Improvement of Communication System for 1U CubeSat

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ABSTRACT

The Joint Global Multi-Nation Birds Satellite project abbreviated as "BIRDS" project started with a first-generation constellation of five 1U satellites in October 2015. Currently, BIRDS project is on its fourth-generation of CubeSat constellation. The 1U CubeSats in each generation follow the heritage of the previous satellites. The Communication subsystem has undergone multiple iterations to improve the performance on orbit. Until the second-generation of satellites (BIRDS2 CubeSat constellation), the two-way communication between the satellite in orbit and the ground station was difficult even though the ground test results seemed promising. BIRDS3 satellites went through major changes and succeeded in establishing a strong link between the satellite and the ground station. This paper describes findings that were made based on the on-orbit test results of the previous satellites that caused difficulty in the communication and some of the major changes that were made on both the BIRDS3 satellite side and the ground station side to improve the communication. BIRDS3 satellites have been operating exceptionally better in the orbit. The orbital link measurement result is also included in this paper.

INTRODUCTION

The Joint Global Multi-Nation Birds Satellite project abbreviated as "BIRDS" project started with a first-generation constellation of five 1U CubeSats in October 2015. This is a satellite development project in which students from developing countries get a hands-on experience in developing and operating satellites as a first step towards indigineous space activities in their countries after they return. Some of the participating countries developed the first satellite for their countries. Currently, BIRDS project is on its fourth-generation of CubeSat constellation. Eleven CubeSats have been developed and put in orbit until now, three more satellites, BIRDS4, are complete and ready for delivery as of June 2020.

The 1U CubeSats in each generation follow the heritage of the previous satellites with minor changes in the bus system to improve and to accommodate newer missions. One of the subsystems that have undergone multiple iterations is the Communication Subsystem. Until the second-generation of satellites (BIRDS2 CubeSat constellation), the two-way communication between the satellite in orbit and the ground station was difficult even though the ground test results seemed promising. The BIRDS3 CubeSats were released from ISS on June 17, 2019. During BIRDS3 CubeSats development thorough investigation was made on the communication issues and major changes were incorporated to eventually succeeded in establishing a strong link between the satellite and the ground station.

This paper describes findings that were made based on the on-orbit test results of BIRDS-2 satellites that caused difficulty in the two-way communication. The improvements made both on the BIRDS3 CubeSat side and the ground station (GS) side is also described with the net link budget improved after each change.

Improvement Points from BIRDS2 to BIRDS3

There are two main areas of improvement for the improvement of communication in a CubeSat, the satellite side and ground station (GS) side. The changes that were made are listed in Table 1. Each of these changes will be detailed in the following sub-sections.

Table 1: Improvement Points from BIRDS2 to BIRDS3

CubeSat Side	
A.	Change from monopole antenna to dipole antenna
B.	Improvement of ground plane
C.	EMI countermeasures
Ground Station Side	
D.	Change from linear polarization antenna to circular polarization antenna
E.	Change transceiver from radio (IC-9100M) to signal generator (SG)
F.	Increased in RF output power; from 14W to 50W
G.	Decrease in baud rate: from 9600bps to 4800bps
H.	Decrease in number of uplink command byte: from 33 byte to 14byte

To calculate and improve the link budget, the antenna gain, the transmission power level and the required threshold power at the transceiver at which it is possible to decode the signals are important parameters. The list of improvements made in the BIRDS2 communication system in Table 1 is categorized based on the parameter each of these changes were focused on improving. This categorization is listed on Table 2.

Table 2: Link Improvement from BIRDS2 to BIRDS3

No.	Content	Points
1	Antenna gain of GS	D
2	Uplink power	F
3	Required power at CubeSat receiver	A, B, C, G, H
4	Improvement at GS transceiver	E

A. CHANGE FROM MONOPOLE ANTENNA TO DIPOLE ANTENNA

BIRDS2 CubeSat had two monopole antennas, one was for main communication and the other one for Store and Forward mission. The main communication frequency band was UHF and the mission frequency band was VHF[1]. BIRDS3 CubeSat has one dipole antenna; its frequency band is also UHF. BIRDS2 and BIRDS3 CubeSat models are shown in Figure 1.

