Analytical Results of BSE Beam Pointing and Attitude Control Performance

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Variations in the received signal strength at the ground stations due to beam pointing error of the broadcasting satellite for experimental purposes (BSE) are studied. The analyses about status and causes of seasonal and nonseasonal variations are made. In addition, all the variations which appear at the moment of routine operations, such as wheel unloading, orbit control, etc., are investigated; consequently, the attitude control performance of BSE has been confirmed.

Introduction

THE Japanese medium-scale broadcasting satellite for experimental purpose (BSE) was launched from the United States eastern test range in April 1978 and placed into the geostationary orbit at 110° E longitude.

After the initial check of satellite performance, various kinds of satellite broadcasting experiments started in July 1978 and ended in January 1982 because the BSE consumed all of the fuel for the attitude and orbit control. These experiments were conducted in order to obtain the technical data necessary for establishing future operational domestic satellite broadcasting systems.[3,4]

The BSE is the first broadcasting satellite in Japan and one of a few in the world having direct television broadcasting capability. A broadcasting satellite is normally required to have high beam pointing accuracy. To achieve this requirement, BSE utilizes a three-axis zero-momentum attitude control system (ACS) which is shown in Fig. 1.

The ACS of BSE has three attitude sensors. These are a static infrared Earth sensor (ES), a radio-frequency (rf) monopulse sensor (MP), and a sun sensor assembly (SSA). As a normal sensor combination, the ES is used for roll and pitch control and SSA or MP-ES (MP and ES combination) for yaw control. Other sensor combinations, such as MP or SSA, are also available for the roll or pitch control. Sensor outputs are processed by the attitude control electronics (ACE). The ACE drives each of the three reaction wheels independently and keeps the spacecraft attitude error within the requirement in normal operation. If necessary, one or more of 14 thrusters are fired by ACE drive signals to perform wheel unloading and orbit control maneuvers to keep BSE within 110°E±0.1 deg.

The rf beam pointing accuracy for BSE has been within 0.2 deg with some exceptions. However, the rf beam pointing accuracy for a future operational broadcasting satellite is required to be within 0.1 deg, as defined by the World Administrative Radio Conference for Broadcasting Satellite (WARC-BS) in 1977.

Downlink received signal strength from BSE has had various kinds of variations due to the rf beam pointing fluctuation and others. To satisfy the requirement of 0.1 deg beam pointing accuracy for future operational broadcasting satellites, the necessity is felt to investigate the causes of these received signal variations. Therefore, a working group was organized in March 1980 for the purpose of investigating the causes of the aforementioned variations.

All the causes and magnitude of variations due to rf beam pointing fluctuation and corrective actions for the satellite were investigated by this group using all the data relating to these signal variations, such as the telemetry data, operation history record, signal strength data at various ground stations, antenna direction data determined from received signal strength, ground test data of BSE, etc.

Variation Status of Received Signal Strength

In order to cover all of Japan, including its remote islands but avoiding spillover into adjacent countries, the BSE transmitting antenna has a shaped-beam gain footprint, shown roughly in Fig. 2. Consequently, at the ground stations the received signal strength variation that corresponds to the antenna gain footprint appears when the satellite has attitude errors.

Before the organization of the working group, BSE attitude control performance has been analyzed in three ways. The first is by attitude error determination using received signal data at the main transmit and receive station (MTRS), command history, and telemetry data. The second is by antenna direction determination system using received signal strength data received at various ground stations together with rainfall amounts and data of the ground stations' antenna direction. The third is by using test data on the ground, telemetry data of initial check on orbit, and housekeeping and command history data.

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Table 1 Summary of the received signal strength variation

Variation	Condition	Pointing error	Magnitude (max.) deg
Daily	1) From about 5:00-6:00 JST in winter[a] and around 18:00 JST in summer	Negative pitch Positive roll or pitch	≈0.2 ≈0.05
	2) From about 0:00-12:00 JST and around 21:00 JST (non-seasonal)	Negative pitch Positive pitch	≈0.15 ≈0.05
Related to the operation	1) Yaw control with SSA	Yaw	≈ ±2~6
	2) Yaw sensor mode change (SSA↔MP = ES)	Yaw	≈ ±0~0.5
	3) Sun interference on ES	Roll and pitch	≈ ±0.1
	4) Wheel zero crossing	Pitch	±0.2~0.4
	5) Thruster firing		
	Wheel unloading	Positive pitch	≈0.2
	E-W orbit control	Pitch	≈ ±0.2
	N-S orbit control	Roll or yaw	≈ ±0.3~0.6 ≈ ±3~6

[a]Winter season: between the autumnal equinox and the vernal equinox and summer season: between the vernal equinox and the autumnal equinox.

