Part IV. Characteristics of CS On-Board Communication Equipment and the Satellite Link

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One of the main features of the CS is the 30/20 GHz band transponder and narrow beam despun antenna installation. CS is the first communications satellite which used 30/20 GHz bands. Therefore, it is important to evaluate the in-orbit 30/20 GHz band characteristics of the on-board equipment.

This study describes the performance characteristics of the antenna pattern and long-term transponder characteristics based upon periodical measurement taken over 7 years, with emphasis on the 30/20 GHz band performance. In addition, new methods of evaluating the two-dimensional antenna pattern and the nonlinear transponder characteristics are presented. Measured characteristics of the CS on-board communications equipment agree well with the prelaunch data, and no particular change has been observed since the CS was launched 7 years ago.

Some factors affecting the CIN0 characteristics are also discussed, and it is confirmed that the CIN0 is significantly influenced by fluctuation of the spin axis during orbit inclination maneuvers and by Sun interference.

1. INTRODUCTION

Special attention has recently been paid to the 30/20 GHz band to achieve the high-capacity satellite communications system. The primary attraction of this band is the width of 2.5 GHz allocated for satellite use, five times as wide as that of either the C-band or the Ku-band. However, when the bands are used commercially, many technological problems must be solved, such as rain attenuation and communications equipment characteristics at these high frequencies.

In this study, the characteristics of the CS 30/20 GHz band on-board communications equipment, composed of a despun antenna and transponders, are discussed, based upon the results of periodical measurements taken over 7 years. In addition, a feasible CIN0 and some factors affecting the CIN0 characteristics, such as an eclipse, Sun interference, and maneuver, are clarified. The effect of rainfall attenuation is discussed in Part V of this paper. These results are useful for designing the next generation of 30/20 GHz band satellite communications systems.

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II. DESPUN ANTENNA

The CS despun horn-reflector antenna has a shaped-beam pattern which effectively covers the territory of Japan in the 30/20 GHz band. It is important to grasp its radiation pattern in the geostationary orbit. Therefore, the method shown in Section A below has been developed in order to measure the radiation pattern [20]. In this method, the satellite antenna beam pointing is changed and a two-dimensional radiation pattern can be obtained from the single station data.

Measurement by this method has been carried out once or twice every year since July 1979.

A. Method for Radiation Pattern Measurement

In order to describe the antenna pattern, an azimuth-elevation (Az, El) coordinate system was adopted.

A continuous daily variation of pointing direction was obtained by tilting a satellite attitude (spin axis). The tilt angle was selected as 1.0 deg to obtain an elevation variation range of 1.0 deg.

Despum antenna pointing in the azimuth direction was varied by despun-bias commands, which were transmitted every 2 min by 0.1 deg increments. The azimuth scan ranged between −0.5 deg and +1.5 deg, which corresponds to the azimuth angle from −1.0 deg to +1.0 deg at the pattern center, as the normal azimuth angle of the Kashima station is about +0.5 deg.

The Earth station transmitter provides adequate power to make the satellite transponder work in the AGC region. The input power level of the satellite transponder was obtained by telemetry and used for measuring the uplink antenna patterns. Owing to the AGC function, the output power of the transponder is considered to be constant. Therefore, a down-link antenna pattern at the communication channel frequency can be measured from the variation of signal strength received at the ground station.

The AGC voltage of the down-converter at the ground station indicates received signal strength on the ground, and it is sampled and read into the data processing unit at the rate of 20 samples/s. The cross-polarization-pattern is also measured by using the 20 GHz band beacon signal. The cross-polarization-component in the beacon signal is separated from the copolarization component at the antenna feed section. It is decomposed into the in-phase and quadrature-phase components.

B. Data Processing Method for the Radiation Pattern Measurement

The received signal at the Earth station has a short-term variation which synchronizes with the satellite spin frequency. This periodic phenomenon is designated "spin modulation."

