저궤도 위성 TT&C 시스템에서 최적 변조지수 설계 및 수신성능 예측 방법

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요 약

지도제작, 해양생태감시, 기상관측, 및 우주환경감시 등의 분야에 이용되는 저궤도 위성을 관제(위성추적, 원격측정 및 명령)하기 위해 본 논문에서는 최적의 PM 변조지수를 결정하는 방법을 기술하고 수신 데이터의 성능을 평가한다. 이 저궤도 위성인 아리랑 위성은 한국에서는 첫번째 저궤도 위성이며 1999년 12월 발사되어 현재 임무를 충실히 수행하고 있다. 아리랑 위성 관제시스템의 파라미터에 의해 위성링크를 설계하면, PB 원격측정 신호의 최적 변조지수는 Eb/No마진과 PFD마진의 교차점이 되며 1.92라디안으로 결정된다. 또한 위성의 통과시간에 따라 예측되는 BER은 RT모드에서 최고의 성능을 나타내고, RT+RNG모드에서 최악의 성능을 나타내기 때문에 데이터 전송순서를 위성의 통과시간에 따른 BER 성능 순서인 RT, PB, RT+RNG모드의 순서로 결정함으로써 수신성능을 높일 수 있다.

Optimized Modulation Index Design and Receiving Data Performance Estimation of LEO Satellite TT&C System

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ABSTRACT

This paper describes the determination method of optimum modulation index of the PM modulator and the performance estimation of received data for tracking, telemetry, and command of LEO satellite, which is utilized in the field of cartography, ocean color monitoring, biological oceanography, and space environments observation. KOMPSAT I, which is the first LEO satellite in Korea, was launched on Dec. of 1999, and works well. According to the link budget of TT&C system of KOMPSAT I satellite, the optimal modulation index of playback telemetry is determined at cross point of Eb/No margin and PFD margin and this value is 1.92 radians. And the estimated BER according to satellite pass time is the best at real-time mode and the worst at real-time plus range tone (RT+RNG) mode. Therefore transmission sequence of telemetry data are determined such as BER sequence according to pass time, namely, real-time, playback, and real-time plus range mode.

키워드 : 저궤도 위성(LEO Satellite), 링크 설계(Link Budget), 변조 지수(Modulation Index)

1. Introduction

The first version KOrea Multi-Purpose SATellite (KOMPSAT I) system, which is the first LEO satellite of Korea, incorporates multipurpose missions designed to perform cartography of Korea, to provide large-scale multi-spectral images of ocean, and to provide information about ion layer and LEO particle environment during the designed life. And it is maintained and operated on the circular sun-synchronous orbit with 685km nominal altitude and 98.13degree inclination, and controlled and monitored by S-band Tracking, Telemetry, and Command (TT&C) station. The KOMPSAT makes about 14.6 revolutions around the earth in a day including 2 or 3 day time passes and 2 or 3 night time passes over 28 day revisit time.

In this paper, we will describe tracking, telemetry, and commanding of LEO satellite. Generally, link budget is designed to enlarge link margin under the conditions of satellite transponder and ground station parameters, losses at transmission path, and modulation scheme. But, owing to use of S-band frequency for the KOMPSAT project, downlink signal is restricted by ITU-R Regulation Art 28 [1].

Therefore, to solve the low link margin and PFD restriction simultaneously, the optimum modulation index should be selected. And to obtain the transmission sequence of downlink modes for the best performance, the error probabilities

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and packet error rates may be estimated according to pass time and elevation angle.

2. Transmission Methods of KOMPSAT TT&C

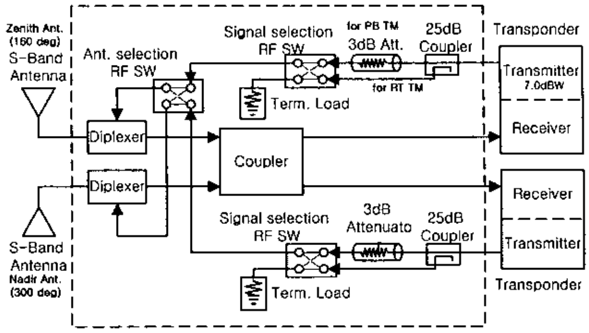
The command signal is utilized for mission and payload controlling of LEO satellite and the range tones are utilized for range and range rate measuring between TT&C station and moving satellite for satellite tracking and orbit estimation. The housekeeping telemetry data are spacecraft SOH (State of Health) and science instrument data. And these data are separated with low rate RT (real-time) and high rate PB (real-time plus playback) TM (telemetry) data. The transmission methods of command, range tone, and telemetry signals are determined by recommendation of the reference [2, 3] and summarized in <Table 1>.