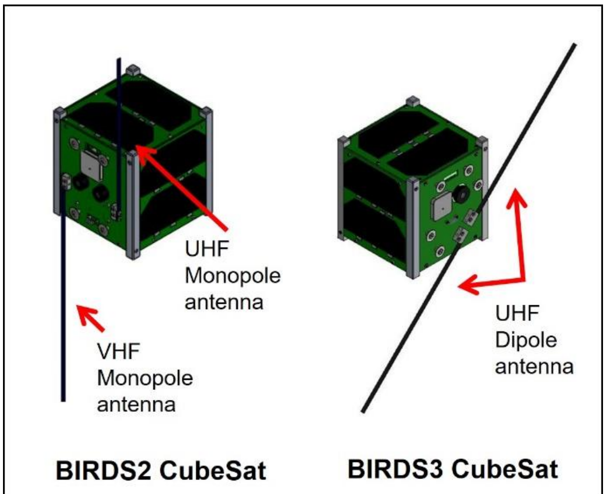
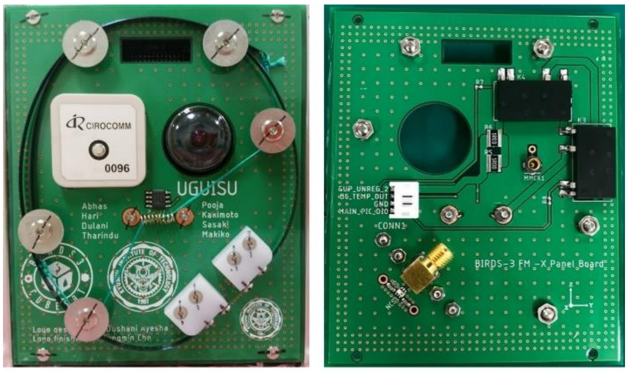


Figure 1: Models of BIRDS2 and BIRDS3

The antennas are encompassed in FR4 Printed Circuit Board (PCB) on one face of the CubeSat. The deployment mechanism of these antennas was discussed in the paper[2]. Monopole antenna requires ground (GND) of sufficient size to function as a monopole antenna, but BIRDS2 antenna panel board which is shown in Figure 2 did not have enough size of GND. Dipole antenna does not require specific size of GND and 1U CubeSat is too small to have enough size of GND, therefore in BIRDS3 CubeSat the antenna was changed from monopole antenna to dipole antenna. The BIRDS3 antenna panel board is shown in Figure 3.

Outside of Panel Inside of Panel

Figure 2: BIRDS2 Antenna Panel Board



Outside of Panel Inside of Panel

Figure 3: BIRDS3 Antenna Panel Board

Dipole Antenna Design Improvement

There are few points to be careful about when designing dipole antenna board as listed below:

I) The dipole antenna connector must be placed in the area where the overlap with the substrate of board is minimized, and the length of the antenna overlapped with the substrate of board is aligned both on the left and right.

II) Proper impedance matching circuit must be designed using balun. The matching circuit is shown in Figure 4.

