In-Flight Validation of Akatsuki X-Band Deep Space Telecommunication Technologies

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Akatsuki is the Japanese first Venus exploration program. The spacecraft was successfully launched in May 21st 2010 from Tanegashima Space Center via H II-A vehicle. One of her missions is a flight demonstration of her telecommunication system developed for supporting Japanese future deep space missions. During her half-year cruising phase heading for Venus, we had conducted checkouts of the system. The key technologies are a deep space transponder, a set of onboard antennas, and power amplifiers. They all were newly introduced into Akatsuki. Their performances had been tested through the half-year operations and been investigated by using collective data obtained in the experiments. Our regenerative ranging was also demonstrated in these activities. We proved that the newly introduced telecommunication system worked exactly as we had designed and that the system performances were the same as evaluated on the ground. In this paper, we will summarize these in-flight validations for the Akatsuki telecommunication system.

Key Words: Akatsuki, PLANET-C, Deep Space Telecommunications, Regenerative Ranging

1. Introduction

Akatsuki is the Venus exploration program of Japan Aerospace Exploration Agency (JAXA) ¹⁾. It is the second JAXA challenge sending a planetary orbiter except for the earth. Another aspect of the mission is to establish JAXA deep space technologies for the coming decade. It was why new technologies demanded for coming JAXA deep space missions were actively incorporated into the Akatsuki system. One of them was a telecommunication system.

Figure 1 is the Akatsuki spacecraft viewed externally. The spacecraft coordinate system is indicated in it, too. We sometimes use expressions in this paper referring to this coordinate system. The spacecraft body has a dimension of 1.45 m in width, 1.4 m in depth, and 1.04 m in height and has wings of solar panel of 1.2 m² on the both sides. The wet mass is 500 kg.

Akatsuki was launched by H-II-A vehicle from Tanegashima Space Center in May 21st 2010. She was directly placed onto an orbit heading for Venus. The launch process was successful according to tracking data acquired soon after the launch. It took half a year until her Venus encounter. During these six months, we had done the checkout of the onboard instruments and carried out tests in preparation for scientific activities in the Venus orbit. The validations of the newly introduced telecommunication system had been conducted as one of these checkout activities.

The Akatsuki telecommunication system is as follows. The new onboard instruments to be flight qualified are digital transponders (TRPs), a set of high-gain antenna (HGA), low-gain antennas (LGAs), and a traveling wave tube amplifier (TWTA) ²⁾. Figure 2 is the telecommunication system

block diagram of Akatsuki. The redundancy is given to TRPs and 10 W solid-state power amplifiers (SSPAs). The TWTA is provided for the increase of scientific data acquisition. Its

Fig. 1. External view of Akatsuki spacecraft with her coordinate system. Schematic antenna beam patterns are indicated for the help of finding respective antenna locations. HGAs are slot array antennas. MGAs are horn antennas. LGAs are horn antennas capped with a lens.

Fig. 2. Block diagram of Akatsuki telecommunication system. HGA: high gain antenna, MGA: medium gain antenna, LGA: low gain antenna, SW: switch, DIP: diplexer, SSPA: solid state power amplifier, TWTA: travelling wave tube amplifier, EPC: electric power conditioner, PCU: power control unit, HYB: hybrid coupler, TRP: transponder. The suffix such as A or B expresses redundancy of items.

output power is twice as high as the SSPA. The available output power is strictly limited by the thermal conditions imposed to the spacecraft in the Venus orbit. The TWTA and SSPAs are connected with antennas via switches. The switch matrix is to keep redundant routes among them. The antennas are a set of HGA composed of HGA-T (for transmission) and HGA-R (for reception), medium gain antennas (MGAs), and LGAs. The safety measures to keep uplink and downlink of the spacecraft are the MGAs and the LGAs. In general, the LGAs are selected in the spacecraft safe mode (spin mode along the Sun pointing +X-axis). The LGAs are also applied to any situations when the secured links are necessary. Each LGA covers each hemisphere independently so as to form the whole spherical view angle. No link interruptions due to body spin occur because the LGAs are installed so that their pattern symmetric axis matches with the spin axis or X-axis in Fig.1. The spacecraft can receive commands in any attitudes thanks to this configuration. After a recovery from the safe mode, the spacecraft re-establishes downlink with an appropriate MGA in the three-axis stabilized mode.

The telecommunication system indicated in Fig.2 is a basic model to initiate designing the telecommunication system for JAXA future deep space missions. It is applicable to any JAXA missions. Akatsuki paved its way and catalogued onboard components necessitated for its realization. Designing on the common model will allow future missions to save their development cost and enable to invest intensively in their most critical component. Our future missions such as Bepi Colombo MMO (Mercury exploration program) and HAYABUSA-2 (Next Asteroid Sample Return Mission) actually make the best use of this concept established by the Akatsuki program.