<Table 1> Transmission specifications for TT&C

Items		Characteristics
RF Frequency	Uplink	2025~2120MHz
	Downlink	2200~2300MHz
Modulation	CMD RNG tones	BPSK/PM PM
	RT TM PB TM RNG tones	BPSK/PM PM PM
Subcarrier Frequency	CMD	16KHz
	RT TM	1.024MHz
Data Rate	CMD	2kbps
	RT TM PB TM	2.048kbps 1.5Mbps

The downlink signals for tracking and telemetry of LEO satellite are consisted of real-time telemetry, playback telemetry, and range tones. The data rate of playback telemetry is 1.5Mbps and real-time telemetry is 2.048kbps. So, the required transmission power between real-time and playback telemetry data to ground station are different. And large transmission power is restricted by power flux density limitation according to ITU-R regulation. Therefore, we determine the transmission power and RF assembly of transponder by rough link budget. According to rough link budget, the transmission power of playback telemetry path is more required about 22dB than real-time telemetry or range tones path. So, we chose 25dB commercial coupler for real-time telemetry and range tones path and 3dB attenuator for playback telemetry path.

The block diagram of RF assembly of KOMPSAT transponder is shown in (Figure 1). The measured RT and PB path losses of actual RF components of flight model KOMPSAT are 30.43dB and 8.73dB, respectively.



(Figure 1) RF Assembly of KOMPSAT Transponder

3. Link Budget of Downlink

3.1 Modulation Loss of PM Modulation

A PM modulation signal, in the cases of PCM/PSK/PM, PCM/PM, and tone/PM, may be represented mathematically by Eq. (1) [4].

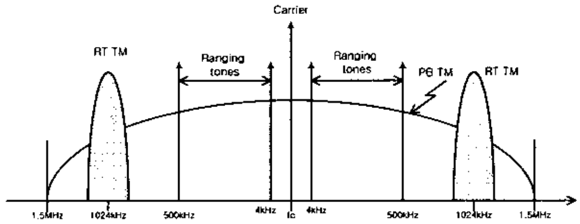
$$S_{PM}(t)=\sqrt{2}\,\sin[\omega_c t+\sum_{i=1}^{M}\beta_i s_i(t)] \qquad (1)$$

Where, β_i is modulation index, ω_c is carrier angular frequency of PM modulation, i = 1,2, ⋯, M are the number of subcarriers or data channels, and $S_i(t)$ is the source signal for PM modulation.

$S_i(t)$ represents a normalized data sequence (in the case of PCM/PM), a normalized tone signal (tone/PM), or a normalized PSK modulated signal (PCM/PSK/PM). This is given in the Eq. (2).

$$S_i(t)=\begin{cases} d_i(t) & PCM/PM \\ \sin\omega_r t & tone/PM \\ d_i(t)\sin\omega_s t & PCM/PSK/PM \end{cases} \qquad (2)$$

where $d_i(t)$ = ±1 is the normalized data sequence. Power spectrums of PM modulated signals are obtained by autocorrelation and Fourier transformation of Eq. (1), and prepared in (Figure 2).



(Figure 2) Power Spectrum of TM and Range Signal

Using the well-known trigonometric function, Jacobi equations, Bessel functions, and (Figure 2) we may obtain the modulation loss as <Table 2> [5] according to the modulation indices. Where the 0th order Bessel function $(J_0)^2$ is carrier power component, and the 1st order Bessel function $(J_1)^2$ is data power component. However data power components are $2(J_1)^2$ because data components are double sided with as the central carrier frequency fc (refer to (Figure 2)) and double sided data power affects to recovering the receiving data.

In case of PB TM, square wave signal filtered by 4-pole LPF located between OBC(On Board Computer, NRZ-L generator) and transponder (PM modulator) is directly PM modulated. The analyzed results are shown in <Table 2>.