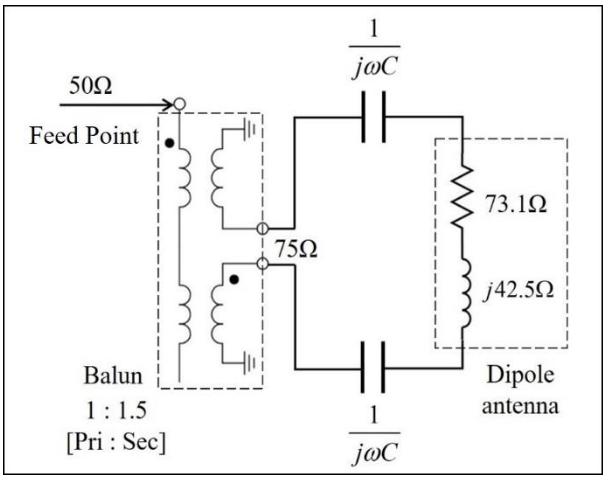


Figure 4: Impedance Matching Circuit

III) The line from the SMA connector to the balun must be designed considering the coplanar waveguide. The waveguide must be designed to be straight and as short as possible. The coplanar waveguide is shown in Figure 5.

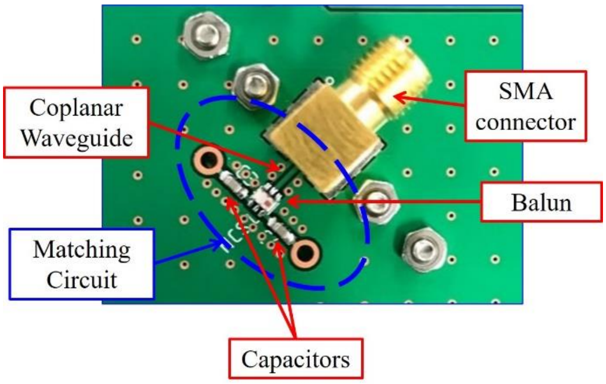


Figure 5: Coplanar Waveguide and Matching Circuit

B. IMPROVEMENT OF GROUND PLANE

The improvement of ground plane is also an important change for design of the dipole antenna board.

I) The GND plane must be laid as much as possible to minimize the effect of noise from inside of the CubeSat. The dipole impedance matching circuit is laid down on inside of panel as shown Figure 3. To have better performance in that circuit, the ground plane layer is needed. The ground plane layer is needed for the coplanar waveguide transmission line.
Also, BIRDS2 antenna panel design should have had larger GND plane since BIRDS2 antenna is monopole antenna, the sensitivity of the antenna gets affected. Noise can come to monopole antenna, and also the impedance matching of monopole antenna can be bad.

II) Via is a drill in the PCB which connects multiple GND plane layer. Enough GND vias must be placed on the board to stabilize the GND potential and minimize the effects of GND noise.

C. EMI COUNTERMEASURES

During the testing of Engineering Model (EM) of BIRDS3 CubeSat in the Anechoic Chamber, it was confirmed by the spectrum analyzer (SA) that the EM had high noise floor level. On further investigation it was found that the source of the noise is from DCDC converter of On-Board Computer/ Electric Power System (OBC/ EPS) board and Front Access Board (FAB). The DCDC converters generated switching noise. To reduce the effect of noise from DCDC converters, OBC/ EPS board and FAB were covered with aluminum tape and the tape was grounded. The boards were shielded as shown in Figure 6, Figure 7.

Figure 6: Shielded DCDC Converter of OBC/EPS Board

Figure 7: Shielded DCDC Converter of FAB

IMPROVEMENT OF GROUND STATION SIDE

D. Change from Linear Polarization Antenna to Circular Polarization Antenna

Linear polarized antenna was used in GS until BIRDS2 CubeSat Constellation, but it was unable to send successful uplink commands to the satellite. Therefore, the antenna was upgraded. This measure was implemented in order to improve the communication link as much as possible. Up to BIRDS3 CubeSats, no active attitude control system was implemented in the satellites. Therefore, there is approximately 3dB loss due to the antenna polarization loss. Circularly polarized antenna was then installed to solve this problem. The antennas are shown in Figure 8.

The gain of the linear polarized antenna was 18dBi whereas the gain of circular polarized antenna is 22dBi. It was improved by **4dB** from BIRDS2 to BIRDS3. In BIRDS3 case, the antenna polarization loss of 3dB is included in the calculation to estimate the worst case in the link budget.