2. Ground Supports for Akatsuki Operations

Akatsuki has an X-band channel for her uplink and downlink. The uplink and downlink frequency are 7.1 GHz and 8.4 GHz respectively and their ratio is 749 to 880. The mission

uses Usuda Deep Space Center 64 m station (UDSC64) for its tracking, telemetry, and command operations. Uchinoura Space Center 34 m station (USC34) also supports its critical events. USC34 is usually reserved as a backup station. Additionally, Deep Space Network (DSN) of National Aeronautics and Space Administration (NASA) plays an important role in the launch and Venus orbit insertion (VOI) event. It enhances the coverage of Akatsuki operations and offers more secured operation services than we do only with UDSC64 and USC34.

Contrary to the original station assignment plan for the mission, USC34 had mainly worked for its first consecutive three months after the launch due to the unexpected occupation of UDSC64 by the other mission. We did the most of checkout activities of Akatsuki from USC34. It was from the beginning of September that UDSC64 started playing a major role in the Akatsuki operation. Since then, the VOI preparation toward the beginning of December had started with an intensive effort.

Most results stated in this paper were obtained during the operation at USC34. Thus, the calibration of parameters related with link budgets was primarily applied to USC34. Then, it was examined and compared with that obtained at UDSC64 in the later operations. There were little differences in the estimation errors between the two stations. Therefore, we do not specify the differences of stations any more in the succeeding chapters.

3. The First Signal Acquisition of Akatsuki

The first pass over the domestic stations of Akatsuki after the launch began at May 21st 7:40:00 (UTC), just at the predicted time. Her first signal had already been received at DSN Goldstone stations (DSS-14 and DSS-24) before it. Her remote operations via DSN proved that the onboard Akatsuki system including the telecommunication system worked well. The tracking result at DSN matched with predicted one. No errors in azimuth and elevation data were found during the DSN pass. No time offset from the prediction was requested

Fig. 3. Received uplink and downlink carrier levels of the Akatsuki first pass over USC34. Predicted levels in +X-axis Sun pointing attitude are also indicated.

for the following domestic pass operation. Fig.3 is the summary of the first USC34 Akatsuki tracking.

The LGAs were selected for the first pass. Thus, the uplink signal was relayed via LGA-A and TRP-A, and sent back to UDSC64 and USC34 via SSPA-A and LGA-A so as to close a coherent loop for a Doppler measurement. LGA-B was used only for the uplink reception. The vertical axis of Fig.3 is the downlink carrier level received at USC34 and the uplink automatic gain control (AGC) level of TRP-A. The downlink was phase modulated by 65.536 kbps telemetry signal with the use of 262.144 kHz subcarrier. The modulation index was 1.3 rad. When the spacecraft rose above a horizon mask of USC34, we started sending 15.625 bps command signal phase modulated onto the uplink with the use of 16 kHz subcarrier. Then, we changed to 1kbps via the command. The modulation index was 1.2 rad.

The predictions in Fig.3 are applied only to a spacecraft attitude with +X-axis oriented toward the Sun. It is in good accordance with the measured results including behaviors at a lower elevation. The spacecraft was spinning along the X-axis when the signal was acquired, and then, three-axis stabilized around at 10:00. It was why the measured signal levels till 10:00 are fluctuated and then smoothed after that. The SSPA-A mode change to a higher output power was done at 9:00. The output power was changed from 1 W to 10 W. The level shift of 10 dB was observed as expected. From 14:30 to 16:27, we carried out a ranging operation for an orbit determination. The telemetry acquisition was interrupted during this period. Thus, the measurement of the uplink level stopped at this moment. The differences between measured and estimated results of the uplink AGC level are slightly observed in Fig.3. It is due to an imperfection of the temperature com-

pensation for the onboard AGC output. The temperature dependency of the onboard analog AGC output is inevitable. Hence, they were corrected using a monitored onboard temperature history. But Fig.3 indicates that it is not sufficient. This is not the case for the downlink level measurement. Therefore, the level estimation for the downlink is good in the entire pass except for the transitional moments in which commanding from USC34 changes the spacecraft downlink conditions.

During the period of imaging the earth, LGA-B and XTRP-B was used for the downlink transmission. The use of SSPA-A was remained unchanged. Due to both changes of spacecraft attitude and signal route during the imaging, the level shifts during this period for the uplink and downlink are not necessarily the same. It is notable that the reasonable level estimation in this period was also possible though it is not indicated in Fig.3.

