3-7 Experimental Reports of APAA Health Test

Akira AKAISHI, Mitsugu OHKAWA, and Takashi TAKAHASHI

As a health test of the WINDS APAA, Rotating Element Electric Field Vector Method (REV) was applied between the satellite and the earth station. This report shows the problems on orbit REV, the data acquisition method, the data evaluation method and the phase compensation experiment.

The REV problems on orbit are that the clocks of the satellite and the earth station are not synchronized and the received REV signal fluctuates due to the atmospheric disturbance. We have resolved those problems that the two times measurements for a phase setting are applied for the non-synchronization, and the averaging method is applied for the signal fluctuation.

As the results of the trend assessments for the measured data, the relative amplitudes and the relative phases for the all antenna elements were almost reappeared for the beginning data. The health of the WINDS APAA was confirmed consequently.

1 Introduction

The WINDS APAA (Active Phased Array Antenna) has a function to point its antenna beam in an arbitrary direction towards the earth from geostationary orbit. This antenna consists of a receiver and a transmitter, both of which have 128 antenna elements, an amplifier and a BFN (Beam Forming Network). Both the receiving and the transmitting systems can form two beams simultaneously. These two beams share antenna elements and the amplifier, while separate BFN is installed for each beam. A soundness verification test for long-term operation is required because, in general, the APAA is composed of many parts and it has not been used for the Ka band of a satellite before. In this paper, we report on the results of a soundness verification test for long-term WINDS APAA operation by applying an in-orbit rotating element electric field vector method [1] to measure the feed amplitude and feed phase. In addition, we also report on the results of a phase compensation experiment that maximizes the antenna gain by correcting APAA systematic errors as an application of the REV method.

The REV evaluation of the WINDS APAA was also performed by JAXA [2].

2 Outline of WINDS APAA

A function block diagram of the RF system of the APAA is shown in Fig. 1. Both the receiving and transmitting systems consist of a small horn antenna with 128 elements that are aligned in a plane, an amplifier and two systems of BFN (Beam Forming Network). The BFN consists of phase shifters, multiplexers or dividers. Each phase shifter is an analog phase shifter of 5 bits and it can shift a phase by 11.25° by one bit. In the receiving system, the phase of signals received by antennas of 128 elements are shifted to an appropriate phase by the phase shifter in BFN. Then, the signals are synthesized by the multiplexer to form a receiving beam to be input to a down-converter. In the transmitting system, the transmitted signals from the up-converter are distributed to 128 elements by the divider to be input to the phase shifter. The transmitted signals pass through the phase shifter from the transmission beam by being radiated from the 128 antenna elements.

3 Outline of REV

The merit of the REV method is that it enables simultaneous measurement of the feed amplitude and feed phase of the antenna array by measuring only the amplitude using a facing antenna pair, using the phase shifter installed in the antenna. Moreover, it enables retrieving an optimized feed phase that maximizes antenna gain as compensation phase. Also, the REV method enables failure diagnosis of elements by applying the method to all the APAA elements.

Here, an outline of the REV method is described using a schematic diagram of the electric field vector shown in Fig. 2. The electric field vector of the APAA at initial phase in the REV method is $\dot{E}_0 = E_0 e^{j\phi_0}$. Here, if the phase of element n is changed by the phase shifter installed in it, the synthetic electric field vector $\dot{E}$ is obtained. Because the relative power of synthetic electric field vector $\dot{E}$ changes like a cosine function, the relative electric field vector of the element, $\dot{E}_n = E_n e^{j\phi_n}$, can be obtained from the amplitude and initial value, by fitting the obtained data to a cosine function. Also, the compensation phase to maximize antenna gain can be derived from the peak value of the cosine function.

Here, the relative phase of an element means the difference of the phases $\dot{E}_0$ and $\dot{E}_n$, $\phi_n - \phi_0$. The compensation phase is the angle (Δ_0) formed by the direction of the maximum synthetic electric field vector and the electric field of a certain element when the concerned element and electric field vector are rotated. That is, when the phase of the concerned element is rotated corresponding to the compensation phase, the synthetic electric field contributed by the concerned element reaches the maximum. By applying this method to all the elements, the antenna gain reaches the maximum.

4 Practical method

4.1 Retrieval of REV data

On-orbit REV of WINDS was measured with the configuration shown in Fig. 3. REV was performed by the element phase control command by JAXA, shifting the phase of receiving or transmitting the APAA phase of WINDS 360° divided by 11.25° of the minimum step of phase setting. The REV of the receiving APAA was performed by the fixed phase of the beam of the transmitting APAA to the Kanto area. The REV of the transmitting APAA was performed by the fixed phase of the beam of the receiving APAA to the Kanto area. The satellite transponder is set to a non-regenerative transponder mode.

As there are two systems of transmitting the APAA and receiving the APAA, REV of the WINDS APAA was per-