The following two methods, in which the effect of the spin modulation is taken into consideration, were applied to data processing.

Fig. 34. Antenna pattern measured by mean value method (19.45 GHz).

One is the “mean value method” which takes the algebraic average of the maximum and minimum value in the spin modulation. It is applicable to an up-link, a down-link, and a beacon channel. This method enables one to measure the practical antenna pattern.

The other is the "spin coherent detection method" [21] which is based on coherently sampling a received signal with the spin period and is applicable only to the downlink. The spin modulation is assumed to be caused mainly by the wobble effect so that the stability of the spin frequency is sufficient for the measurement. The pointing direction fixed at a specific point on the locus can be detected by sampling it synchronously with the satellite spin frequency, since the pointing direction moves periodically. Therefore, this method enables us to measure the static antenna pattern at a specific phase point of the spin period.

C. Results

Fig. 34 shows the antenna patterns measured by the mean value method and calculated from prelaunch data, respectively, at the beacon frequency. Fig. 35 shows the peak-to-peak signal variation due to the spin effect at beacon frequency, which is much larger than the value expected from the prelaunch test data which was about 1 dB even in the worst case. It is found that a steep slope in the pattern of Fig. 34, which does not appear in the
prelaunch data in Fig. 35, corresponds to a large signal variation in Fig. 35. This fact leads to the conclusion that the large signal variation is mainly caused by the spin dynamics of the spacecraft.

Fig. 36 shows the antenna pattern obtained by the spin coherent detection method at the beacon frequency. There is fairly good coincidence between Fig. 36 and the prelaunch data in Fig. 34. The slight difference in these patterns is probably due to both the sampling jitter of a timing signal for coherent detection and the gain fluctuation in the receiver of the ground station. It is concluded that the expected performance has been achieved in the in-orbit condition.

Fig. 37 shows the patterns in every 30 deg of sampling phase. These patterns correspond to their respective phase points of the satellite spin motion and they are shifted in parallel so as to coincide with each other by the amount caused by the difference of the antenna-pointing direction in their phase points. This result supports the belief that the spin modulation is mainly caused by the wobble effect, and that the locus of the antenna-pointing direction due to the wobble is elliptic which is approximated as follows:

$$\text{Az} = a \sin (w_s t)$$

$$E_1 = b \cos (w_s t + c)$$

where $w_s$ is the spin frequency (deg/s), $a$ is 0.15 deg, $b$ is 0.19 deg, and $c$ is $-45$ deg.

This antenna-pointing deviation strongly affects about 20 percent of the service area, and the wobble effect cannot be disregarded. Considering this fact, CS-2, launched in 1983 as the successor to CS, was equipped with a wobble corrector, which reduces the wobble by adjusting the satellite weight balance.

III. TRANSPONDER

As shown in Fig. 38, CS has two 6/4 GHz band and six 30/20 GHz band transponders and is the first satellite to use the 30/20 GHz bands. Therefore, it is important to examine the long-term stability of 30/20 GHz band transponder characteristics in the geostationary orbit for future transponder and satellite link designs.

CS transponders are used in a nonlinear operation, and the frequency response and the noise figure (NF) are affected by the nonlinearity, so that their true characteristics cannot be obtained with the conventional methods. To evaluate the nonlinearity, linear amplifier frequency response, and noise figure followed by a nonlinear amplifier, new methods are introduced.
A. Trend of Characteristics

Evaluation of the transponder performance has been carried out every six months since 1978. The evaluation items are as follows:

1) input–output characteristics
2) frequency (amplitude and delay) characteristics
3) spurious signals
4) frequency stability.

1) Input–Output Characteristics: The input–output characteristics of the 30/20 GHz band transponder are shown in Fig. 39.

The 6/4 GHz band transponder input and output power and 30/20 GHz band transponder input power were obtained from the telemetry data. For lack of a telemetry circuit for each 30/20 GHz band transponder, the 20 GHz band output power was estimated from the received signal level of the Earth station. The estimated 20 GHz band output power includes the error due to the estimation error of atmospheric attenuation at 20 GHz which varies widely depending on the atmospheric condition.