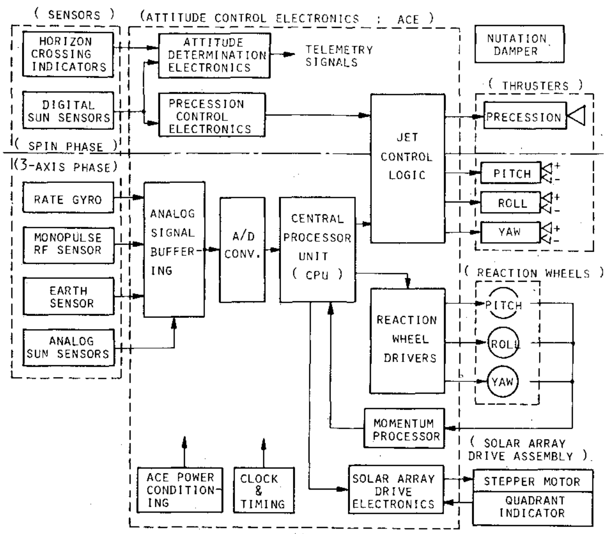

Fig. 1 Attitude control subsystem block diagram.

Each analysis has led to the conclusion that telemetry data show the successful attitude control performance but, also, the existence of undefined received signal strength variations. These variations do not correspond to the telemetry data but seem to be caused by rf beam pointing fluctuations.

In order to make the cause of these variations clear, including other variations which occur at the time of routine operations, the research results of each analysis were introduced and evaluated. The meeting's findings were as follows.

In short, received signal strength variations due to rf beam pointing fluctuation have roughly two kinds of variations. One is a variation which appears every day at certain times although telemetry does not show any change, and the other is a variation which corresponds to a change on the telemetry. The causes of the former type of variations are estimated to be the ES error and the antenna pointing error caused by rapid temperature change. Some attitude changes which cause the latter kind of variations are described in Refs. 1 and 2. They occur at the moment of roll acceleration command control (RACC), large sun declination bias (SDB) command error, yaw sensor change, thrusting for wheel unloading and East-West (E-W) and North-South (N-S) orbit control, ES mode change to prevent sun interference, and wheel zero crossing.

All the variations are summarized in Table 1 with the approximate beam center pointing error magnitude deter-

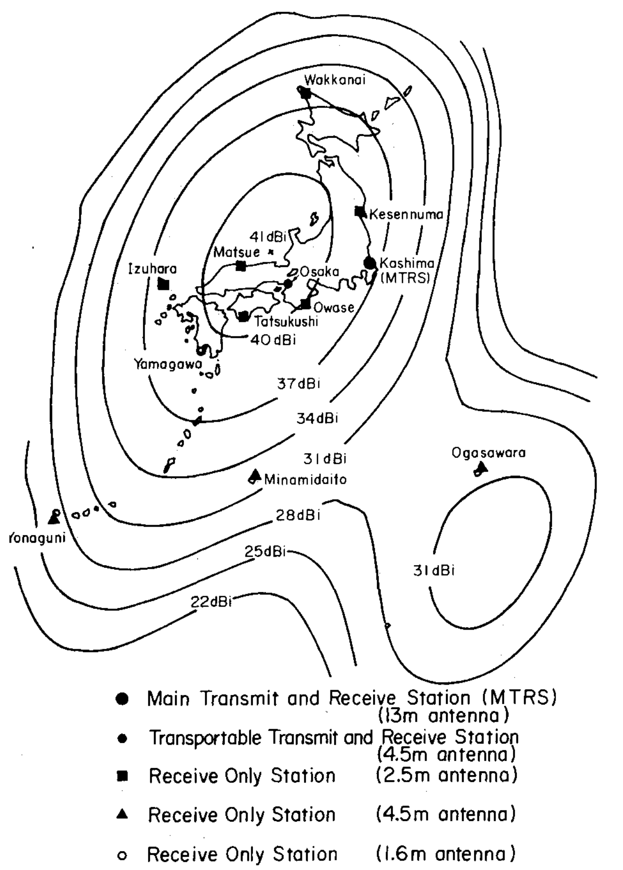

Fig. 2 BSE antenna footprint and the location of the ground stations.

mined from received signal strength change. Each of Figs. 3-5 shows the roll, pitch, and yaw telemetry data, received signal strength data of MTRS, received signal strength data at various ground stations, and the pointing error determined from them and ES and antenna reflector temperature rate. October 24, 1978, Feb. 14, 1979, and May 29, 1979 are the examples of one-day changes of winter season using SSA, winter season using MP-ES, and summer season using SSA, respectively. Several kinds of daily variations are seen in these figures.