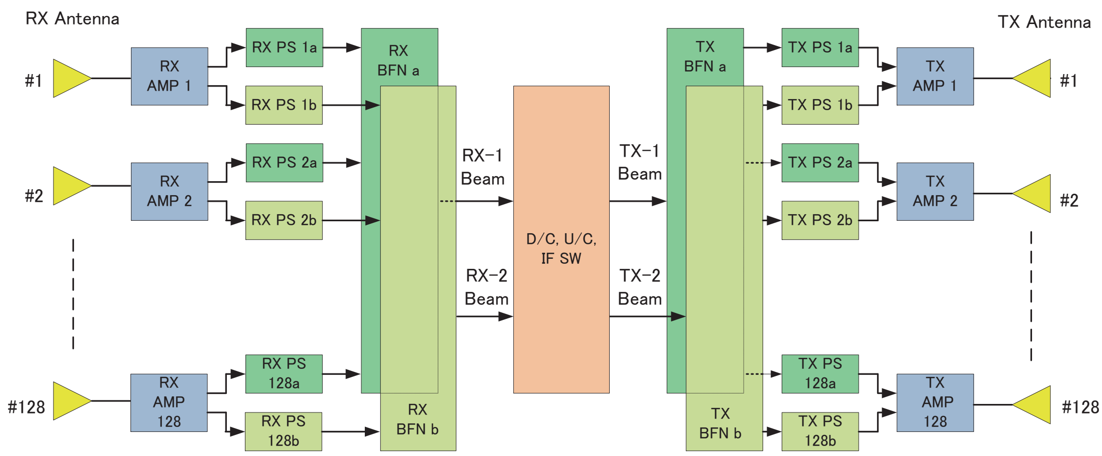

Fig. 1 APAA block diagram

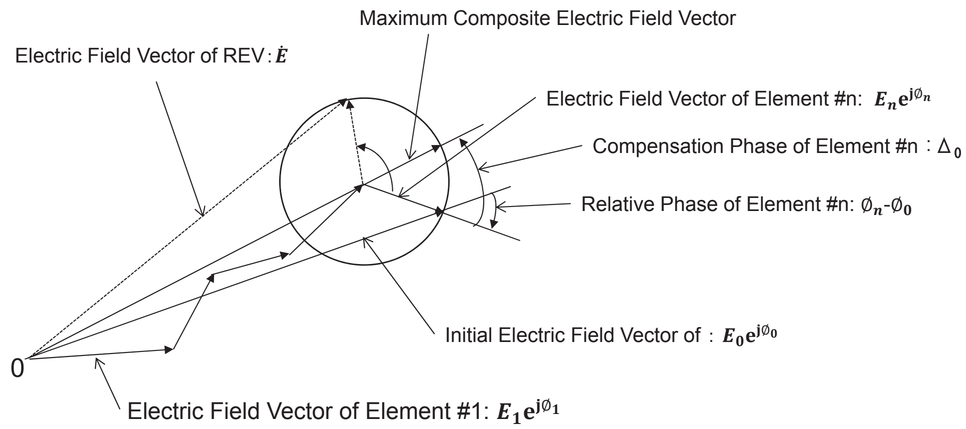

Fig. 2 Electric field vector of REV

formed four times. The phase shifter integrated in each antenna element is five bits in dynamic range, so the phase shift for one bit is 11.25°. Then, if the phase shifter is set 32 times, it changes 360°. During the WIND REV, one phase condition is kept for every 80 ms. Moreover, in order to distinguish the REV starting point, a transient phase of 0°, 112.50° and 236.25° is added at the beginning of phase rotation. For the WINDS REV, the phase shifter is set 35 times including phase setting of 32 points from 0° to +348.75° (phase propagation direction) by steps of 11.25° and a transient phase setting of 3 points.

The measurement time of the REV is about 6 minutes for 128 elements. In addition, as the starting time of measurement of the satellite and that of the earth were not synchronized, the measurement was started one minute before the starting time of REV and the termination of REV was extended one minute. Then, the measurement duration was 8 minutes. Moreover, as the timing of the phase setting of the satellite and the measurement timing at the receiver did not coincide precisely, the measurement duration was 40 ms which was half of the period. Therefore, the duration time of 40 ms may fall in the period of 80 ms. Although the real data that falls in the period of 80 ms and false data that crosses the boundary of the 80 ms period as well appear one by one, they can be distinguished in the data post-processing. Figure 4 shows the measurement timing of the REV data.

Here, there is no time difference of measurement because the phase setting timing of the APAA and measurement timing of the REV data are synchronized with a GPS clock.

4.2 REV data processing method

The REV data for receiving power for phase shift of the antenna element derive 1,024 points of data in a 40 ms interval in the setting of a real-time spectrum analyzer. As this data contains signal and noise including atmospheric fluctuation, the effect by atmospheric fluctuation is reduced by averaging these 1,024 data points.

There are two REV data sets of real data and false data after the averaging process. The false data of the two should be discarded as the data contains the boundary of the 80 ms interval. In order to extract the false data, the amplitudes of the waveforms can be compared. The amplitude

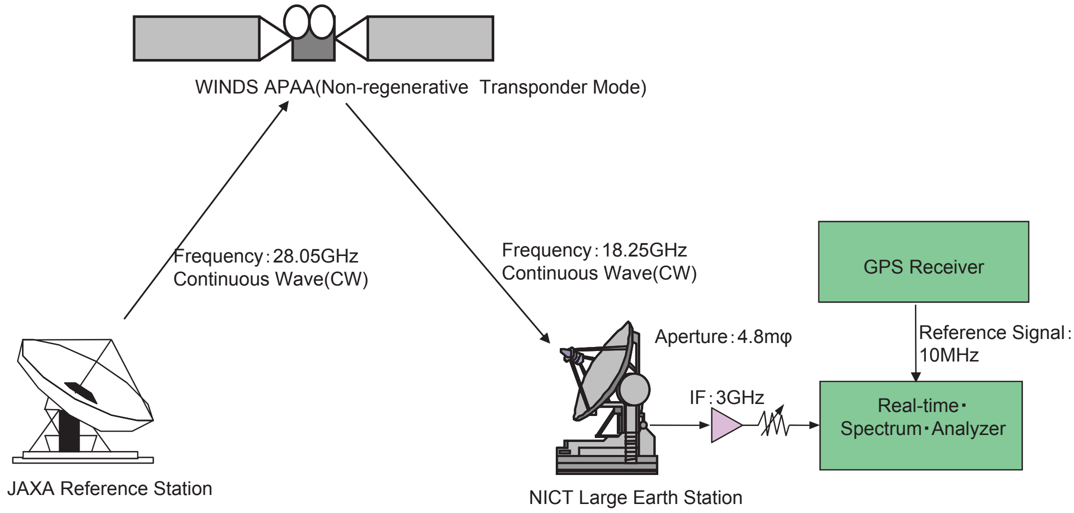

Fig. 3 REV signal measurements

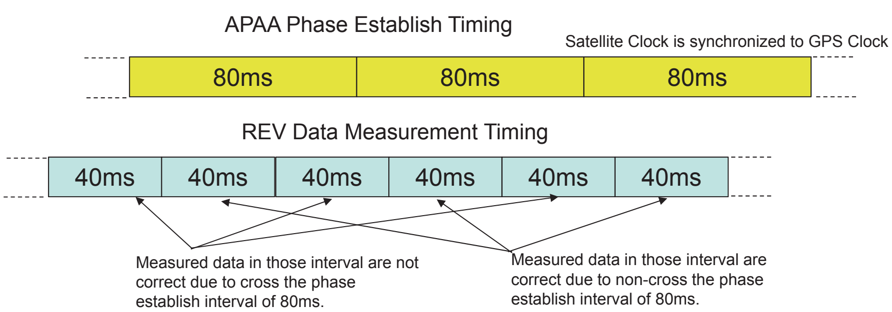

Fig. 4 REV data measurement timing

of the transient waveform containing the boundary is smaller or almost the same as that not containing the boundary. The data set containing more waveforms of smaller amplitude is discarded as a false data set. An example of the results of averaging REV data is shown in Fig. 5. An example of a false data set with a small-amplitude transient phase is shown in Fig. 6.

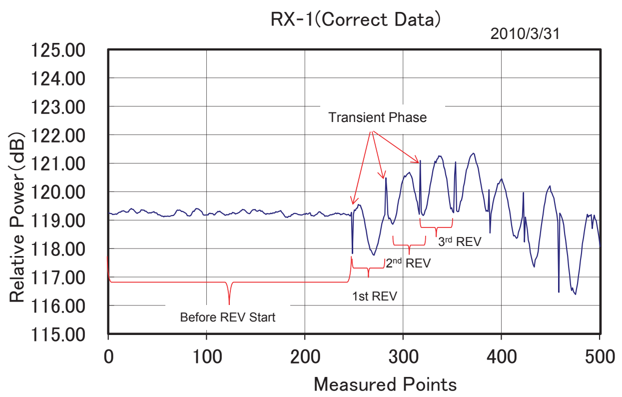

Fig. 5 Data processed sample (Correct Data)

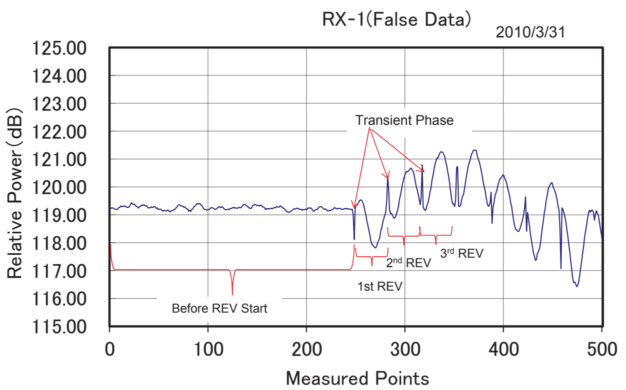

Fig. 6 Data processed sample (False Data)