Linear Polarization   Circular Polarization

Figure 8: Linear and Circular Polarization Antenna

E. Changed Transceiver from Radio to Signal Generator

It was also taken into consideration that it was difficult to succeed in sending uplink commands using a radio. The radio has Band Pass Filter (BPF) inside of the hardware, and it was considered that the waveform was distorted by BPF. Therefore, the signal generator (SG) was used to transmit commands instead of radio. SG is able to generate more accurate waveform than radio. To output higher power, SG and the power amplifier were used together.

F. Increased the Output Power

For the frequency co-ordination, BIRDS2 CubeSats applied and got accepted with an allowable output power of 14W(41.5dBm) from the GS. On the other hand, for BIRDS3 CubeSats the output power was changed to 50W (47dBm). It was improved by **5.5dB** from BIRDS2 to BIRDS3.

G, H. Decrease in Baud Rate and Number of Uplink Command Bytes

The slower the baud rate and the fewer the number of uplink command bytes, the higher the uplink success rate. To increase the uplink success rate, BIRDS3 changed the baud rate from 9600bps to 4800bps and the number of uplink command bytes from 33bytes to 14bbytes.

LONG-RANGE TEST OF BIRDS2 AND BIRDS3

Outline

Before doing the Long-Range Test (LRT), the antenna radiation pattern and the sensitivity of the receiver in fully assembled CubeSat is measured in the anechoic chamber. LRT is done to confirm the communication in an environment closer to the communication between space and the ground. The CubeSat was taken to the top of the mountain within the line of sight from the GS. The communication range of the anechoic chamber is 3.7m, and the range of LRT is 6.4km. Additional attenuators were added on the GS side to make an equivalent path loss between the satellite in orbit and GS.

Method

To compare the performance of radio and SG uplink, both of them were used for the LRT. The block diagrams of GS side setup are shown in Figure 9 and Figure 10. Also, CubeSat side setup is shown in Figure 11.

LRT is done by the following method:

1. Uplink commands from GS to CubeSat about ten times at each variable attenuator value. The uplink power is 47dBm (50W). In the SG setup case, uplink command from 1st GS antenna as shown in Figure 9.
2. Count the success rate of uplink at GS by recording the number of times acknowledgement is received from CubeSat. At the same time, measure the received RF power at CubeSat. In the SG setup case, receive acknowledgement at 2nd GS antenna.
3. Continue the measurement until the uplink success rate becomes from 100% to 0% while changing the variable attenuator value.