Figures 6 and 7 show the seasonal variation of ES and antenna reflector temperature, respectively. Figure 7 indicates that antenna reflector temperature does not have much seasonal dependence.

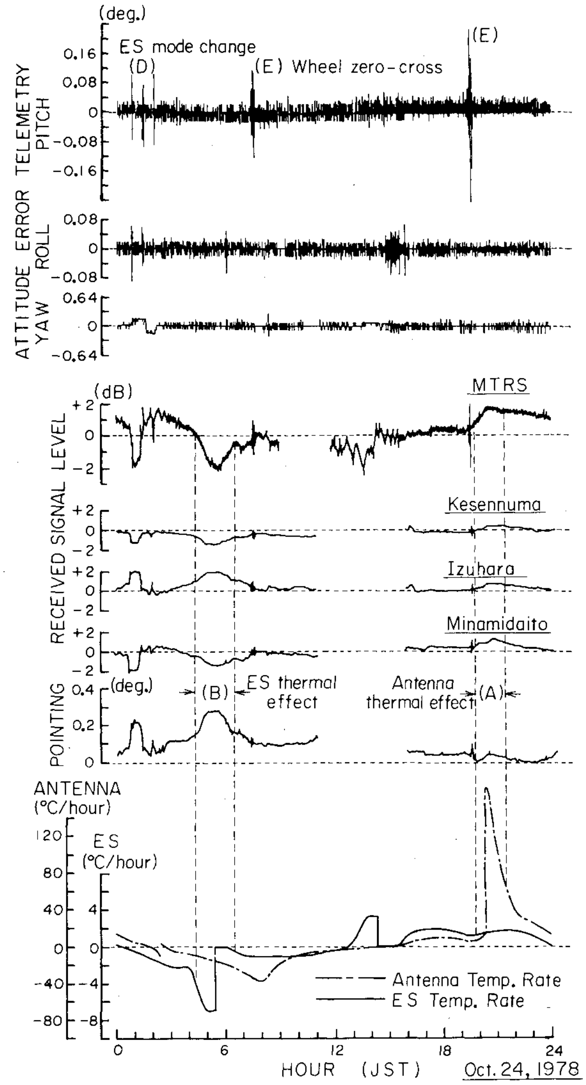

Fig. 3 Example of winter variation using SSA.

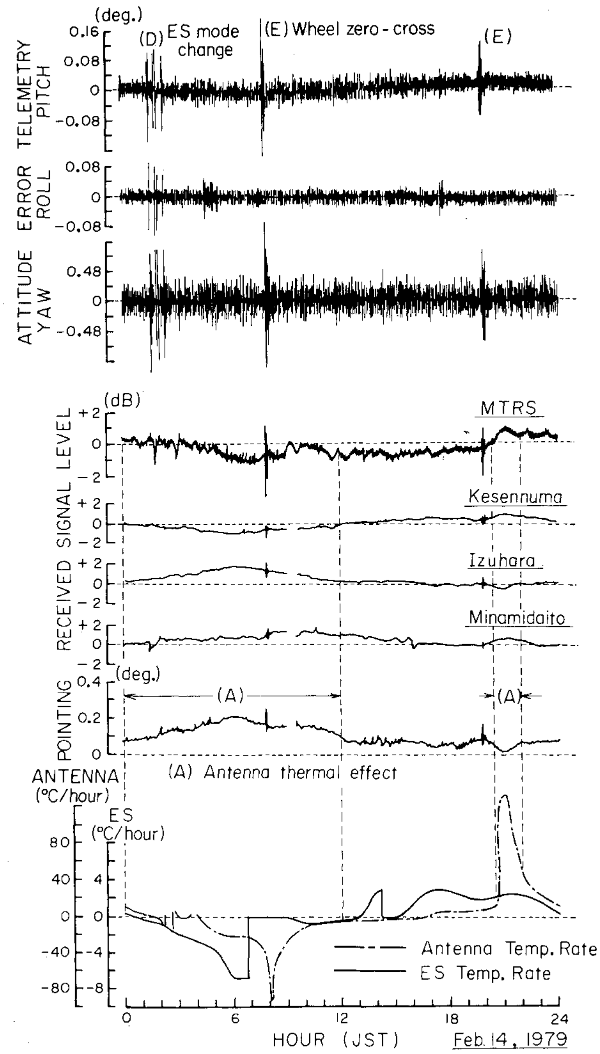

Fig. 4 Example of winter variation using MP-ES.