<Table 2> Mod. Losses for Link Margin Calculation [5]

Mode	Channel	Modulation Loss
RT only	Carrier	$20*\log[J_0(\beta_{tr})]$
	RT TM	$10*\log[2J_1^2(\beta_{tr})]$
RT+RNG	Carrier	$20*\log[J_0(\beta_{tr})J_0(\beta_{rjt})J_0(\beta_{rmt})]$
	TM	$10*\log[2J_1^2(\beta_{tr})J_1^2(\beta_{rjt})J_0^2(\beta_{rmt})]$
	Ranging	$10*\log[2J_0^2(\beta_{tr})J_1^2(\beta_{rjt})J_0^2(\beta_{rmt})]$
PB only	Carrier	$10*\log[0.122J_0^2(\beta_{tp})]$
	PB TM	$10*\log[0.878J_0^2(\beta_{tp})]$
RNG only	Carrier	$20*\log[J_0(\beta_{rjt})J_0(\beta_{rmt})]$
	Ranging	$10*\log[2J_1^2(\beta_{rjt})J_0^2(\beta_{rmt})]$

Where, β_{tr} : mod index(MI) of RT mode, β_{tp} : MI of PB mode
β_{rjt} : MI of major RNG mode, β_{rmt} : MI of minor RNG mode

Modulation losses for PFD calculation are same as for link margin calculation except to RT TM data and range tones. The 1st order Bessel function $(J_1)^2$ is data or range power component. So absolute power $(J_1)^2$ affects to PFD calculation because PFD is limited in any 4kHz band and data or range power components are separated more than 4kHz shown in (Figure 2). Therefore in case of PFD calculation $2(J_1)^2$s of <Table 2> are substituted with $(J_1)^2$.

3.2 Downlink Budget

Signal to Noise power density ratio $(S/No)_{down}$ is represented by reference [1, 2] and includes carrier and data components power. Where $EIRP_{S/C}$ is downlink signal strength emitted from satellite, FSL is free space loss according to propagation distance, L_{pol} is polarization loss, L_{atm} is atmospheric and rain loss, K is Boltzmans constant (-228.6(dBK)) and $(G/T)_{G/S}$ is equivalent antenna gain to noise temperature ratio of a ground station.

$$(S/N_0)_{down} = EIRP_{S/C} + FSL_{down} + L_{pol} + L_{atm} - K + (G/T)_{G/S} \quad (3)$$

E_b/N_o which is the reference of received TM data performance is given by Eq. (4). Where R_b is data rate of TM data, ML_{TM} is modulation loss of TM data, and DLTM is demodulation loss of demodulator. E_b/N_o of 3 modes TM data are calculated respectively by Eq. (4) and modulation losses of <Table 2>. E_b/N_o margins are calculated by difference between calculated E_b/N_o by Eq. (4) and required E_b/N_o

Carrier SNR($SNR_{car,down}$) is calculated as Eq. (5) from $(S/No)_{down}$ of Eq. (3), carrier mod. loss $ML_{car,down}$ of <Table 2>, and noise bandwidth of PM demodulator $BW_{car,down}$.

$$(E_b/N_O)_{TM} = (S/N_O)_{down} - 10\log R_b + ML_{TM} - DL_{TM} \quad (4)$$

$$(SNR)_{car,down} = (S/N_O)_{down} + ML_{car,down} + 10\log BW_{car,down} \quad (5)$$

3.3 Effective Carrier SNR Calculation

Since the PB TM data and carrier occupy the same bandwidth as shown in (Figure 2), the PB telemetry acts as a noise signal to the carrier. So this noise signal must be accounted for when computing the SNR for the carrier.