4. Checkout Activities of Akatsuki Telecommunication System

Table 1. Checkout results of Akatsuki telecommunication components of Fig.2.

Component	Suffix	Status	Checkout Date
TRP	A	Done	2010/5/21 for CMD, TLM, RNG
	B	Done	2010/5/21 for CMD 2010/5/22 for TLM, RNG
HGA	T, R	Done	2010/5/28 for peak gain
MGA	A	Done	2010/5/22 for gain & gimbals
	B	Done	2010/5/28 for gain & gimbals
LGA	A	Done	2010/5/21 for gain
	B	Done	2010/5/21 for gain
TWTA		Done	2010/12/17 for output power & power consumption
SSPA	A	Done	2010/5/21 for output power & mode change (1W, 10W)
	B	Not yet	
SW1		Done	2010/5/28 for response
SW2		Done	2010/5/28 for response
SW3	A	Done	2010/5/28 for response
	B	Done	2010/5/22 for response
	C	Done	2010/5/28 for response
SW4		Not yet	

We found that the X-band link via LGAs and SSPAs were normal soon after the launch as indicated in Fig.3. The more

intensive checkout work of the Akatsuki telecommunication system followed after that. It took for a month for the quick check of functions. The experiments of the regenerative ranging and so on that need more careful investigations were assigned for later days.

Table 1 is the quick check summary of the telecommunication components in Fig.2. The column named as suffix in Table 1 expresses redundancy of the components. Except for the TWTA to be activated after VOI, the SSPA-B reserved as a backup and its associated switch, SW-4 (See Fig.2.), the functional check was completed within eight days after the launch. Their performances were proved to be normal. In later days after VOI, TWTA was also found normal.

In addition to Table 1, the following tests were done taking as many chances as possible before VOI. We will discuss the regenerative ranging experiment in the later chapter.

- Regenerative ranging experiment.
- Evaluation of onboard ranging delay.
- Calibration of orbit determination.
- Calibration of link budget estimation.

On the whole, the flight performance of the Akatsuki telecommunication system was good. It was what it had been before the launch. The behaviors of the system have also been stable for a year since the launch. The current performances are sufficient to support the Akatsuki mission.

5. Gain Estimation of Akatsuki HGA

Akatsuki employed the new HGA for her mission²⁾. It is a slot array antenna made on a flat quartz honeycomb substrate. It was selected mainly for avoiding a focal point in the system that might cause an unacceptable serious heating problem during the flight. Its simple structure also contributed to a mass reduction. The HGA is composed of HGA-T and HGA-R (See Fig.2).

The HGA radiation profiles were measured before its integration. The peak gain of HGA-T was 35.6 dBi and that of HGA-R was 22.3 dBi²⁾. Their diameters were 0.9 m and 0.3 m respectively. Both were measured for right hand circular polarization (RHCP). We conducted the gain estimation of the in-flight HGA for the comparison.

The spacecraft attitude was stabilized so that a HGA gain peak is oriented toward the earth. This pointing direction should ideally agree with the +Z-axis of the spacecraft. In this measurement, we re-defined this pointing direction in the experiment as +Z-axis of the spacecraft. Then, we rotated the spacecraft by square root two degrees in four directions indicated in Fig.4. Figure 4 is the downlink AGC history that we obtained at USC34 during the experiment. Both the received level and its translation to HGA-T gain are indicated. The gains at 5 points near the peak of the main lobe were obtained. They were fitted by the cosine-approximated pattern of the HGA main lobe. The fitting result gave us a peak gain, tilted angles of the peak against +Z-axis, a beam width and so on. Table 2 is the summary of the HGA gain estimation. As mentioned, we used USC34 for this experiment. Naturally, the link budget estimation had to be well established before applying

Fig. 4. USC34 AGC history of Akatsuki HGA downlink. The HGA was oriented toward the earth with and without an indicated offset for the gain estimation.

Table 2. Comparison between estimated in-flight HGA parameters and ground test results.

	HGA-T (8.4 GHz)	HGA-R (7.1 GHz)
Peak Gain (Flight Estimation)	35.7 dBi	23.6 dBi
Peak Gain (Ground Test)	35.6 dBi	22.3 dBi
3dB Beam Width (Flight Estimation)	2.5 deg	6.8 deg
3dB Beam Width (Ground Test)	2.4 deg	8.8 deg
Tilted Beam Angle (From +Z-Axis)	0.27 deg	0.14 deg
Tilted Beam Angle (From +X-Axis, Counter-clockwise in X-Y Plain)	82.15 deg	90 deg

this method to the gain estimation. We can read the estimation errors in this experiment as less than 0.5 dB for downlink and 2 dB at most for uplink from Fig.3. The estimation using the uplink is worse than that of the downlink due to uncertainty of the AGC temperature calibration.