Analytical Results

Analytical results about status and causes of variations shown in Table 1 and corrective actions for the satellite are described in this section.

Daily Variation

There are two kinds of daily variations: occurrence and magnitude of one kind has seasonal dependence, while those of the other are independent of such causes. It was concluded that ES error seems to cause the former variation, and shift of antenna beam pointing the latter.

Seasonal Dependent Daily Variation

One variation appears around 5:00-6:00 Japan Standard Time (JST) in winter season and its maximum magnitude is about 1 or 2 dB. Another variation appears around 18:00 JST for about 1 h and its maximum magnitude is about 1 dB. The first variation is shown in Fig. 3 and the second in Fig. 5. Pointing errors determined from received signal strength variation data indicate that the first one is about 0.2 deg negative pitch error and the second one is about 0.05 deg positive roll or pitch error.

A peak time of variation in winter season moves depending on the date as shown in Fig. 8. The tendency of this movement and nonappearance of this peak in summer season almost correspond to those of ES temperature rate change when the ES is getting cool. In the same way, the variation in summer corresponds to the time when the ES is getting warm. In conclusion, these seasonal dependent variations are caused by sensor error affected by rapid temperature change. Therefore, more stringent temperature control will eliminate this kind of sensor error.

When MP-ES is being used the variation becomes small, as shown in Fig. 9. This is because the pitch error of ES causes the inverse sign yaw error according to the principle of MP-ES and this cancels the beam center pointing error.

Nonseasonal Dependent Daily Variation

One variation appears gently from about 0:00-12:00 JST with a peak time of about 6:00 JST; its maximum deviation is about 1 or 2 dB. Another variation appears around 20:00-21:00 JST for about 1 or 2 h with maximum deviation of about 1 dB. Pointing error determined from received signal strength variation data indicates that the first is about 0.15 deg negative pitch error and the second is about 0.05 deg positive pitch error.

The satellite antenna reflector has a daily temperature change of about 180°C, peak to peak. These temperature changes nearly correspond to the daily variation of received signals according to the time of occurrence, as shown in Figs. 3-5. From this fact, it is determined that the movement of the reflector's shadow on itself is causing the rapid temperature change of the reflector and is causing a shift in beam pitch direction. It is therefore desirable to perform more wide-range ground tests for thermal distortion and select more heat-proof materials and structures.

Figure 10 shows the attitude error change generated from the antenna and ES temperature rate change using these

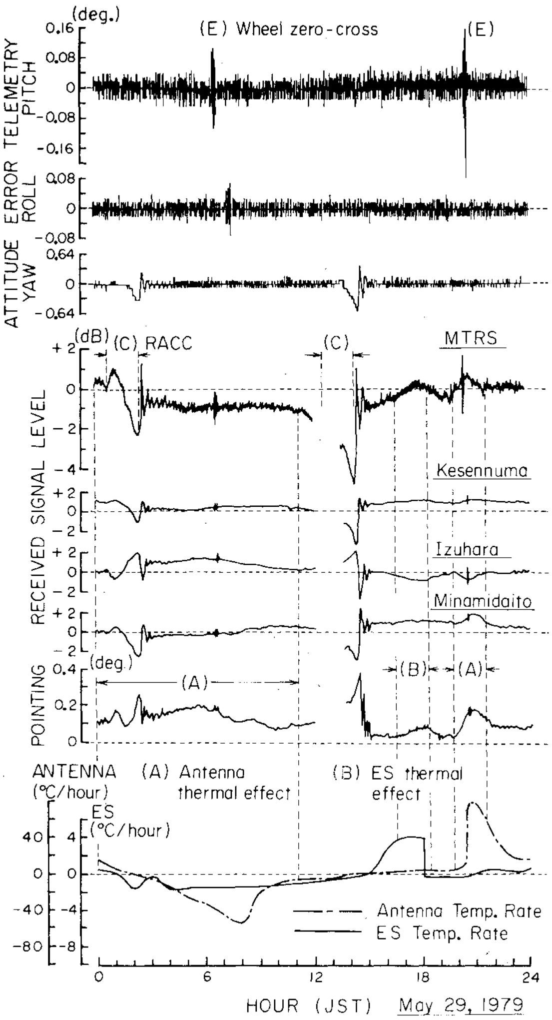

Fig. 5 Example of summer variation using SSA.