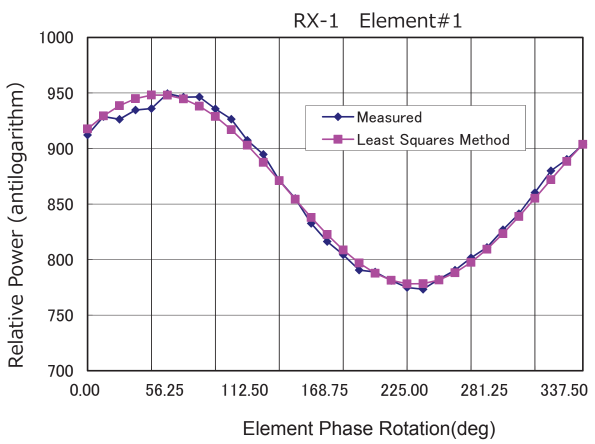

Fig. 7 Data processed sample

As the waveform of the real data of each element selected above is deformed due to atmospheric fluctuation, the data set for each element is fitted to a cosine function by the least-squares method. One example of the results of fitting is shown in Fig. 7. The compensation phase (Δ_0) that maximizes the relative amplitude of element n is derived from the fitted cosine curve. Then, the relative amplitude and relative phase of the element are derived as the following equations [1]. Here, we define $\Gamma = (r-1) / (r+1)$ by expressing the difference between the maximum and minimum receiving level as r.

If the phase compensation for all elements is performed by retrieving the correction phase, the antenna gain at the REV measuring point reaches the maximum and the antenna beam of the APAA faces the measuring point.

Relative amplitude of the element：

$$\frac{\Gamma}{\sqrt{1+2\Gamma\cos\Delta 0+\Gamma^2}} \tag{1}$$

Relative phase of the element：

$$\tan^{-1}\left(\frac{-\sin\Delta 0}{\cos\Delta 0+\Gamma}\right) \tag{2}$$

5 Results of experiments

5.1 Waveform of received data

As an example, we will look at the results of the received REV data performed on February 6, 2017. The level of the received signal was obtained by a real-time spectrum analyzer for 2,048 points (1,024 points for 40 ms interval) by the update cycle of the REV of 80 ms interval. Then, the data were averaged by 40 ms interval and are shown graphically in Figs. 8 to 11. Each figure shows antenna RX-1, RX-2, TX-1, and TX-2, respectively. In the figures, the initial part of the receiving level is a continuous wave without the REV, and the subsequent REV part corresponds to 128 elements, and the last part to the end is a continuous wave without the REV.

The waveform of the REV part is a cosine function which implies that the element operates normally. Here, the waveforms of the cosine function are not the same because the initial phase of each element at the REV is randomized intentionally. This is because the level variation of the elements at the REV are relatively enlarged by decreasing the peak gain of the antenna. The fact that the level variation of the transmitting system is smaller than that of the receiving system is caused by the setting of initial phase.

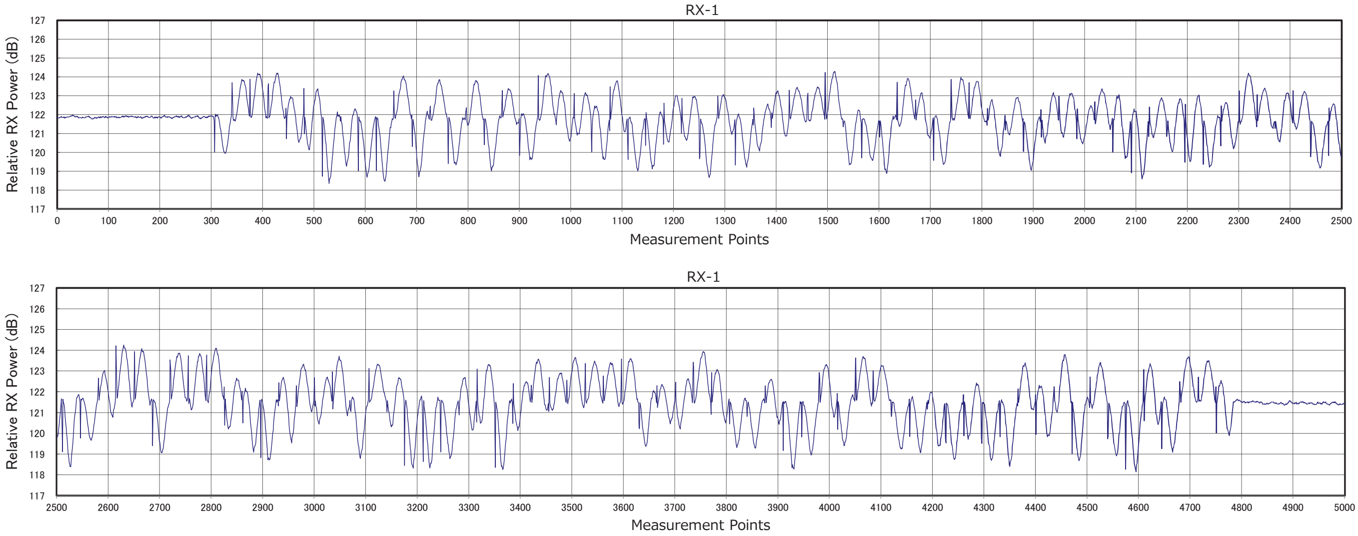

Fig. 8 REV data (RX-1)

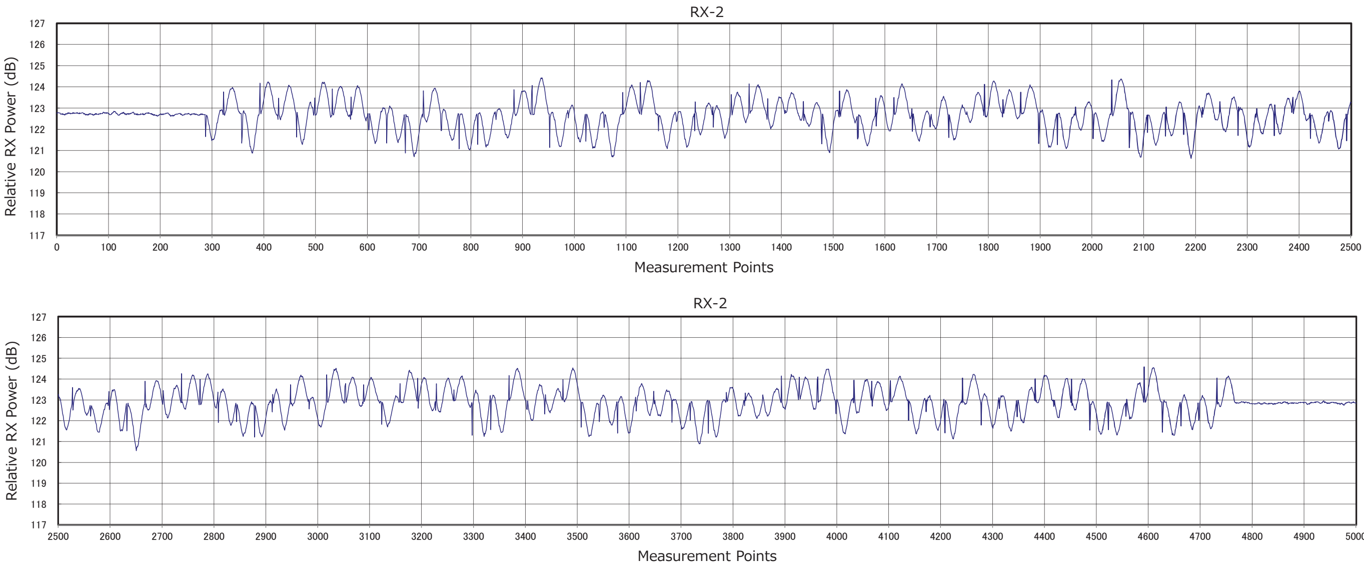

Fig. 9 REV data (RX-2)