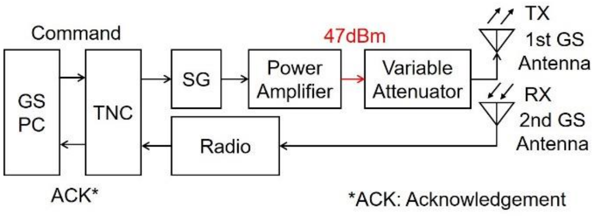


Figure 9: GS Setup for Uplink with SG and Power Amplifier

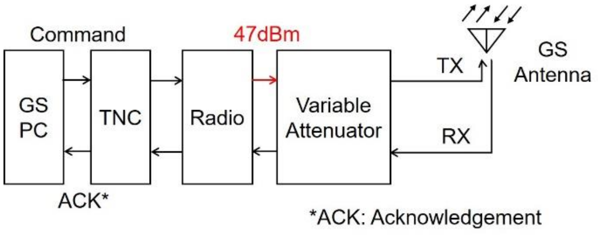


Figure 10: GS Setup for Uplink with Radio

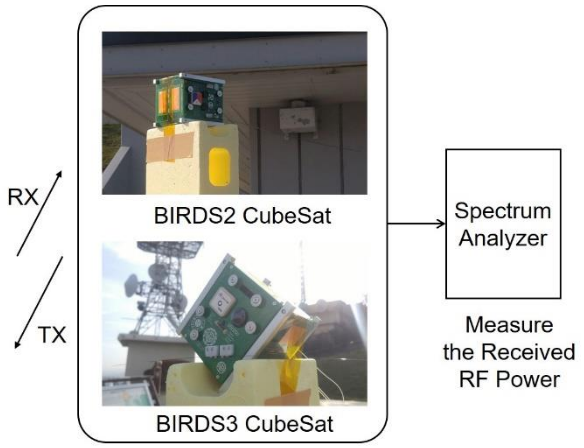


Figure 11: CubeSat Setup at Top of the Mountain

Results

The result of BIRDS2 and BIRDS3 CubeSat is shown in Table 3 and the data is plotted in Figure 12 where the received power range is from -100dBm to -80dBm. Uplink success rate of over 60% was considered to estimate required power to decode the uplink command inside the CubeSat from Figure 12.

Table 3: Result of BIRDS2 and BIRDS3 CubeSat

Received power at CubeSat [dBm]	Total effective attenuation [dB]	Success rate [%]		
		BIRDS2 SG setup	BIRDS3 SG setup	BIRDS3 radio setup
-64	109	100	-	-
-74	119	67	-	-
-77	122	100	-	-
-82	127	-	-	70
-83	128	100	-	-
-84	129	-	-	60
-85	130	-	100	90
-86	131	-	-	60
-87	132	100	-	-
-88	133	-	83	80
-90	135	0	100	50
-92	137	-	80	70
-93	138	0	-	20
-94	139	0	-	20
-95	140	-	50	-
-96	141	-	0	-

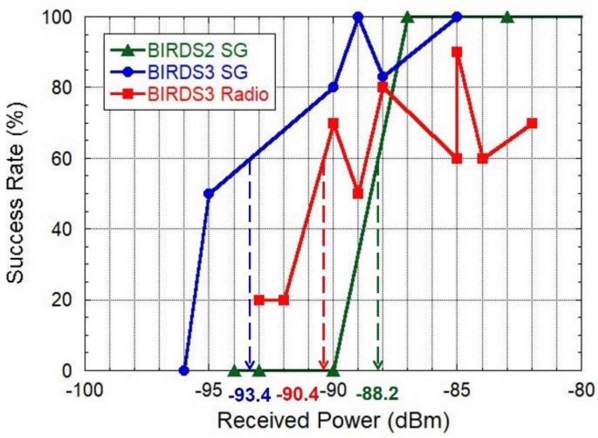


Figure 12: Result of BIRDS2 and BIRDS3 CubeSat

The required power for BIRDS2 using SG setup was -88.2dB, for BIRDS3 using SG setup was -93.4dB and BIRDS3 using radio setup was -90.4dB. It was improved by **5.2dB** from BIRDS2 SG setup to BIRDS3 SG setup. It corresponds to improvement of No.3 in Table 2.

Comparing BIRDS3 radio setup and BIRDS3 SG setup, the improvement of gain from radio to SG can be known. According to the result of Figure 12 when SG setup is used for this communication, it was improved by **3dB** compared to radio setup. It corresponds to improvement of No.4 in Table 2.

LINK BUDGET CALCULATION

BIRDS3 needed to improve the link budget for uplink. The parameters for link budget improvement from BIRDS2 to BIRDS3 are listed up again with the summarized value of the improved gain value in Table 4.

Table 4: Summary of Link Improvement from BIRDS2 to BIRDS3

No.	Content	Gain [dB]
1	Antenna Gain of GS	4
2	Uplink Power	5.5
3	Required Power of CubeSat Receiver	5.2
4	Improvement by GS Transceiver	3
Total Gain		**17.7**

It was shown that BIRDS3 succeeded to improve link budget by **17.7dB** from the ground test result.

