

Dual circularly polarization X band 2Gbps downlink communication system of earth observation satellite

Tomoki Kaneko
The University of Tokyo
7-3-1, Hongo, Bukyo-ku Tokyo, 113-8656 Japan; 81-42-759-8104
kaneko.tomoki@ac.jaxa.jp

Hirobumi Saito, Makoto Mita,
Japan Aerospace Exploration Agency, Institute of Space and Astronautical Science
3-1-1, Yoshinodai, Chuo, Sagamihara, Kanagawa, 252-5210 Japan; 81-50-3362-2657
saito.hirobumi@jaxa.jp

Yasuhiro Ohikata
Mebius Corporation
2-10-27 Kitasaiwai, Nishi-ku, Yokohama, Kanagawa, 220-0004, Japan; 81-45-290-0135
y_ohikata@mebius.co.jp

ABSTRACT

We are developing 2.8Gbps down link in X band (8025-8350MHz) from small SAR observation satellites. The modulation is 64APSK of DVB-S2X with symbol rate of 300Mpsps. Dual polarization channels are applied to the system. We have tested an engineering model of the transmitter, and the on-board antenna with high cross-polarization discrimination (XPD). The ground antenna with high XPD is also developed. This down link system will be demonstrated in 2019 by JAXA advanced small satellite.

1 INTRODUCTION

Technologies of small satellites have so rapidly developed that many earth observation missions with small satellites are developed. Especially constellations of small earth observation satellites are significant. In constellation missions [1-3], several tens to several hundred small earth observation satellites are launched to observe any places on the earth with very short observation intervals. Then image data taken from the orbit have to transmit quickly to earth stations with a low cost. Since the number of satellites is very large, frequency-band-efficient data down link seems critical at any frequency bands. Small satellites have only limited mass and power resources and onboard instruments should be light-weighted and low-power consumed.

Another type of a small earth observation satellite is a responsive mission [4-6]. Just after a natural disaster or a sudden security issue occurs, a small synthetic aperture radar (SAR) satellite is responsively launched into a relatively low-altitude orbit that is suitable for observation of the specific area. The SAR observation is conducted immediately after launch and the SAR observation data is transmitted to the ground station. In general SAR observation has larger volume of data than optical observation. The down link communication link should be robust for rain in order to be responsive for a

natural disaster. Therefore we have to select a frequency band that is robust for rain/cloud attenuation.

Conventionally medium/large earth observation satellites utilize radio frequency X band (8025-8400 MHz, 375MHz width) for their observation data down link with 300-600M bit per second with use of full bandwidth of 375MHz. Their modulation methods are mainly quadrature phase shift-keying (QPSK), 8 phase shift-keying (8PSK) since these phase modulations keep an advantage of constant envelope and can avoid a problem of power amplifiers' nonlinearity. A large earth observation satellite, Worldview 3 utilizes dual polarization (RHCP and LHCP) channels in X band with 8PSK modulation and symbol rate of 200Mpsps, achieving totally 1.2Gbps down link [1]. A small earth observation satellite, Skysat has three down link channels of 8PSK modulation with 45Mpsps, achieving totally 400Mbps [7]. Dove satellite constellation utilizes DVB-S2 X band down link with QPSK-32APSK, 220-320Mbps [8,9]. In 2014, Japan launched two earth observation satellites ALOS-2 [10] and ASAR [11], which utilize 16 quadrature amplitude modulation (16-QAM) with 800 Mbps in X band with use of full width of 375MHz.

The merits of X band are small RF attenuation due to rain and technology maturity. The demerits of X band are relatively narrow bandwidth (375MHz) and frequency license issue.

Another candidate is Ka band (25,500 ~ 27,000 MHz 37,500 ~ 40,500 MHz). We can utilize its wide band and it may be easy to obtain frequency license in Ka band. However, technology of Ka band is not matured yet and it suffers from large rain attenuation. There have not been practical down link systems of earth observation that utilize Ka band yet.

Taking the frequency issue into account, we select X band in this development. It is because our target mission is the responsive SAR mission where the down link should be robust to heavy rain condition. Also in our mission, down link sites may be in Japan territory due to security reason. It seems easy to obtain frequency license in X band.