The HGA-T parameters were estimated using the downlink. The estimated gain of HGA-T in Table 2 was in good accordance with the ground result. The difference was only 0.1 dB. The angle offset of the beam direction was only 0.27 degrees. It was around one tenth of the estimated beam width of 2.5 degrees. Thus, the pointing error of HGA-T was negligible. Considering this very small offset of the beam axis from +Z-axis, we concluded that the mechanical pointing alignment of HGA-T before the launch and the attitude control for pointing the HGA were very accurate.

Table 3. Conditions for tests comparing conventional bent-pipe and regenerative ranging. 10 out of the 20 cases are indicated. The test was programmed so that the uplink conditions are varied with the downlink ones unchanged. By varying only the uplink conditions, we can focus only on the onboard regenerative function.

Date	Spacecraft Attitude	Uplink Received RNG S/No Prediction [dBHz]	Conventional Ranging		Regenerative Ranging			Integration Time (Regenerative/ Conventional)	Ground Station	TRP Used for Experiment
			Received Carrier Level Prediction [dBm]	Received RNG S/No Prediction [dBHz]	Received Carrier Level Prediction [dBm]	Received RNG S/No Prediction [dBHz]	Measured Received Carrier Level [dBm]			
2010/7/8	+X-Axis Sun Pointing	67.2	-146.7	39.0	-141.7	67.2	-141.8	10s/10s	USC34	TRP-B
2010/7/20	+Z-Axis Earth Pointing	45.4	-146.7	21.4	-143.5	45.4	-143.5	10s/10s	USC34	TRP-B
2010/7/22	VOI Attitude	65.1	-148.4	36.5	-143.8	65.1	-143.9	10s/10s	USC34	TRP-B
2010/7/29	+Z-Axis Sun Pointing	48.1	-147.7	27.5	-144.5	48.1	-144.5	10s/10s	USC34	TRP-B
2010/8/20	+Z-Axis Earth Pointing	33.9	-149.3	7.5	-146.1	33.9	-146.5	10s/40s	USC34	TRP-B
2010/8/24	+Z-Axis Earth Pointing	39.2	-149.4	11.7	-146.2	39.2	-146.8	10s/10s	USC34	TRP-B
2010/8/26	+Z-Axis Earth Pointing	23.9	-149.5	-3.8	-146.3	23.9	-147.0	10s/80s	USC34	TRP-A
2010/8/27	+Z-Axis Earth Pointing	20.5	-149.5	-6.2	-146.3	20.5	-146.2	10s/250s	USC34	TRP-A
2010/8/31	+Z-Axis Earth Pointing	30.5	-144.1	10.6	-140.9	30.5	-140.8	10s/20s	UDSC64	TRP-A
2010/9/1	+Z-Axis Earth Pointing	26.0	-144.1	6.1	-140.9	26.0	-140.0	10s/NA	UDSC64	TRP-A

The HGA-R parameter estimation was based on the uplink. Thus, its estimation should not be as good as HGA-T. The estimated gain was different from that of the ground test by 1.3 dB. We think it reasonable taking the larger uplink estimation error of 2 dB into account. The HGA-T and HGA-R are located on the same +Z-panel of the spacecraft. The tilted beam angle from +Z-axis should be on the same order of the HGA-T. The estimation was actually a small value similar to the HGA-T and was again negligible compared with its beam width. No difference was found between HGA-T and HGA-R on this point.

6. Performance of Regenerative Ranging

The TRP developed for Akatsuki has a regenerative ranging function ^{2,3)}. The comparison between our conventional bent-pipe ranging and the regenerative ranging was done. The regenerative function is enabled or disabled by commanding. It means that we can obtain the conventional ranging result when it is disabled and the regenerative ranging result when it is enabled. The ranging system at our ground station is common for both ranging methods.

The ranging data for the comparison was obtained in the following manner. We set the parameters such as a modulation index, a transmission power, and an onboard antenna selection so that we can obtain an appropriate uplink and downlink conditions for the experiment. Then, we obtain the conventional ranging data for hours enough for a later analysis. We continue the experiment by enabling the regenerative ranging and obtain the corresponding data. Both data were always obtained successively in the same spacecraft view so that climate and ground station conditions are common for the both. As a result, we can obtain a set of data for the comparison by changing the link conditions experimentally. In our experiment, the comparison was done by changing only uplink received ranging signal power to noise ratio while the downlink ones are kept at a sufficiently good condition. Table 3 is the extract of our experimental conditions.