Fig. 39 shows that significant changes were not observed in input–output characteristics of four out of six 30/20 GHz band transponders. The other two 30/20 GHz band transponders were out of order 7 years ago. Once an output power drop in one of two 6/4 GHz band TWTs and a helix current increase in one of four 30/20 GHz band TWTs was observed, respectively. At present, the output power has recovered, the helix current is in a stable condition, and all of the alive CS transponders have stable characteristics.

The transponder input power levels that give the 1 dB backoff output power were measured. All the 30/20 GHz band transponders have an AGC function. From the results obtained, it is found that 1 dB backoff points are almost constant and so the AGC function works well.

Usually, the helix current is considered to be an index for the TWTA degradation and is expected to increase at the end of life. Judging from the above-mentioned result, the TWTs are expected to be in normal condition, although 7 years have passed since the launch.

2) Frequency Characteristics: The frequency-amplitude and frequency-delay characteristics for the 6/4 GHz band and 30/20 GHz band transponders were measured. As the directly measured data include the Earth station's characteristics, the transponder frequency characteristics were obtained by subtracting the characteristics of the Earth station from the measured ones. From the obtained data, the characteristics are considered to have remained constant.

3) Spurious Signals: The main spurious signal level trend in the 30/20 GHz band transponder was measured when no channel received a signal. The measurement showed that the spurious level has almost been constant. In general, a spurious level depends upon a level diagram of a transponder. Therefore, it is expected that the 30/20 GHz band transponders have maintained their initial level diagrams.

Fig. 38. Transponder block diagram.

Fig. 39. Input–output characteristics of 30/20 GHz band transponder.
TABLE XIII
Example of Measured Nonlinearity Factors of Japan’s CS Spacecraft

<table>
<thead>
<tr>
<th>Factors</th>
<th>F1</th>
<th>F3</th>
<th>F4</th>
<th>F5</th>
<th>G2</th>
</tr>
</thead>
<tbody>
<tr>
<td>c</td>
<td>1.03</td>
<td>0.912</td>
<td>0.914</td>
<td>1.06</td>
<td>1.00</td>
</tr>
<tr>
<td>kp</td>
<td>2.9</td>
<td>4.76</td>
<td>3.24</td>
<td>4.02</td>
<td>3.39</td>
</tr>
</tbody>
</table>

Fig. 40. Trend of 30/20 GHz band input-output frequency difference.

![Image](image0.png)

Fig. 41. (a) Transmitting spectrum. (b) Receiving spectrum.

4) Frequency Stability: The history of the 30/20 GHz band transponder frequency difference between uplink and downlink is shown in Fig. 40. The nominal frequency difference is 9.8 GHz. The maximum frequency deviation is 70 kHz. The frequency deviation of the 30/20 GHz band transponder corresponds to the total deviation of down-converter and up-converter local oscillators. From the results, it is clear that the 30/20 GHz band oscillator is as stable as $4 \times 10^{-6}$ for a long time on the satellite environmental exposures.

B. Nonlinear Characteristics

1) Compression and AM/PM Conversion Factors: The nonlinear effect is expressed by an amplitude compression, i.e., AM/AM conversion, and an amplitude-dependent phase modulation, i.e., AM/PM conversion.

A compression factor ($C$) can be obtained from the input-output power transfer characteristic of a transponder. On the other hand, an AM/PM conversion factor ($k_p$) cannot be measured by the conventional method which measures phase difference between the input and output signal of the transponder, because of frequency conversions and Doppler shifts in a satellite link. In this section, an unbalanced two-tone method is described [22,23] which is simple and is able to measure both $C$ and $k_p$ simultaneously.