Therefore, the purpose of this research is to develop an extremely high-data-rate (typically 2-3Gbps) in X band which is almost practical limit in state of the art. We utilize high frequency-band efficiency modulations such as Amplitude Phase Shift Keying (64 APSK) and dual polarization channels.

2. HIGH SPEED COMMUNICATIONS SYSTEM

In this section we describe high-data-rate down link system as shown in Fig.1, including an onboard RF amplifier and a transmitter, onboard dual polarization antennas, a dual polarization X band ground station, and a demodulator. Table 1 summarizes our novel communication system with high data rate for small

Table1. Down Link System Summary

System	Frequency	8025-8340MHz
	Occupied Bandwidth	315MHz
	Symbol Rate	300Mpsps
	Com. Standard	DVB-S2X(LDPC)
	Modulation	QPSK-64APSK option 256APSK
	Pol. Channel	RHCP/LHCP 2ch
OnBoard	H/W System XPD	>33dB
	Com. Speed	max 2.9Gbps/2ch
	TX RF Power	1W/ch
	DC Power	75W/2ch
	TX Size	200x200x200mmm ³
	TX wight	6kg
Ground	TX Antenna	Corrugated Horn
	TX Ant. Gain	17dBi
	TX Ant.XPD	>37dB
	RX Antenna	10m, Cassegrain
	RX Ant.Gain	56.6dBi at Pol input
	RX Ant. XPD	>36dB
LNA Noise Tem.	5k in 18K Cooler	
Sys. Noise Tem.	55K at EL90deg	

satellites.

2.1 Communication Standard DVB-S2X

DVB-S2X is a relatively new standard of satellite communication [12]. DVB-S2X is an extension version of DVB-S2 that has been mainly applied to Geostationary broadcasting and communication

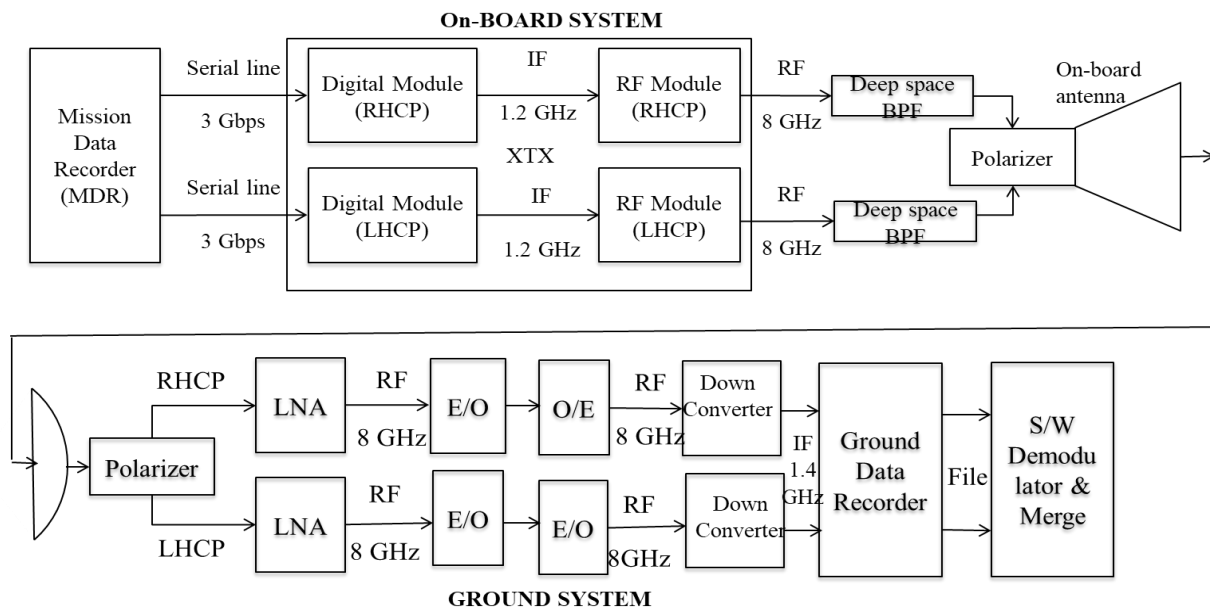


Fig.1 System bolock of high speed down link. Upper part is on-board segment and lower part is ground segment.

satellites. DVB-S2X includes several advanced technologies for high frequency efficiency unlike other standards. It contains wide range of modulation from QPSK to 256APSK and roll-off coefficient $\alpha=0.05$ of SRRC filter. Satellite communication with $\alpha=0.05$ SRRC filter has been firstly demonstrated by Nippon Television Network in 2014. We select this DVB-S2X for our high speed down link system since it is suitable for communications with high frequency-efficiency.