3.3.1 Normalized Signal Power

NRZ-L signal d(t) which is PB TM data is written as Eq. (6). Where T_B is time interval of NRZ-L data and Fourier transformed data is rewritten as Eq. (7).

$$d(t) = rect(t/T_B) = \begin{cases} 1, & |t| < T_B/2 \\ 0, & |t| < T_B/2 \end{cases} \quad (6)$$

$$d(f) = \int_{-T_B/2}^{T_B/2} rect(t/T_B)e^{-j2\pi ft}dt = T_B\frac{\sin(\pi fT_B)}{\pi fT_B} \quad (7)$$

If the PLL BW of PM receiver is ±f1, PB TM power affected by this receiver BW is represented as Eq. (8).

$$P_b = \frac{1}{T_B}\int_{-\infty}^{\infty}|d(f)|^2df = T_B\int_{-f1}^{f1}\left[\frac{\sin(\pi fT_B)}{\pi fT_B}\right]^2df \quad (8)$$

3.3.2 Carrier vs. TM Data Power Ratio

As described in the above explanation TM data power is accounted for noise of carrier SNR. So carrier vs. TM data power ratio is needed for when computing the effective carrier SNR.

The carrier power ratio of PB TM mode is $0.122(J_0)^2$ and TM data power ratio is $0.878(J_0)^2$ as <Table 2>. The above ratios are modulation losses. So Carrier vs. PB TM data power ratio ($P_{car/TM}$) considered modulation losses is given in Eq. (9).

$$P_{car/TM} = \frac{0.122J_0^2(\beta_{tp})}{0.878J_0^2(\beta_{tp})T_B\int_{-f1}^{f1}\left[\frac{\sin(\pi fT_B)}{\pi fT_B}\right]^2df} \quad (9)$$

3.3.3 Effective Carrier SNR

The effective carrier SNR reflects noise level contributions from both carrier SNR and Carrier/TM data power ratio. The two noise signals are added together to represent a combined noise signal. Therefore the effective carrier SNR is represented as Eq. (10).

$$Eff.(SNR)_{car,dB} = -10\log\left(10^{\frac{-(SNR)_{car,dB}}{10}} + \frac{1}{P_{car/TM}}\right) \quad (10)$$

4. Optimized Mod. Index Design of PB TM

4.1 Power Flux Density(PFD)

In accordance with the provisions of the ITU-R Regulations Art. 28, the PFD at earth's surface produced by emissions from a spacecraft shall not exceed the values given in <Table 3>. That is for the protection of terrestrial radio communications from satellite signal. In the case of KOMPSAT satellite, the limits relate to the PFD which would be obtained under assumed free space loss and incidence angle.

〈Table 3〉 PFD Limits at the Earths Surface [1]

Frequency (MHz)	Incident angle above horizontal plane(θ deg)	Power flux density (dBW/m^2 /4kHz)
136~1525	not applicable	no limit
1525~2300	0 ~ 5 5 ~ 25 25 ~ 90	-154 -154 + 0.5(θ -5) -144
8025~8500	0 ~ 5 5 ~ 25 25 ~ 90	-150 -150 + 0.5(θ -5) -140

$$PFD = EIRP + FSL + G_{eff} + L_{atm} + ML + 10\log(4KHz/BW) \quad (11)$$

$$PFD = EIRP - 10\log(4\pi d^2) + L_{atm} + ML + 10\log(4KHz/BW) \quad (12)$$

PFD is the power density strength affected by satellite EIRP at effective surface of 1m^2 of the Earth's surface, and the power density in any 4kHz band for elevation angle θ. So we may represent as Eq. (11), where EIRP is the equivalent isotropically radiated power of satellite, G_{eff} is the gain over effective antenna area, L_{atm} is atmospheric loss, and ML is modulation loss according to transmission modes. By modification of FSL and G_{eff}, Eq. (11) may be rewritten by Eq. (12).

Distance between a moving satellite and a ground station is determined by Eq. (13) [4], where R_E is earth radius, H is satellite altitude, and θ is elevation angle determined by satellite position. The FSL is determined by Eq. (14), where f is down link frequency.

$$d = R_E\sqrt{(1+H/R_E)^2 - \cos^2\theta} - R_E\sin\theta \quad (13)$$

$$L_{FSL} = 20 \times \log(4\pi fd/c) \quad (14)$$

The PFD of each transmission modes must be calculated respectively. In case of PB TM data, using Eq. (12) and <Table 2>, the data PFD is rewritten by Eq. (15), where data rate of PB TM is 1.5Mbps.