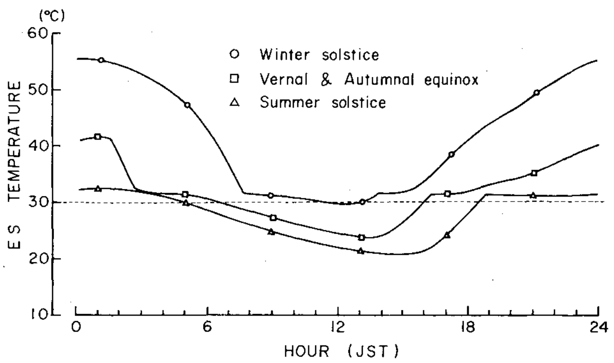

Fig. 6 Seasonal variation of ES temperature.

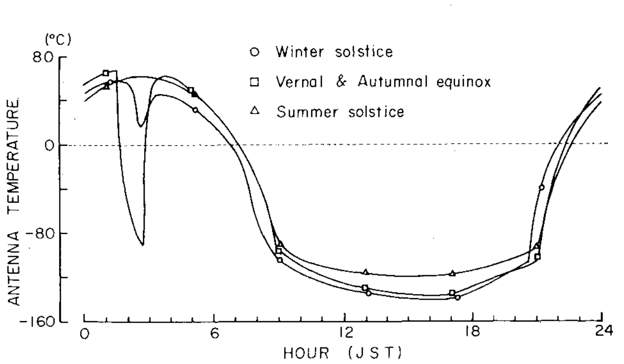

Fig. 7 Seasonal variation of antenna temperature.

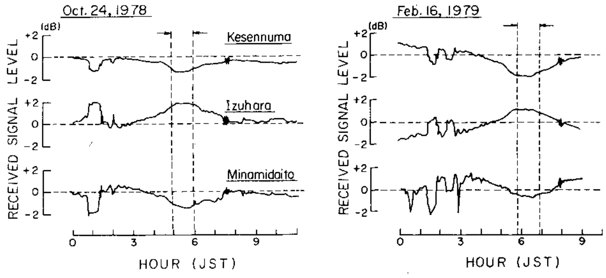

Fig. 8 Seasonal change of daily variation.

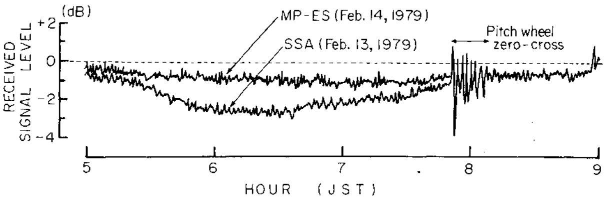

Fig. 9 Received signal strength at MTRS.

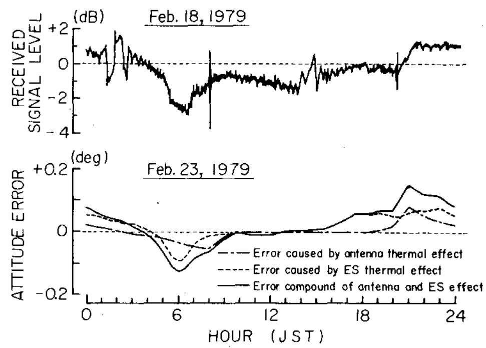

Fig. 10 Received signal strength at MTRS and attitude error caused by antenna and ES temperature change.

analytical results and received signal strength variation at MTRS of close date. The attitude error has almost the same tendency as the received signal strength variation of MTRS, which has a high sensitivity in satellite pitch error, as shown in Fig. 2.

Variation Related to the Operation

As described earlier, there are several kinds of operations, such as SDB and RACC commanding, sensor mode change, wheel unloading, etc., used to keep rf beam pointing within requirements. Received signal strength variations occur at the moment of these operations. There are some variations the causes of which are related to daily operations to maintain sensor performance, and occasional maneuvers like thruster firing for wheel unloading to control the attitude and E-W and N-S orbit control to keep the satellite within ± 0.1 deg.

Yaw Control by SSA

As BSE is using three-axis zero-momentum attitude control, it has three sensors to detect the attitude error about each axis, and as a yaw sensor, SSA is usually used. In this case, however, the sun declination angle must be canceled by an SDB command from the ground since SSA is using the angle against the sun. If this commanded value has an error of $\Delta\psi$, a yaw error ψ_{SDB} $(=\Delta\psi/\sin\lambda)$ will appear. λ is an orbit angle measured from satellite local noon.