ACTUAL LINK OF BIRDS3 CUBESAT ON ORBIT

To know the effective attenuation between GS and BIRDS3 CubeSat in orbit, the CW power received from CubeSat after the satellite release into orbit was measured by spectrum analyzer at GS as shown in Figure 13.

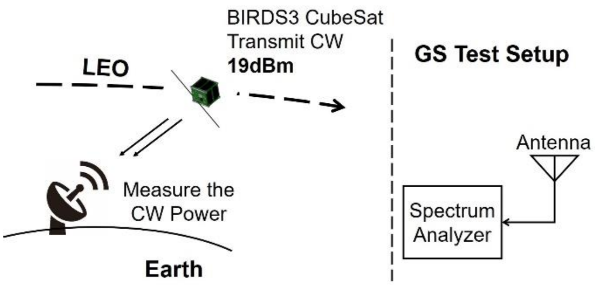


Figure 13: Setup of the CW Measurement Test

The received CW powers from the orbit were measured at 9-degrees and 49-degrees of elevation. Table 5 shows the measurement and theoretical values at 9-degrees and 49-degrees.

Table 5: Measurement and Theoretical Values at 9-degrees and 49-degrees

Contents		Unit	9-degree	49-degree
Measurement value	Pr	dBm	-117	-108
	ATTe	dB	136	127
	Ge	dB	-	12.7
Theoretical value	Distance	km	1528	530
	Lpath	dB	148.9	139.7
	ATTe	dB	136.2	-
	Ge	dB	-	12.5

Pr is the received power from CubeSat, ATTe is the effective attenuation value of the link, Ge is the effective gain of the link, Distance is the distance between GS and CubeSat, and Lpath is free space path loss. Distance was calculated using the elevation, and the Lpath was calculated by Equation (1).

$$Lpath = 32.44 + 20\log_{10} F + 20\log_{10} d \quad (1)$$

F[MHz] is the communication frequency, BIRDS3 CW frequency is 437.375MHz[3], therefore this value was substituted to F. d[km] is the communication distance which is Distance in Table 5.

BIRDS3 CubeSat transmitted CW at 19dBm, the value comes from the measurement before launching to the space. The measured effective attenuation is calculated by subtracting the measured received power from the transmitted power from CubeSat in decibel notation. In 49 degree, the received power is -108dBm. Then the effective attenuation is 19-(-108)=127dB. The measured effective gain is calculated by subtracting the effective attenuation from the free space path loss. The measured effective gain for 49-degrees elevation is 139.7-127=12.7dB.

Then, the theoretical effective gain at 49-degree was calculated. Figure 14 gives the overview of the link budget. Pt is the transmitted power by CubeSat and Pr is the received power at GS. The 19dBm of Figure 13 corresponds to Pt and the measured CW power at the spectrum analyzer corresponds to Pr. The effective gain: Ge is calculated by Equation (2) by using the assigned values as shown in Table 6.

$$Ge = Gsat - (Lai + Lp + Lant + Lc) + Ggs \quad (2)$$

Table 6: Assigned Value of Equation (2)

Name	Contents	Value
Gsat	CubeSat antenna gain	1.1
Lai	Atmospheric and ionospheric loss	1
Lp	Antenna polarization loss	3
Lant	GS antenna pointing loss	3
Lc	GS antenna cable loss	3.6
Ggs	GS antenna gain	22

The theoretical effective gain at 49-degrees is 12.5dB and the measured effective gain is 12.7dB, therefore this power measurement using CW can be considered as the correct measurement method.

This power measurement using received CW was reconfirmed in another way. The theoretical effective attenuation at 9-degrees is calculated by adding the measurement of effective attenuation at 49-degrees and the difference in the free space path loss at 49-degrees and 9-degrees, which is (127+148.9-139.7). The value was 136.2dB and the measured effective attenuation was 136dB, therefore it was reconfirmed that this power measurement using CW can be considered as the correct measurement method.

