross-correlation function at the peak was about 0.13 and the coefficient of other ones was less than 0.05. The arrival time interval, τ, was 5.25 nsec in this experiment.



(a) the observed signal



(b) the expansion

Fig. 7: The relationship between time and the cross-correlation function of the received signals.

C. Comparison between theoretical values and experimental results

The arrival time interval in theory, the results using single pulse detection and that using pulse correlation method are shown in Table 3.

TABLE 3: THE ARRIVAL TIME INTERVAL IN THEORY AND EXPERIMENTAL RESULTS.

	arrival time interval τ [nsec]
method I	7.5
method II	5.25
theoretical value	5.00

The velocity error in the circuits of both receiving systems should be discussed. The propagation time difference between both receiving systems was obtained from the experiments in which the 2 GHz CW waves were input to the receiving systems without the antenna. The propagation time difference was 1.00 nsec. The theoretical time interval should be corrected to 6.00 nsec; the time interval of signals, 5.00 nsec, and the propagation time difference, 1.00 nsec. The differences between theory and experiments were also corrected to 1.5 nsec in the single pulse method and 0.75 nsec in the pulse correlation method.

The common reasons for this difference are as follows;

- the misalignments in the antenna formation and the angle
- the waveform change due to the phase difference between a local signal and an input signal at a heterodyne mixer
- the difference caused by the antennas with different characteristics
- noises
- the multipath effect

The decision way in the single pulse method had a few troubles; the 5 pulses just after the impact was used without any correlation of the arrival time interval calculation with all pulses and the wrong pulses were probably used for calculation. The pulse correlation method has an advantage in the aspect of the arrival time interval.

7. CONCLUSIONS

(1) The arrival time interval estimation by using correlation among all pulse waves is more promising than using a single pulse wave.

(2) In the case of correlation among all pulse waves, cross-correlation function was calculated from the observation waveform. The time interval was uniquely estimated by removing the thermal noise from the signals and confirmed its effectiveness.

(3) We carried out the observation of the microwave emission due to a hypervelocity impact using two antennas.

(4) The errors of the experimental time intervals compared with the theoretical value are as follows;
single pulse wave method : 1.5 nsec
correlation among all pulse waves method : 0.75 nsec

(5) We further study to increase the accuracy of the measurements,
- a better antenna formation for measurements
- a calibration of the phase difference between a local signal and an input signal at a heterodyne mixer
- a calibration of the receiving system inclusive the antenna

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