Since the sign of SDB changes at 0:00 and 12:00 in local satellite time (LST), the yaw error in the satellite local morning and evening are different. This causes the difference of received signal strength, as shown in Fig. 11 at A. When the SDB command value is updated, the corresponding yaw error change causes a step variation of the received signal strength, as shown in Fig. 11 at B. Also, around the time when the sun,

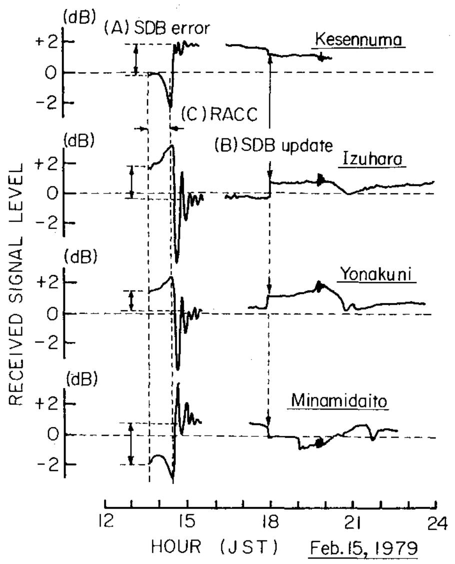

Fig. 11 Received signal strength data at the moment of RACC and SDB update.

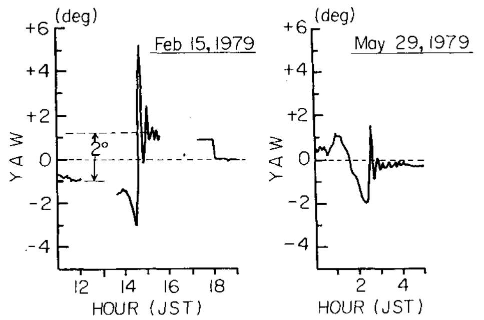

Fig. 12 Yaw error change at RACC determined from received signal strength data.

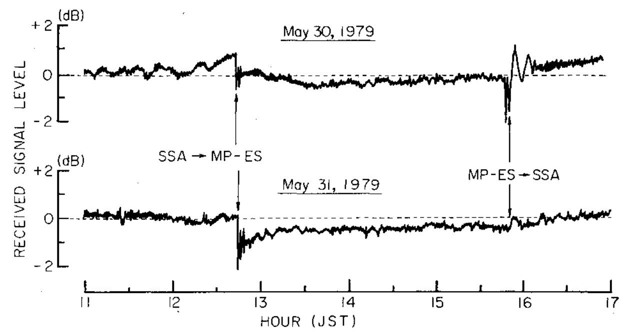

Fig. 13 MTRS received signal strength data at the moment of yaw sensor change.

the Earth, and the satellite are aligned, yaw sensitivity of SSA decreases sharply and the open-loop yaw control using the command acceleration value is adopted. If this commanded value is inadequate, yaw drift occurs in this open-loop period (RACC) and causes the received signal variation, as shown in Fig. 11 at C.

Just after the end of RACC and at the beginning of closed-loop control, yaw error transient depending on the sign of the SDB error appears. Even if the magnitude of drift is almost the same, differences of the SDB error polarity affect the magnitude of transient, as shown in Fig. 12. Thus it is necessary to command the correct value for SDB or RACC.

Yaw Sensor Change

When the yaw sensor is changed from SSA to MP-ES or vice versa, the step variation appears with about 1 dB

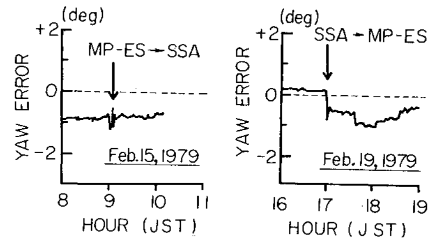

Fig. 14 Yaw error change at the moment of yaw sensor change determined from received signal strength data.

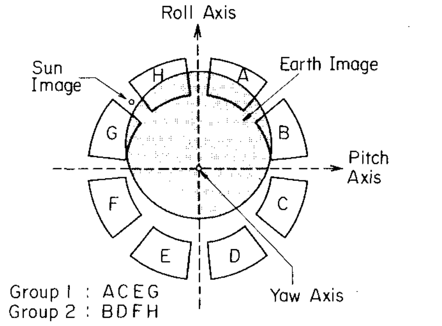

Fig. 15 Constitution of ES detectors.