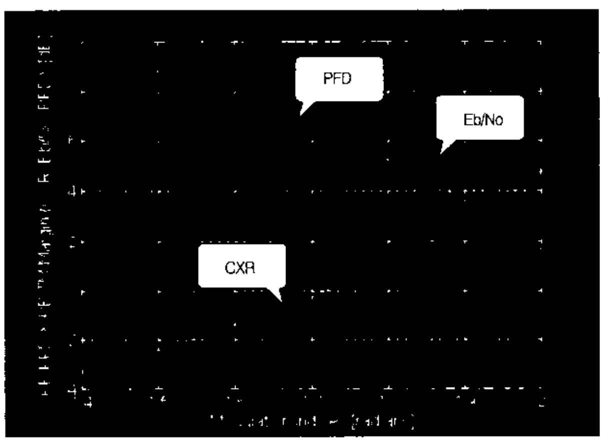
The carrier PFD of PB TM is rewritten by Eq. (16), where the bandwidth component is ignored because the carrier bandwidth of PB TM is negligible in comparison with 4kHz. The PFD of carrier, TM data, and ranges according to transmission modes must be calculated respectively as the above methods. And PFD margins are calculated by difference between calculated PFD and limited PFD of <Table 3>.

$$PFD = EIRP - 10\log(4\pi d^2) + L_{atm} + 10*\log[0.878 J_2^0(\beta_{tp})] - 10\log[1500/4] \quad (15)$$

$$PFD = EIRP - 10\log(4\pi d^2) + L_{atm} + 10*\log[0.122 J_2^0(\beta_{tp})] \quad (16)$$

4.2 Optimal MI Design of PB TM Signal

In case of PB TM the optimal modulation index is determined from link margin and PFD margin. According to the satellite position the link margins and PFD margins vary. The link margins are the worst at low elevation angle, and the PFD margin is the worst at 90 degree elevation angle. The worst link margin (10 deg.) and PFD(90 deg.) margin according to modulation indices are shown in (Figure 3).



(Figure 3). Mod Index vs. Link and PFD Margin of PB TM

From the (Figure 3) optimal modulation index of PB TM is known as 1.92 radians. And carrier and Eb/No link margin and PFD margin of PB TM are 3.15 dB, 5.349dB, and 3.15dB respectively.

The optimal modulation indices of RT TM and range tones according to KOMPSAT conditions are derived from references [3, 6]. So modulation index of RT TM is 1.0 radian, command is 1.0 radian, major and minor range tones are same with 0.4 radians. The KOMPSAT modulation indices were determined by these analyses.

5. Receiving Data Performance According to Satellite Pass Time

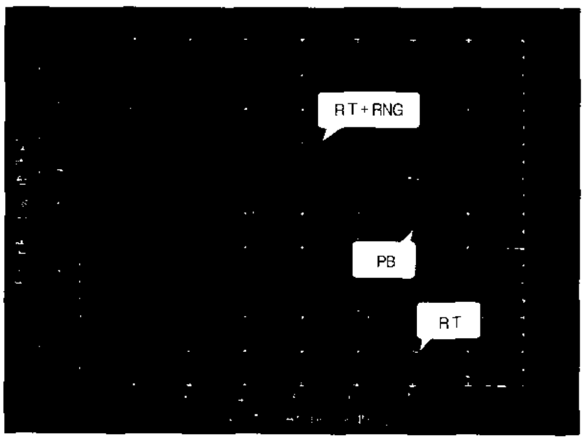
5.1 Link Margin and PFD Margin of Downlink

The link margins of carrier SNR, data Eb/No, and range S/No are calculated according to transmission modes. These are the factor of receiving performance. Where the link margin of RT+RNG is the worst value at 10 degrees elevation angle and the PFD margin of RNG only is the worst value at 90 degrees elevation angle. These results are listed in <Table 4>.

〈Table 4〉 Link and PFD Margin of Downlink(Worst Case)

Mode	Margin	Carrier	Data	Range
RT only	Link	5.83	7.62	-
	PFD	3.37	5.03	-
PB only	Link	3.15	5.34	-
	PFD	3.15	8.56	-
RT+RNG	Link	2.21	4.00	14.23
	PFD	6.90	5.64	17.51
RNG only	Link	8.16	-	20.18
	PFD	2.16	-	12.77