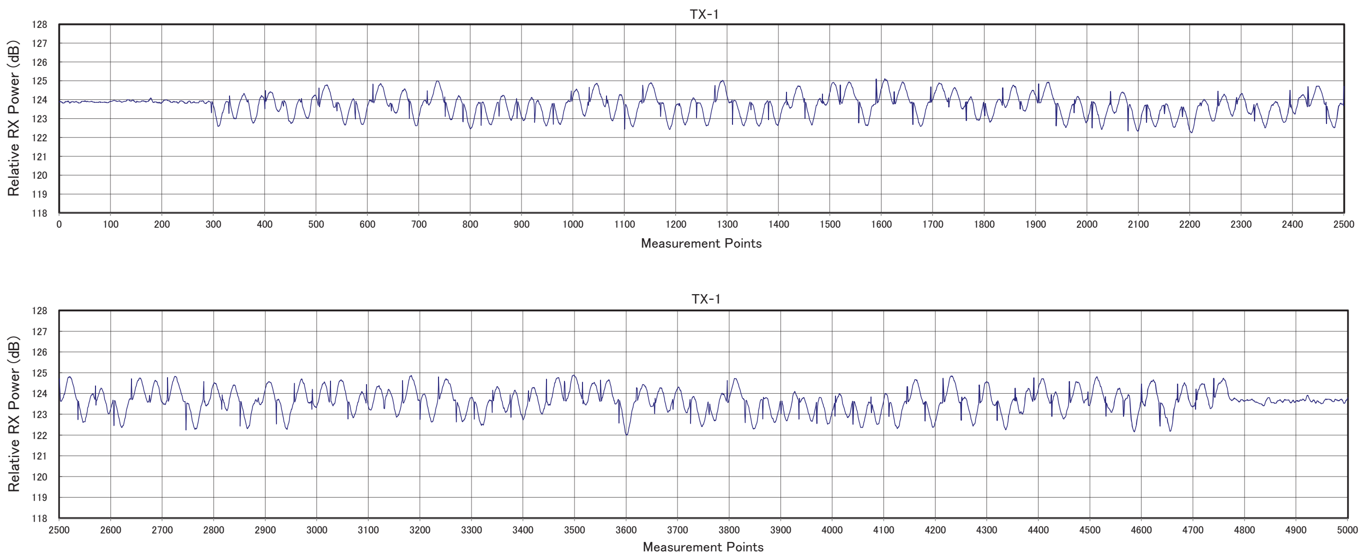

Fig. 10 REV data (TX-1)

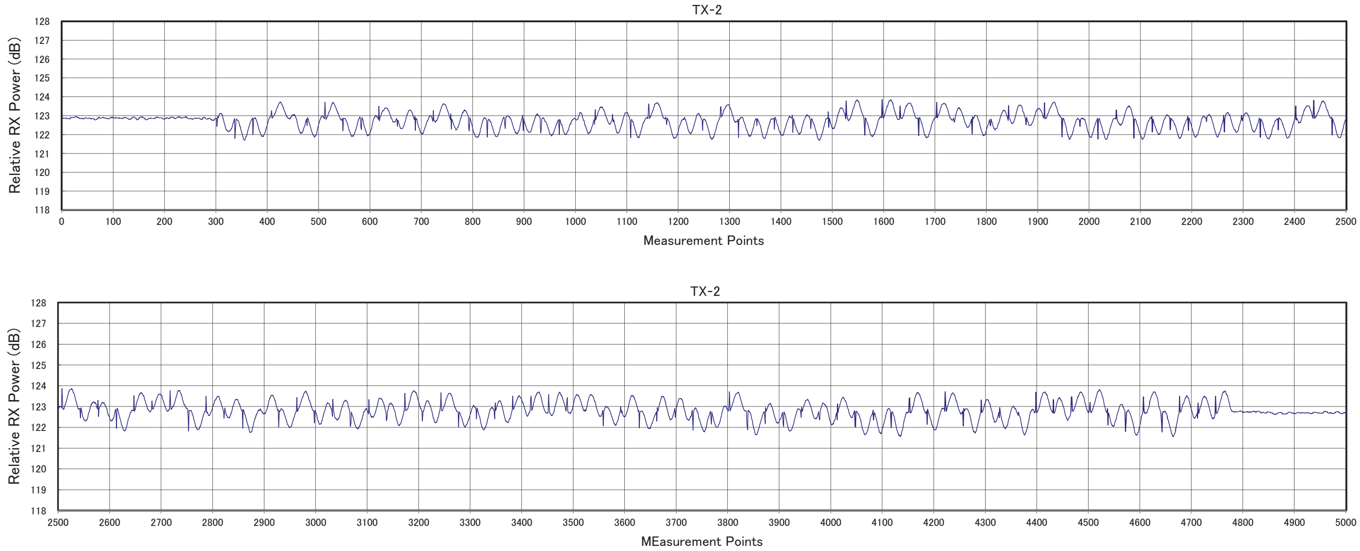

Fig. 11 REV data (TX-2)