We needed many Akatsuki views for the completion of the experiment because one view could accommodate one uplink condition at most. Therefore, the spacecraft attitude, ground station, available TRP and so on were variable during the

experiment. Table 3 contains the history of such experimental conditions. The spacecraft attitude could be +Z-axis earth pointing, +Z-axis Sun pointing, +X-axis Sun pointing and so on. The VOI attitude means that the spacecraft was in the maneuver attitude for the VOI rehearsal at that time. Both USC34 and UDSC64 took part in this experiment though most was done at USC34. Both stations have the same ranging system. In spite of these variable conditions, the link condition was precisely designed so that the error should be within 1 dB without regards to the given conditions. Comparing the received carrier levels of the regenerative ranging between the prediction and the measurement in Table 3, they are within 1 dB. This condition was always satisfied through the experiments.

As discussed and indicated in Table 3, the same uplink received ranging signal quality applies to the both conventional ranging and regenerative ranging. Therefore, we can see the difference of the two ranging quality relayed onboard at the ground station with the uplink quality as a parameter. When we see the case of 2010/08/26 and 2010/08/27 in Table 3, the received ranging signal to noise density ratios at USC34 of the conventional ranging were to be below 0 dBHz. On the other hand, those of the regenerative ranging were to be much higher. In these cases, the conventional ranging no more functions when the integration time is fixed at 10 sec. The integration time that was actually needed for the operation is also indicated in Table 3. For these cases, the conventional ranging needed an integration time of 80 sec and 250 sec respectively. However, the regenerative ranging needed only 10 sec in each condition. This fact quickly shows the effectiveness of the regenerative ranging.

Figure 5 is the ranging deviations dependent on the uplink signal quality acquired through the experiments. The precise orbit determination is necessary to obtain this result. We did another ranging for this purpose independently from the experiments. The ranging method was conventional ranging. The remainder after a subtraction of an orbit variation from raw ranging data is consisted of a ranging bias and random errors. The bias for the conventional ranging was close to zero because the orbit determination was done based on data obtained by the conventional ranging method. However, the bias for the regenerative ranging exists and comes from a differ-

Fig. 5. Difference of ranging stability between conventional bent-pipe and regenerative ranging. The deviations of which integration time is 10 sec are plotted for the two ranging. All the data for the regenerative ranging were obtained keeping integration time constant at 10 sec. But, those below 40 dBHz for the conventional ranging were obtained by increasing the integration time and were translated to ones at 10 sec.

ence of onboard ranging signal delays. This difference of the bias is considered to be constant during the view and could almost be cancelled based on the delay measurement before the launch. Hence, we can finally obtain only the variation or the deviation due to noise to characterize the performance of the conventional ranging and the regenerative ranging.

In Fig.5, it is notable that no more data with 10 sec integration time were obtainable for the conventional ranging below 40 dBHz. The results for the conventional ranging below 40 dBHz were obtained by increasing the integration time as we mentioned on integration time in Table 3 in the previous paragraph. For the convenience of comparison, the deviation of these data was translated to that for the integration time of 10 sec in Fig.5. However, the regenerative ranging always worked with the fixed integration time of 10 sec. In spite of this, the ranging deviation is much better than the conventional ranging in Fig.5. Though the deviation of the regenerative ranging also increases when the uplink signal quality becomes worse, it is more reduced than the conventional ranging. This gradual degradation of the regenerative ranging comes from the uplink jitter. For example, the deviation of regenerative ranging at 20 dBHz is one ninth of the conventional ranging. This case corresponds to that of 2011/08/27 of Table 3. In this condition, it actually takes an operation time of around 13 minutes to get one ranging result for the conventional ranging, but only around 70 sec for the regenerative ranging. The advantage of the regenerative ranging is available in either way of improving stability and saving an operation time.

7. Conclusion

The in-flight performances of Akatsuki onboard telecommunication system were reported. It was developed as a model of a telecommunication system for future JAXA deep space programs. It has actually been applied to the JAXA next deep space missions such as Bepi Colombo MMO and HAYABUSA-2. The flight validation of the system through the Akatsuki mission is an important and inevitable step for these missions, too. The TRP, HGA, and other newly introduced components onboard Akatsuki worked normally and deserved flight-qualification. The regenerative ranging employed in the new TRP demonstrated the better performance than the conventional one as predicted theoretically. All these flight-proven results obtained by Akatsuki are surely useful for the successive missions using the same telecommunication system and even for cultivating a new deep space missions.

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