A transmitting and a receiving spectrum which was observed during the measurement is shown in Fig. 41. An intermodulation product is shown in Fig. 41(b). From this figure, $C$ and $k_p$ are calculated as follows:

$$C = 1 - (S_1^2 - S_2^2)$$  

(1)

$$k_p = 2(S_1^2 - (S_1^2 - S_2^2)/2)^{1/2}/0.152 \text{ (deg/db)}$$  

(2)

Table XIII shows the result of measured $C$ and $k_p$ near the transponder saturation points. In this table, G2 is a 6/4 GHz band transponder and F1 through F5 are 30/20 GHz band transponders.

2) Frequency Response: In order to evaluate the precise signal transmission characteristics, we obtained the frequency characteristics of the linear amplifier followed by a high power amplifier with an AGC function as well as the total transponder characteristics. For this measurement of the transponder, the sweep method cannot be employed except in the linear region, because the AGC response is usually faster than the sweep speed. Then, we adopted the unbalanced two-tone method, described in the preceding section, which transmits a large and a small signal simultaneously, to measure the frequency response [23].

The large signal transmitted near the center of the frequency band keeps the transponder operating point fixed. Since the AM/AM and AM/PM conversion effects are considered to be constant because of the constant operating point determined by the large signal, the transponder output level of the small signal represents the frequency response of the linear amplifier. Therefore, the frequency response of the transponder can be evaluated by sweeping the small signal. Fig. 42 shows comparisons...
of the results measured by three methods, the two sweep methods with a single carrier signal in the saturation region and near the linear region of the transponder, and the unbalanced two-tone method. The result measured by the unbalanced two-tone method agrees well with that measured by the sweep method near the linear region of the transponder. Therefore, an unbalanced two-tone method is also effective on frequency response measurements of the nonlinear transponder.

3) Noise Figure: Transponder noise characteristics are mainly determined by the front-end linear amplifier. However, it is impossible to evaluate the in-orbit transponder noise characteristics, because of the nonlinear amplifier presence.

When the transponder has a nonlinearity, the NF calculated from the uplink CIN0 and transponder input power does not agree with the front-end linear amplifier noise figure, since the calculated NF contains the effect of AM/AM and AM/PM conversions [23]. The obtained NF is, so to speak, apparent noise figure. Therefore, it needs a correction to obtain the NF of a linear amplifier.

Representing the effect of the nonlinearity with C and \( k_p \) mentioned above, the relation between an apparent noise figure (NF_a) and a linear amplifier noise figure (NF_l) is expressed as

\[
NF_l = \frac{2}{1 + (1 - C)^2 + (0.125k_p)^2} NF_a. \tag{3}
\]

In the case of obtaining the noise figure by the phase noise measurement, \( NF_l \) is expressed as follows:

\[
NF_l = \frac{1}{1 + k_p^2} NF_a. \tag{4}
\]

![Fig. 43. Apparent NF.](image)

**TABLE XIV**

Comparison of the Measured In-Orbit True Noise Figures with the Prelaunch Data

<table>
<thead>
<tr>
<th>Transponders</th>
<th>Prelaunch</th>
<th>In Orbit</th>
</tr>
</thead>
<tbody>
<tr>
<td>F1</td>
<td>13.6</td>
<td>13.6</td>
</tr>
<tr>
<td>F4</td>
<td>11.3</td>
<td>12.3</td>
</tr>
<tr>
<td>G1</td>
<td>7.5</td>
<td>7.5</td>
</tr>
<tr>
<td>G2</td>
<td>8.3</td>
<td>8.6</td>
</tr>
</tbody>
</table>

Fig. 43 gives an example of measured results of the apparent noise figure as a function of satellite input level. The results agree with the values calculated from the prelaunch data using (3) and (4), which are shown with solid lines in this figure. Table XIV shows the comparison between the prelaunch data and the measured data in orbit. It is considered that the CS transponder noise characteristics have not changed.