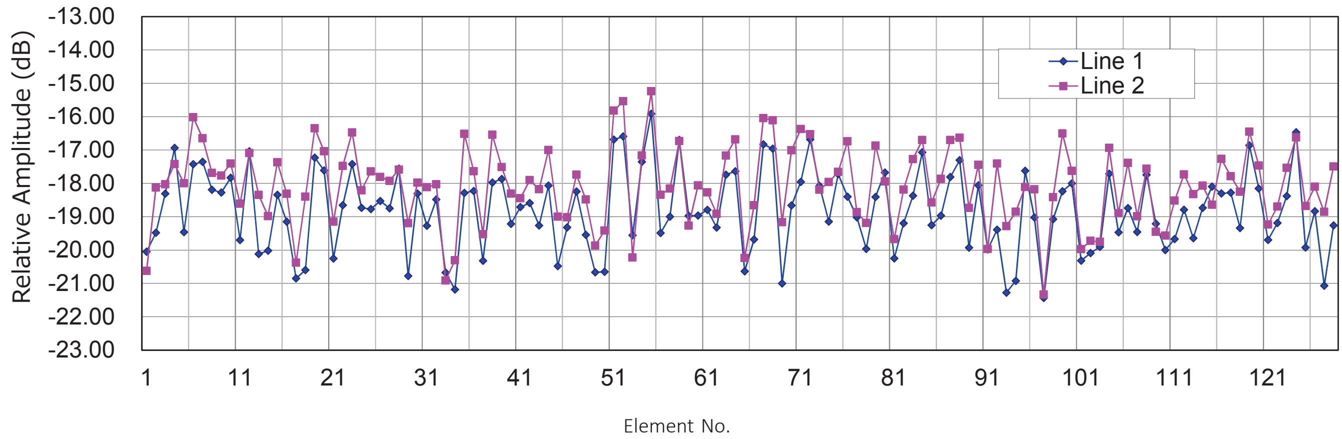

Fig. 12 Antenna RX-1 relative amplitude

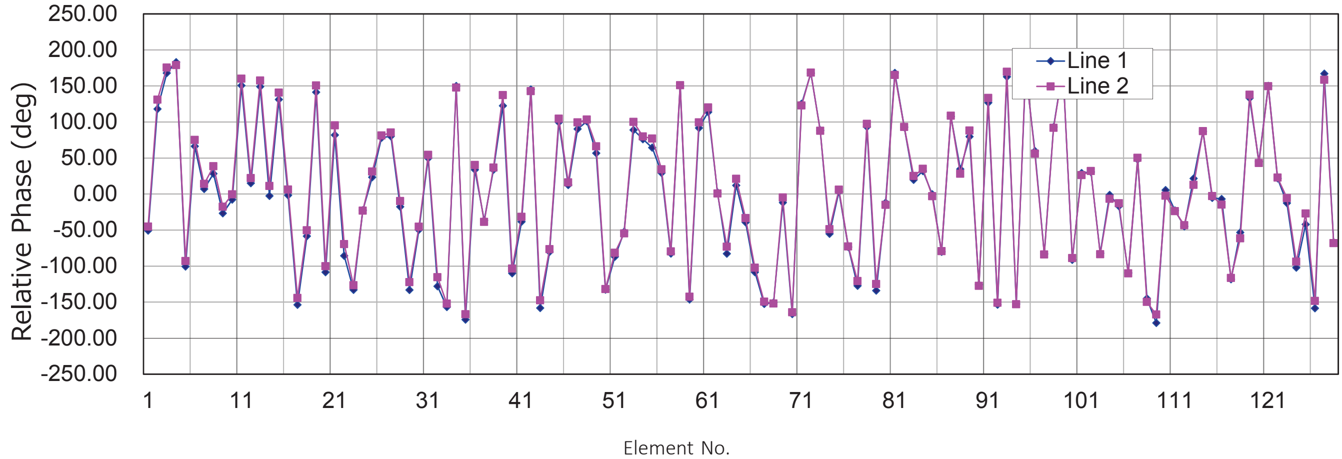

Fig. 13 Antenna RX-1 relative phase

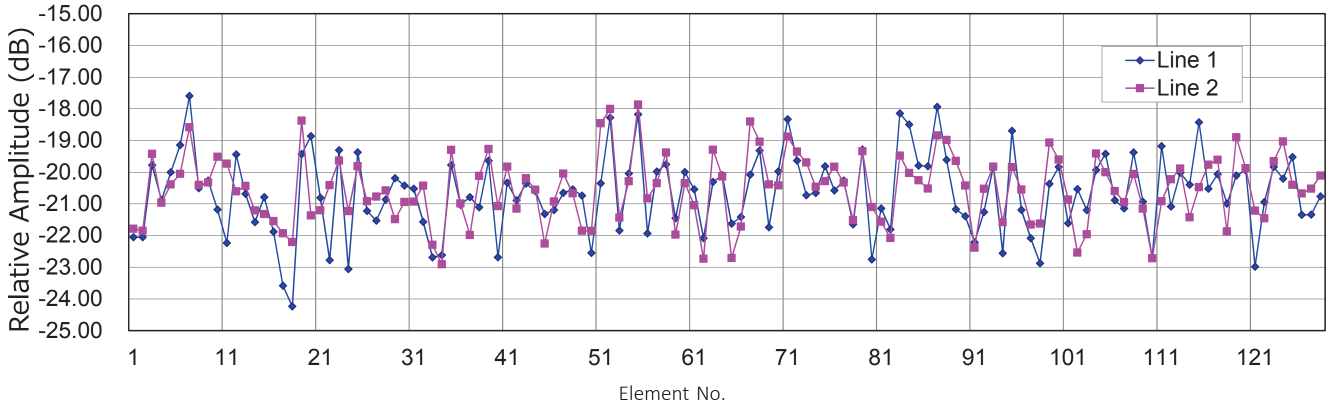

Fig. 14 Antenna RX-2 relative amplitude

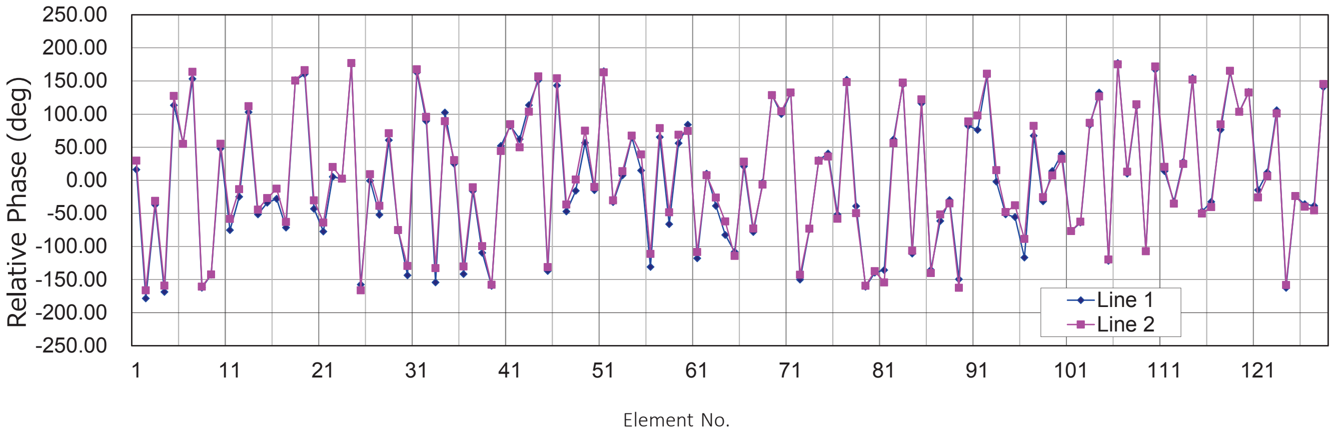

Fig. 15 Antenna RX-2 relative phase

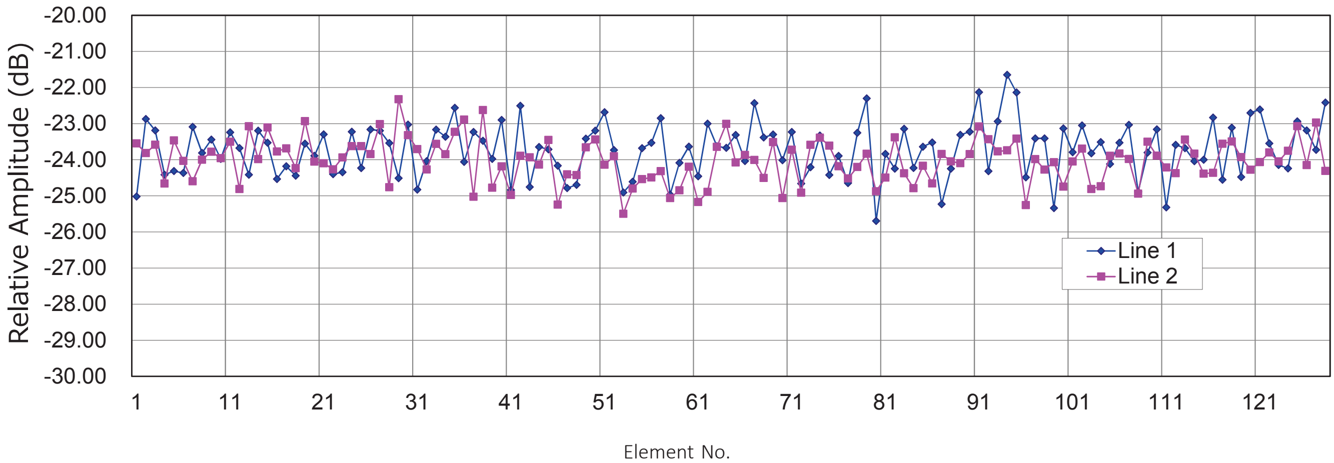

Fig. 16 Antenna TX-1 relative amplitude

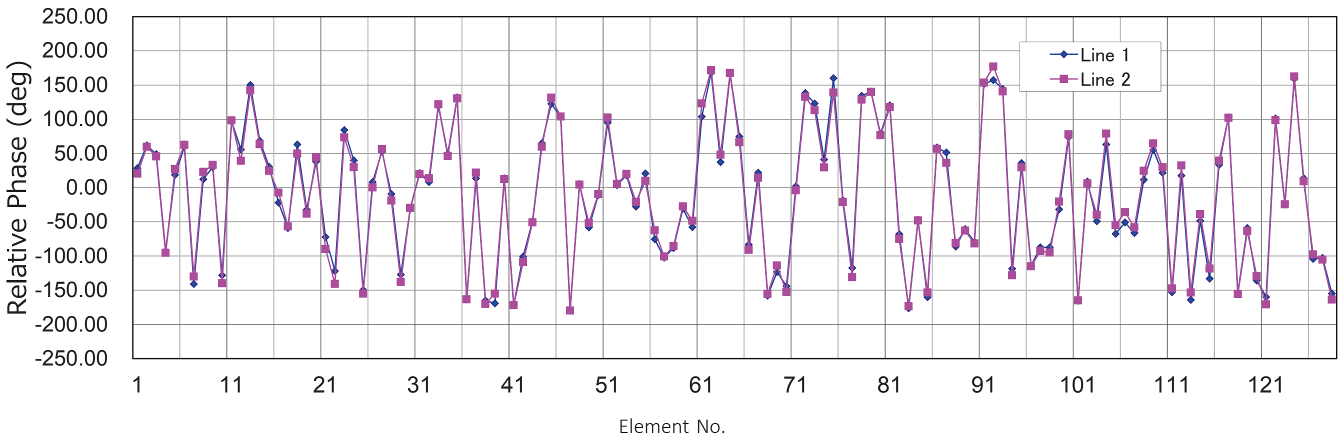

Fig. 17 Antenna TX-1 relative phase

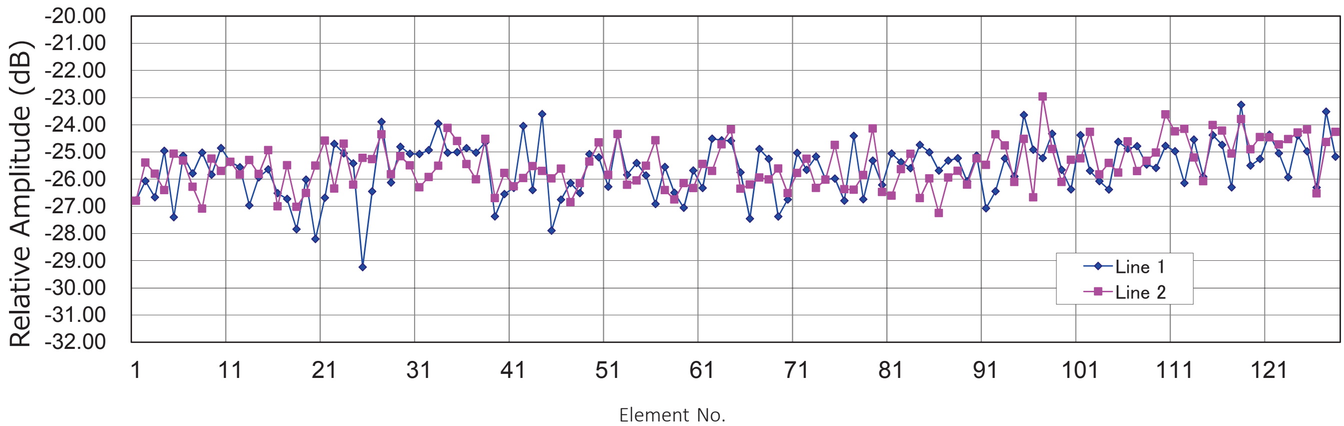