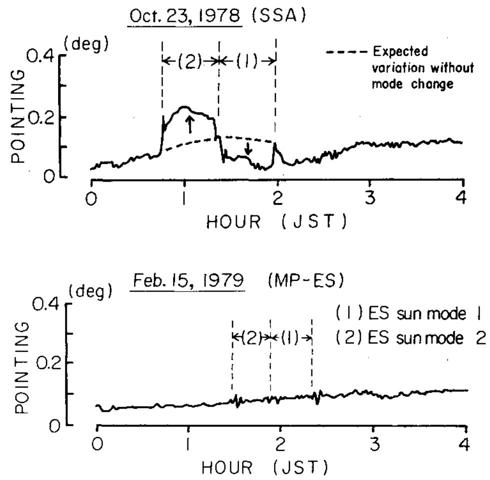

Fig. 16 Beam pointing error change at the moment of ES mode change determined from received signal strength data.

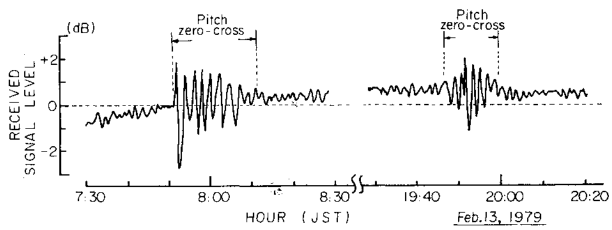

Fig. 17 MTRS received signal strength data at the pitch wheel zero crossing.

magnitude. As seen in Fig. 13, its magnitude is dependent on the day or hour when it occurs. The reason for this variation is the existence of the offset bias angle between MP-ES and SSA zero error directions. If the SDB error has the same polarity as this offset, this variation is hardly recognized, and if SDB error has an opposite polarity with the offset, the step variation becomes remarkable, as shown in Fig. 14. Therefore, if it is difficult to eliminate this offset, it is necessary to command the correct bias angle to either of two sensors so that it may be canceled.

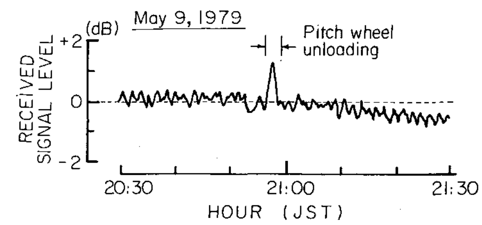

Fig. 18 MTRS received signal strength data at the pitch wheel unloading.

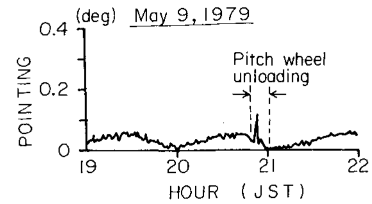

Fig. 21 Pointing error change at the pitch wheel unloading determined from received signal strength data.

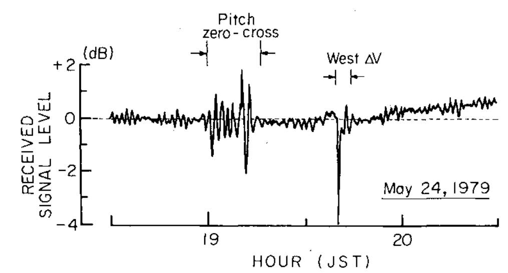

Fig. 19 MTRS received signal strength data at the E-W orbit control (W Δ*V*).

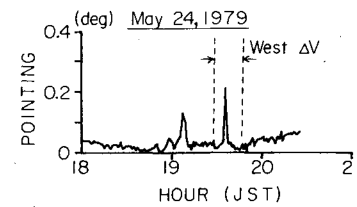

Fig. 22 Pointing error change at the E-W orbit control determined from received signal strength data.

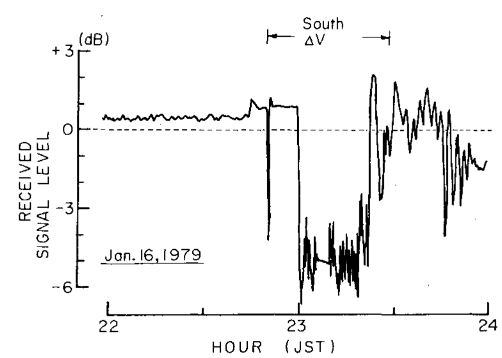

Fig. 20 MTRS received signal strength data at the N-S orbit control (S Δ*V*).

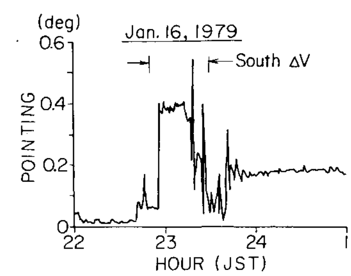

Fig. 23 Pointing error change at the N-S orbit control determined from received signal strength data.