IV. SATELLITE LINKS

To design a satellite communications system using the 30/20 GHz bands, it is necessary to examine the feasible CIN0 value, rainfall attenuation, and several factors degrading CIN0, satellite movement due to an attitude or orbit maneuver, and Sun interference.

In the following section, the designed link budget and the factors affecting satellite link except rainfall are described based upon the data obtained through CS experiments. The rainfall attenuation problem is so important for the 30/20 GHz bands that it is discussed in detail in another study in this paper.
A. Link Budget Under Normal Condition

Table XV shows the CS satellite link budget and the measured \( C/N_0 \) at the Kashima station and the Yokosuka station under normal conditions. In this table, the transmitting power of the Earth station is 50 dBm. The \( C/N_0 \) of 30/20 GHz band satellite links is obtained to be above 100 dB Hz in case of fine weather. The table does not include the effect of the satellite antenna-pointing error, which is estimated to be about 1 dB.

B. Factors Affecting the Satellite Link

1) Eclipses: Since the orbit of geostationary satellites exists on the equatorial plane, they enter the shadow of the Earth during three weeks at the vernal and the autumnal equinox seasons. This eclipse occurs around midnight and lasts about up to 70 min.

The satellite temperature falls during the eclipse and rises after the eclipse, and so the variation is considered to be the cause of the change of transponder characteristics.

In order to clarify the transponder characteristics during the eclipse, received power level, frequency, and \( C/N_0 \) were measured. The satellite temperature variation due to the eclipse is shown in Fig. 44. For example, the 30/20 GHz band TWT temperature fell about 30°C. The other component temperature also fell similarly.

The frequency deviation of the 6/4 GHz band transponder and 20 GHz band beacon transmitter is shown in Fig. 45. These frequency changes correspond to temperature variation.

<table>
<thead>
<tr>
<th>TABLE XV</th>
<th>Link Budget and Measured ( C/N_0 )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Kashima ( \rightarrow ) Kashima</td>
</tr>
<tr>
<td></td>
<td>( F_1 ) Channel (AGC off)</td>
</tr>
<tr>
<td>Uplink</td>
<td></td>
</tr>
<tr>
<td>Output power (dBm)</td>
<td>50.0</td>
</tr>
<tr>
<td>Earth station EIRP (dBm)</td>
<td>116.5</td>
</tr>
<tr>
<td>Free space loss (dB)</td>
<td>212.7</td>
</tr>
<tr>
<td>Atmospheric attenuation (dB)</td>
<td>0.5</td>
</tr>
<tr>
<td>Satellite antenna gain (dB)</td>
<td>37.7</td>
</tr>
<tr>
<td>Satellite receiving power (dBm)</td>
<td>-59.0</td>
</tr>
<tr>
<td>Satellite noise temperature (dBK)</td>
<td>38.0</td>
</tr>
<tr>
<td>( C/N_0 ) (dB·Hz)</td>
<td>101.6</td>
</tr>
<tr>
<td>Downlink</td>
<td></td>
</tr>
<tr>
<td>Satellite EIRP (dBm)</td>
<td>71.6</td>
</tr>
<tr>
<td>Free space loss (dB)</td>
<td>208.9</td>
</tr>
<tr>
<td>Atmospheric attenuation (dB)</td>
<td>0.5</td>
</tr>
<tr>
<td>Antenna gain (dB)</td>
<td>65.5</td>
</tr>
<tr>
<td>Receiver input power (dBm)</td>
<td>-72.3</td>
</tr>
<tr>
<td>Noise temperature (dBK)</td>
<td>22.0</td>
</tr>
<tr>
<td>( C/N_0 ) (dB·Hz)</td>
<td>104.4</td>
</tr>
<tr>
<td>Total ( C/N_0 ) (dB·Hz)</td>
<td>99.7</td>
</tr>
<tr>
<td>Measured ( C/N_0 ) (dB·Hz)</td>
<td>100.7</td>
</tr>
</tbody>
</table>
Fig. 46. Effect of eclipse. (a) Receiving power during eclipse.
(b) Earth width and Sun angle during eclipse.