Fig. 18 Antenna TX-2 relative amplitude

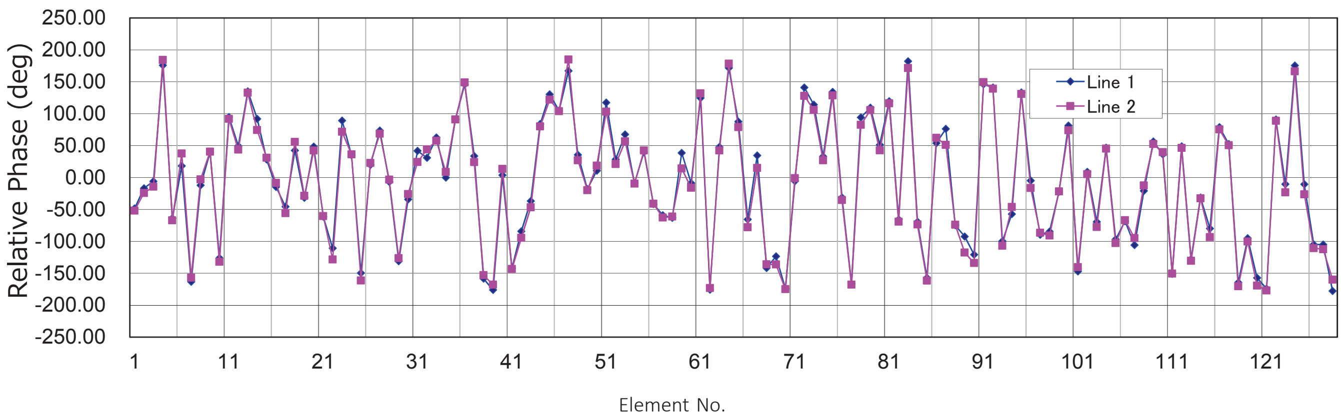

Fig. 19 Antenna TX-2 relative phase

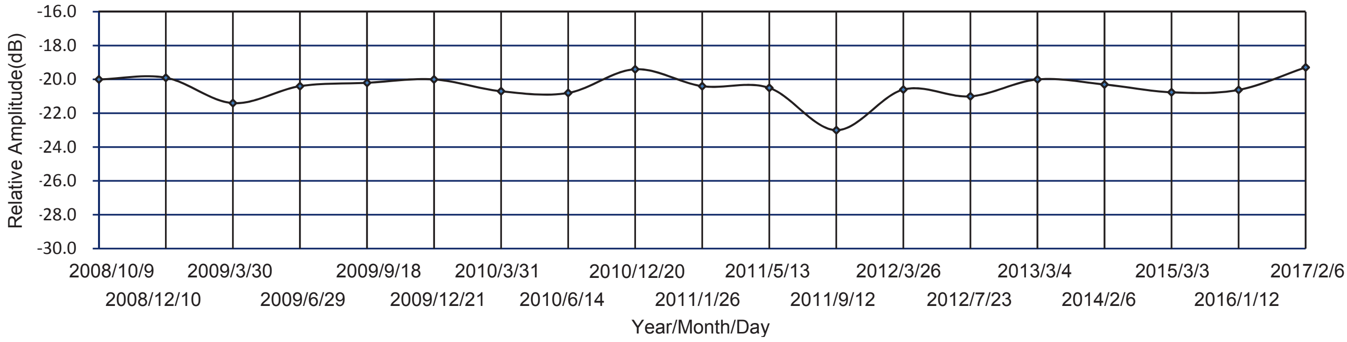

Fig. 20 Amplitude trend (RX-1, element no. 1)

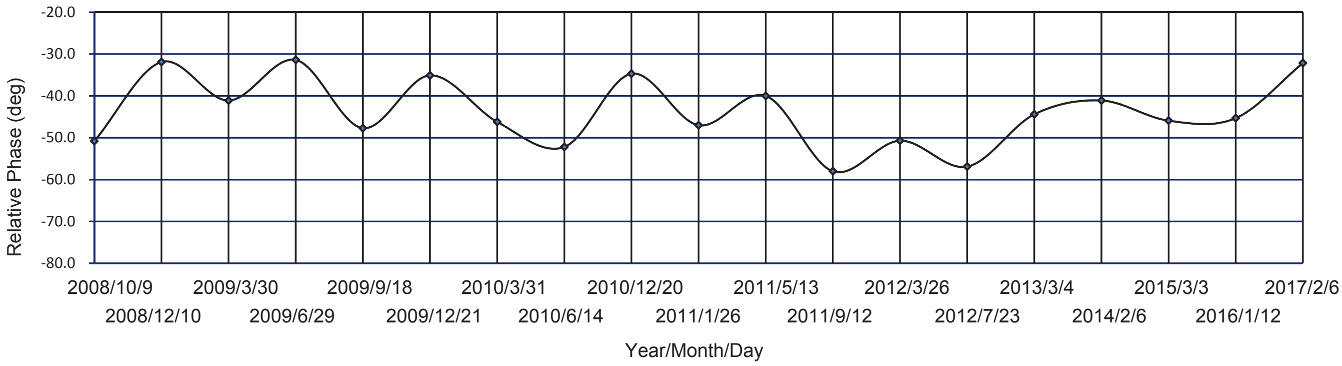

Fig. 21 Phase trend (RX-1, element no. 1)

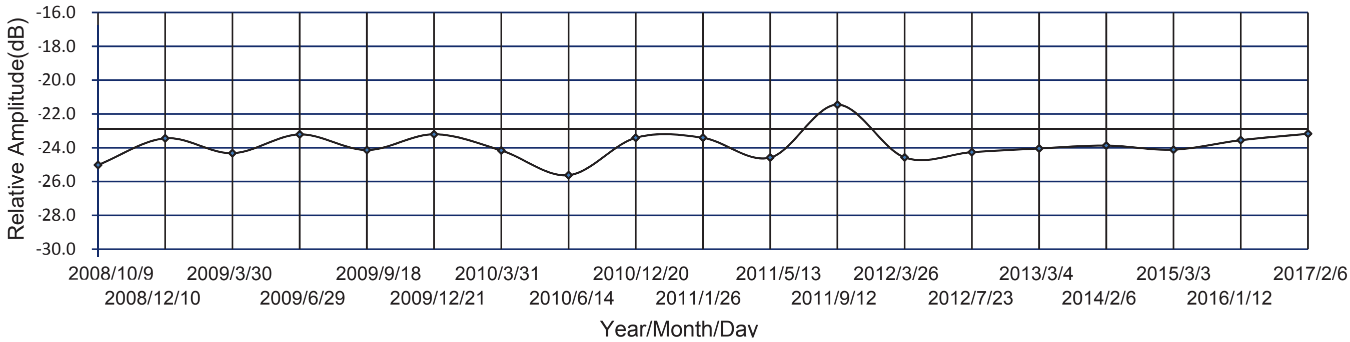

Fig. 22 Amplitude trend (TX-1, element no. 1)

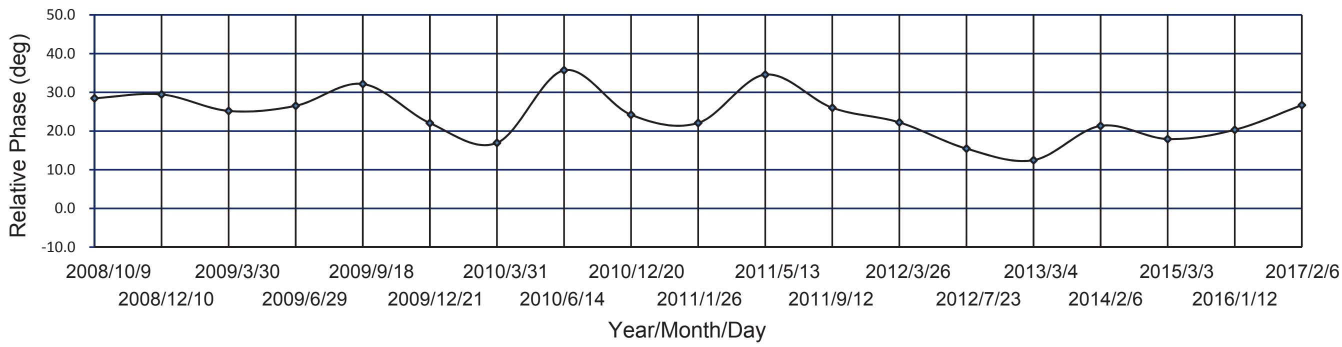

Fig. 23 Phase trend (TX-1, element no. 1)

5.2 Evaluation of amplitude and phase

The relative amplitude and relative phase of each radiating element of the antenna calculated from the REV waveform are shown in Figs.12 to 19. Each figure shows the result of antenna RX-1, RX-2, TX-1 and TX-2, respectively. The datasets collected on October 9, 2008, and February 6, 2017, are plotted as group 1 and group 2, respectively. As the results of both group 1 and group 2 almost coincide, each antenna element of the WINDS APAA works normally even after eight and a half years of operation.