ES Mode Change (*Sun Interference*)

This variation appears around satellite local midnight for about 1 h. It continues for a few tens of days on the season around vernal or autumnal equinoxes. It is seen in Fig. 3 around 1:00-2:00 JST. This occurs because a characteristic difference exists between two groups of ES detectors. Usually, the ES output is a compound of two outputs of detector groups as shown in Fig. 15. When the sun comes into one of these detector group's field of view, twice the output of the single group is used as the ES output automatically.

It is determined from the received signal strength that this variation is about 0.1 deg roll and pitch error, as shown in Fig. 16 under the SSA control. When yaw is controlled by MP-ES, this roll and pitch error causes yaw error, as well. As a result, the beam center pointing error almost disappears, as shown in Fig. 16. As corrective action, it is necessary to make sure before launching that the two detector groups do not have different bias in their usual condition.

Wheel Zero Crossing

This variation appears for about 20 min twice a day around 6:00 and 18:00 LST when the speed of the pitch wheel becomes almost zero. The magnitude of received signal strength variation at this time is almost 1 or 2 dB, as shown in Fig. 17. Although the roll or yaw wheels have a zero crossing time too, only the pitch wheel zero crossing causes the remarkable variation of 0.2-0.5 deg pitch error, due to its smaller moment of inertia. The reason for this variation is the existence of a tachometer sensitivity deadzone and the change of friction property when the polarity of wheel rotation changes. Improvement of the tachometer properties and higher digitalization to achieve a narrower deadzone or adoption of shorter sensor update time will help reduce this variation.

Thruster Firing

At the time of thruster firing for wheel unloading (pulsatile firing for 2-3 min) and E-W (continuous firing for 30-40 s) or N-S (continuous firing for about 20 min) orbit control, there appears a variation during a couple of times of real firing period. Wheel unloading and E-W maneuvering cause 1 or 2 dB variations for a few minutes and N-S maneuvering causes more than 7 or 8 dB for a few tens of minutes.

Examples of these variations are shown in Figs. 18-20. The beam center pointing error changes determined from the same day's received signal strength variation are shown in Figs. 21-23. Pointing error at wheel unloading on May 9, 1979 was about 0.2 deg positive pitch error and it seems that the registered value for rate control correction at the time of thruster firing was too large. Pointing error at the E-W orbit control on May 24, 1979 was about 0.2 deg negative pitch error and was caused by the shift of center of gravity on the yaw axis to negative direction. N-S orbit control on Jan. 16, 1979 caused a pointing error of about 0.4 deg. As thruster plume impingement torque occurs and causes the roll disturbance torque at the N-S orbit control, firing is limited to certain times and it is desirable to improve the position of solar array or the direction of thruster nozzles to minimize its effect.

Conclusion

Of the received signal strength variations which appear during the routine operation, almost all that affected beam pointing error were analyzed and the causes and magnitudes of pointing errors were derived. It is confirmed that the capability of the attitude control system performance of BSE can fulfill the future requirement if the causes of ES error, antenna beam shift, etc. described in this paper were removed. These results are also expected to be well reflected in the designing of BS-2 which is expected to be launched in 1984.[5]

References

[1] Shimizu, S., Saito, K., Arai, K., Yamamoto, A., Yamanouchi, S., Sato, M., and Suenaga, M., "BSE On Orbit Performance," IAF Paper No. 80-D-198, Tokyo, Sept. 1980.

[2] Shimoseko, S., Arai, K., and Matsumoto, H., "Three-Axis Attitude Control Acquisition Results and Regular Operational Status of BSE," *AIAA 8th Communications Satellite Systems Conference*, Orlando, Fla., April 1980.

[3] Imai, N., Matsushita, M., and Kajikawa, M., "Japan's BSE Program," *IEEE Transactions on Broadcasting*, Vol. BC-28, Dec. 1982, pp. 120-124.

[4] Shimoseko, S., Iwasaki, K., Kurakake, Y., and Kajikawa, M., "Aspects of the Satellite Broadcasting Experiments Using the BASE and Its In-Orbit Performance," *IEEE Transactions on Broadcasting*, Vol. BC-28, Dec. 1982, pp. 125-130.

[5] Waki, K., Katayama, M., and Sonoda, S., "Operational Broadcasting Satellite in Japan," *IEEE Transactions on Broadcasting*, Vol. BC-28, Dec. 1982, pp. 176-181.