Fig. 46(a) shows the received signal level of the Earth station during the eclipse where the signal level changes slightly before and after the eclipse. The reason is explained as follows: Fig. 46(b) shows the Earth width, viewed from the satellite, which was obtained from the telemetry data. The occurrence of the signal level change coincides with that of the Earth width change. When the sunlight enters the satellite Earth sensor on which the antenna orientation control is based, the sensor generates signals of larger width than the actual width. Therefore, antenna orientation moves to the west just before the eclipse and to the east just after the eclipse. As a result, the received signal level changes. A change of about 1 dB was observed in the 30/20 GHz band received level at the beginning and the ending of the eclipse. However, these level changes are less than that caused by rain attenuation. In addition, occurrence of the eclipse is predictable and lasts for a short time. Then, limited to these facts, it is expected that the effect of the eclipse on satellite link is small.
2) Sun-Interference (Sun Transit): Whenever a satellite is aligned with the Sun and the Earth station (Sun transit), the Earth station antenna receives a solar noise and then the $C/N_0$ of the channel will degrade. This phenomenon occurs during a few days around the vernal and the autumnal equinoxes and lasts several minutes per day.

The observed maximum $C/N_0$ degradation due to the Sun transit was 16 dB during 2.5 min and 22.7 dB during 9 min for the 30/20 GHz band channel and the 6/4 GHz band channel, respectively. The $C/N_0$ of the 20 GHz and the 6/4 GHz band, when the Sun transit occurred, is shown in Fig. 47.

The Sun transit effect is especially severe on the 6/4 GHz band link, because the effective noise temperature of solar noise is greater in the 4 GHz band than in the 20 GHz band because the beamwidth of the 6/4 GHz band antenna is broader than the 30/20 GHz band antenna. It is said that the effective noise temperature is $7.6 \times 10^3$ K and $2.3 \times 10^4$ K for a 20 GHz band and a 4 GHz band, respectively [24]. The increase of $N_0$ measured at the Yokosuka station almost coincides with the values of $-160$ dBm/Hz and $-155$ dBm/Hz calculated from these effective noise temperatures.

As stated above, the Sun transit greatly affects the 6/4 GHz band, and about a 22 dB and a 14 dB degradation of $C/N_0$ are predicted for a large antenna (11-13 m) Earth station and a small (3 m) Earth station, respectively, which is different from the normal condition.

3) Maneuvers: CS is a spin-stabilized satellite and its orbit inclination control is conducted by firing an axial thruster parallel to the spin axis. As a result, the spin axis fluctuates periodically and so the shaped-beam antenna orientation fluctuates also. The $C/N_0$ fluctuation in the 30/20 GHz band during the orbit inclination maneuver is shown in Fig. 48. Maximum deviation is 16 dB in the 30/20 GHz bands. On the other hand, maximum $C/N_0$ deviation is 1 dB in the 6/4 GHz bands. It is possible to reduce the spin axis fluctuation by firing two thrusters symmetrical with respect to the spin axis. Based upon these results, the communications satellite CS-3 to be launched in 1988 is to have two axial thrusters.

In addition to the orbit inclination maneuver, the E-W and attitude maneuvers are also conducted by a pulsed firing of the radial thruster. However, the $C/N_0$ fluctuation due to these maneuvers is small compared with the orbit inclination maneuver.

V. CONCLUSION

The main features of CS on-board communication equipment are a 30/20 GHz band nonlinear transponder with AGC function and a narrow beam despun antenna.

In order to evaluate these in-orbit characteristics, measurements have been carried out every six months since 1978. Also, the following methods were developed: 1) the spin coherent detection method was introduced to remove the spin modulation effect and is a method of measuring two-dimensional antenna patterns at a single station and of processing data; 2) the other method measures NF and the frequency response of transponders considering nonlinear effects.