The REV of the WINDS APAA was performed 19 times from October 9, 2008, to February 6, 2017. The results of evaluation of the relative amplitude and relative phase of representative element no. 1 of antenna RX-1 and element no. 1 of antenna TX-1 are shown in Figs. 20 to 23. From the results of time dependency, the variation of the amplitude of element no. 1 of antenna RX-1 was 3.7 $dB_{p\text{-}p}$, and that of phase of the same element was $25.9°_{p\text{-}p}$. Also, the variation of the amplitude of element no. 1 of antenna TX-1 was 4.1 $dB_{p\text{-}p}$, and that of phase of the same element was $23.2°_{p\text{-}p}$. From the results, we judged that although both the amount of variation of amplitude and phase shift are slightly large, this trend has not progressed. As for other elements, the same results were obtained.

6 Phase compensation experiment

One of the purposes of the REV method is to maximize the APAA gain by correcting the initial settings of phase. The experiment for this purpose was performed on July 23, 2012 (for RX-1), and on September 6, 2012 (for TX-2), between JAXA Tsukuba Space Center and NICT Kashima Space Technology Center. The evaluation method of the experiment is to establish the phase of the phase shifter for beam settings using direction cosines of the beam directed to Kashima (normal method to determine beam direction). The receiving level for the case of adding the compensation phase to the initial phase of the REV was compared with the level obtained by the normal method. The receiving signal level of a continuous wave for one minute was measured every 40 ms while fixing the phase. The averaged data was plotted to construct a graph.

The results of the received signal with RX-1 at Kashima terminal are shown in Figs. 24 and 25. The former shows the case where the beam was set using direction cosines and the latter shows the case where the beam was set using phase compensation of the REV. As a result, the signal level of the former is higher than the latter by 0.13 dB. This

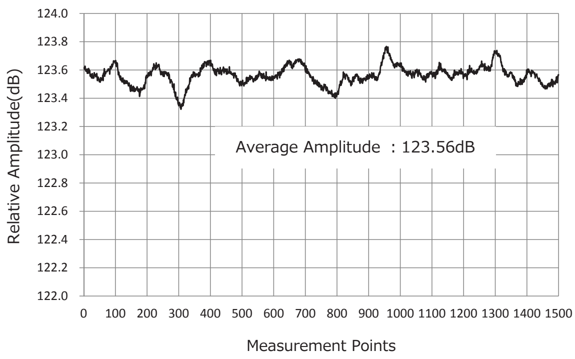

Fig. 24 Relative amplitude of the beam adjusted using direction cosines (RX-1)

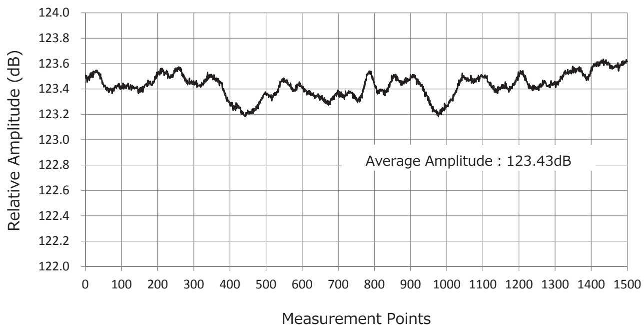

Fig. 25 Relative amplitude of the beam adjusted using phase compensation (RX-1)

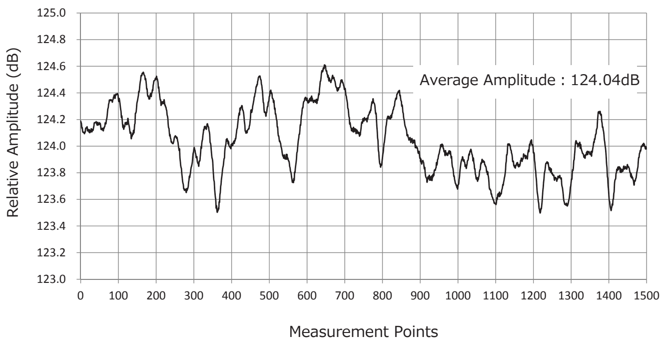

Fig. 26 Relative amplitude of the beam adjusted using direction cosines (TX-2)

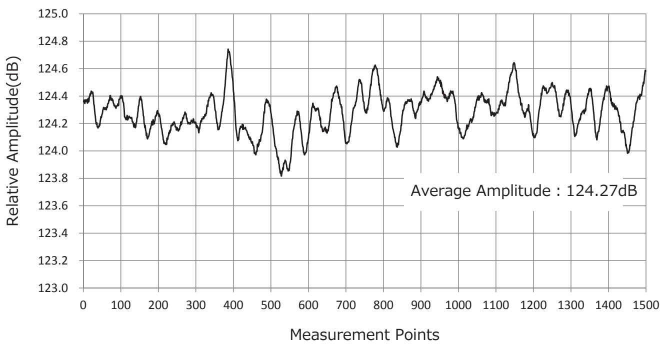

Fig. 27 Relative amplitude of the beam adjusted using phase compensation (TX-2)

can be explained as that the RX beam of the APAA is corrected so as to maximize the gain in the Tsukuba direction, and therefore the gain in the Kashima direction decreases. Hence, in order to correct the phase of the receiving antenna of the APAA, it is necessary to transmit a test signal from Kashima.

On the other hand, Figs. 26 and 27 show the results of receiving signals at Kashima terminal. The former shows the case where the beam was set using direction cosines and the latter shows the case where the beam was set using the compensation of the REV. As a result, the signal level received at Kashima is higher than the case when the beam was set using direction cosines by 0.23 dB, which implies improvement of gain. This can be explained that the gain in the Kashima direction improves by correction because the receiving earth terminal for the TX beam is in Kashima.

7 Conclusion

The application of the REV method to the WINDS APAA soundness verification has peculiar problems regarding the on-board REV: the rotation timing of phase of elements at the REV of the satellite and the measurement timing of the earth terminal are not synchronous and the variation of the received signal level is large due to atmospheric fluctuation. The former was solved by measuring twice during the same measurement period of phase setting, and the latter was solved by averaging 1,024 data points obtained from measurement and a smoothing process using the least-squares method.

As a result of trend evaluation based on 19 measurements performed from October 9, 2008, to February 6, 2017, the amplitude and phase of all the elements were almost the same as those obtained at initial phase after launch. These results confirmed the soundness of the WINDS APAA. Also, a slight effect of improvement in gain was observed from the APAA phase compensation experiments.

References

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2 M. Yajima, T. Horiuchi, M. Nakano, A. Akaishi, M. Ohkawa, and T. Takahashi "Health Check Experiment of Active Phased Array Antennas on KIZUNA(WINDS) by Two Stations Simultaneous Measurement," IEICE Technical Report, vol.111, no.7, SANE2011-7, 2011.

Akira AKAISHI

Space Communications Laboratory, Wireless Networks Research Center
Satellite communications system

Mitsugu OHKAWA, Ph.D.

Senior Researcher, Space Communications Laboratory, Wireless Networks Research Center
Satellite communications system

Takashi TAKAHASHI

Associate Director, Space Communications Laboratory, Wireless Networks Research Center
Satellite communication