From these results, the link budget for radio setup and SG setup was calculated based on 49-degrees measurement result as shown in Table 7. The output power of GS is 50W. The link margin calculation is based on the required powers of radio and SG which are shown in Figure 12.

Table 7: Orbital Link Budget of BIRDS3

Elevation angle [degree]	0	6	9	49	90
Free space path loss [dB]	152.6	150.1	148.9	139.7	137.5
Calculated effective attenuation [dB]	139.9	137.4	136.2	127	124.8
Received power to CubeSat [dBm]	-92.9	-90.4	-89.2	-80	-77.8
Link margin of radio setup [dB]	-2.5	0	1.2	10.4	12.6
Link margin of SG setup [dB]	0.5	3.0	4.2	13.4	15.6

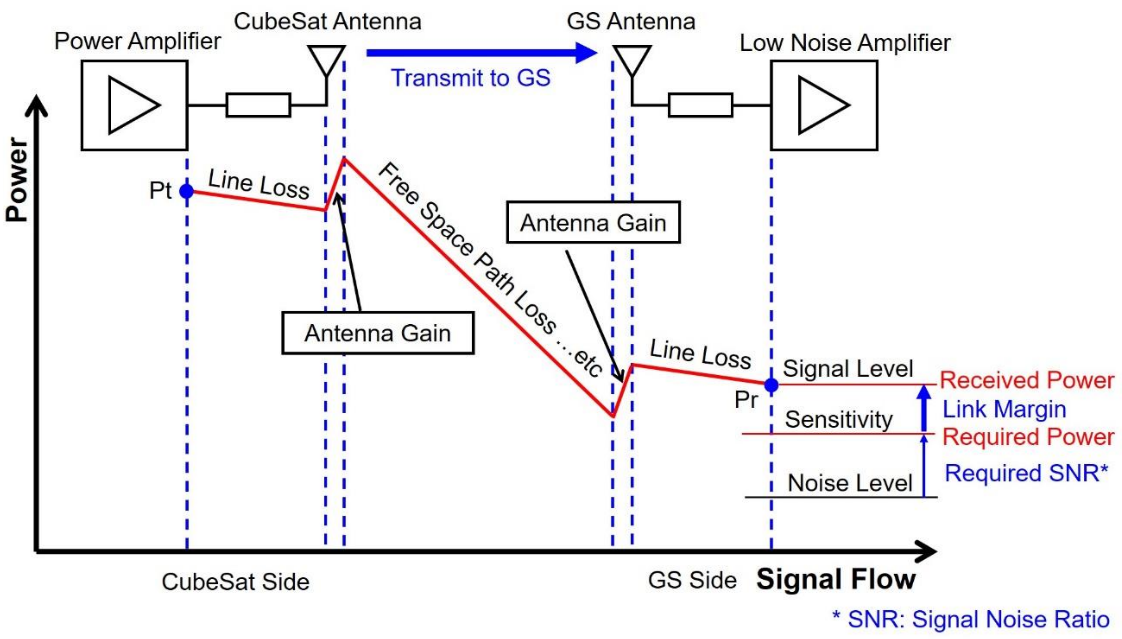


Figure 14: Link Budget Overview

It can be concluded that BIRDS3 CubeSats can communicate with GS with both radio and SG setup except elevations less than 6-degrees for radio setup. However, on-orbit satellite could succeed in establishing communication at less than 6-degree of radio setup. It can be also considered that the required power values which are mentioned in the results of Long-Range Test were overestimated.

CONCLUTION

The link budget was improved by 17.7dB from BIRDS2 CubeSat to BIRDS3 CubeSat by investigating various parameters and implementing counter measures.

BIRDS3 CubeSat could communicate with the GS after its deployment in the orbit. Also considering the orbital link budget, BIRDS3 CubeSats could communicate with not only SG setup but also with radio setup.

Acknowledgments

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