5.2 BER of Receiving Data according to Sat. Moving



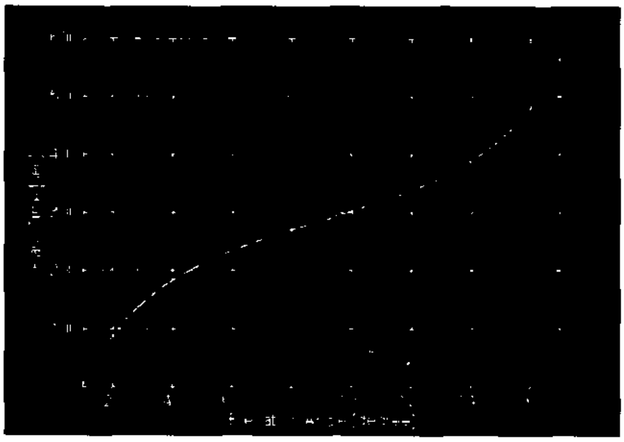
(Figure 4) Error Probability According to Elevation Angle

Generally, error probability (Pe) of receiving data is determined by well-known Eq. (17). So we may obtain the Pe according to elevation angle as (Figure 4) by Eq. (4) and (17).

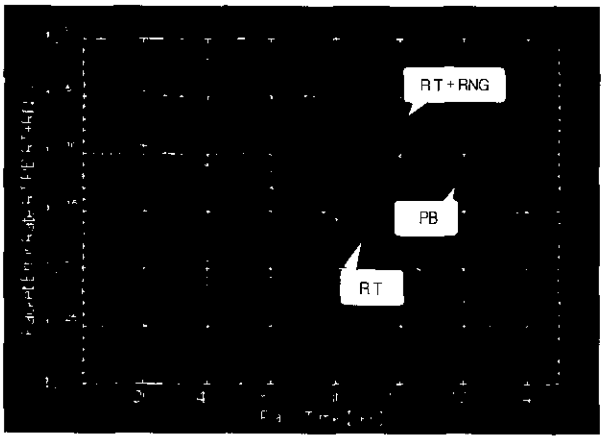
$$P_e(\varepsilon)=\frac{1}{2}\times[1-erf(\sqrt{E_b/N_o(\varepsilon)})] \qquad (17)$$

5.3 EFP Ratio According to Satellite Pass Time

From the reference [7, 8] the relation ship between elevation angle vs. satellite pass time may be derived as (Figure 5), where the altitude of satellite is 685km.



(Figure 5) Relations between Elevation Angle and Satellite Pass Time



(Figure 6) Packet Error Rate According to Pass Time

In case of packet communications, the packet more than 1 bit error is discarded. Therefore packet error rate (PER) is represented as Eq. (18), where PL is 1 packet length (bits) and r is error bits within 1 packet. (Figure 6) shows PER of RT, PB, and RT+GNG according to pass time. From the results of (Figure 4) and (Figure 6) we know that RT TM mode has the best performance and RT+RNG mode has the worst performance. For example, if the reference PER is lower than 10^{-7}, RT TM may be chosen at AOS time from (Figure 6), PM TM after 60 seconds from AOS time, and RT+RNG after 110 seconds from AOS time.

$$PE(\varepsilon) = \sum_{r=1}^{PL} {}_{PL}C_r [P_e(\varepsilon)]^r [1 - P_e(\varepsilon)]^{PL-r} \tag{18}$$

6. Conclusion

In this paper, the determination method of optimal PM modulation index has been derived, and the link and PFD margins according to 4 transmission modes analyzed for carrier, TM data, and range. Since the PB TM data and carrier occupy the same bandwidth the PB TM acts as a noise signal to the carrier. So carrier vs. PB TM data power ratio for carrier link margin calculation of PB TM signal have been analyzed. And Pe and PER of receiving data have been derived.

Applying the KOMPSAT satellite parameters, the optimal modulation index of PB TM was 1.92 radians, carrier and PFD margins of PB TM were 3.15 dB respectively. Eb/No margin of PB TM was 5.34dB, and other results were shown in <Table 4>. All margins were over 2dB. So these margins are large enough to receive telemetry and range tones, and are within the PFD regulations. The results of Pe and PER show that the best performance is RT TM mode and the worst performance is RT+RNG mode as shown in (Figure 4) and (Figure 6). Therefore, to obtain the best operation, transmission sequences of TM data are determined such as Pe or PER sequence, namely, RT, PB, and RT+RNG mode.

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