Demodulators compatible to DVB-S2X with low cost are widely in market for medium communication speed less than 300Mbps. However, there are no commercial demodulators for higher bit rate than 1Gbps as long as the authors know. Therefore we have been developing the on-board transmitter and the ground demodulator in parallel. Unfortunately there is no reference transmitter for DVB-S2X. Communication simulation tool 89600VSA based on SystemVue of Keysight has DVB-S2X transmitter and receiver software library E4729A [13]. Therefore, we utilize 89600VSA and SystemVue as a reference transmitter and a reference receiver in our development.

The required E_s/N_0 with bit error rate of 10^{-5} is 14-16dB for ideal linear channel and 18-21dB for non-linear hard limiter channel of various 64APSK modulation of DVB-S2X standard [12].

2.2 Symbol Rate and Protection for deep space band

Frequency band of 8025-8400MHz is allocated for down link of earth observation. The band width is 375MHz. Based on DVB-S2X, roll-off coefficient $\alpha = 0.05$ is selected to maximize symbol rate f_s . The maximum allowable symbol rate for this frequency band is given as $375\text{MHz}/(1 + \alpha) = 350\text{Msps}$.

However, there is a deep space down link band at 8400-8450MHz. International telecommunication Union (ITU) recommended the criteria for deep-space research ITU SA1157-1[14]. This document gives the maximum allowable interference that will not cause more than the acceptable degradation of earth-station receiver performance. The protection criteria for a deep-space earth-station receiver at the receiver input terminals (LNAs) is -220.9dB(W/Hz) in 8400-8450MHz.

Our ground station is near Usuda Deep Space Center, JAXA, Japan, where there is the 64m diameter antenna (72.5dBi gain in X band). This requirement is very severe compared with usual frequency band allocation.

According to similar link calculation described in section 2.4, the Usuda Deep Space 64m antenna receives our down link in-band signal at level of -165dB(W/Hz). Therefore we have to suppress the out-of-band spectrum level by 56dB ($=-165\text{dB(W/Hz)} - (-220.9\text{dB(W/Hz)})$) compared to the in-band spectrum level.

The transmitter radiates a certain level of out-of-band spectrum at the neighboring frequency region. This level is determined mainly by inter-modulation due to third-order nonlinear distortion of the RF power amplifier in the transmitter. As described in section 3, we successfully suppressed the inter-modulation due to the third-order nonlinear distortion as low as -30dB compared to the in-band spectrum level.

Therefore we have to insert the dedicated filter that has the attenuation level of 26dB ($=56\text{dB}-30\text{dB}$) or higher at 8400-8450 MHz. A conventional coaxial band pass filter that is suitable for on-board instruments is found to have decay slope of attenuation as high as 5dB/10MHz. The stop band of the band pass filter starts at 8350MHz and then the attenuation level reaches 26dB at 8400MHz. Therefore the practically maximum allowable band of the down link is 8025-8350MHz with band width of 325MHz, taking into account the deep space band protection. We select symbol rate 300Msps which corresponds to frequency bandwidth of 300Msps $(1 + \alpha) = 315\text{MHz}$. The frequency band is allocated in 8025-8340MHz in order to avoid the group delay effect near edge of pass band.

2.3 Dual polarization

It is effective to utilize dual polarization to double the communication speed. Right-hand circular polarization and left-hand circular polarization can transmit independent information.

Cross-talk between two polarization channels degrades signal quality. Although interference (cross-talk) signal is not thermal noise, cross-talk signal gives similar degradation to the communication performance. It is possible to cancel the effects of the cross polarization interference in demodulation algorithm. However, their effect is not clear yet. In later phase of this development, we may introduce cross-polarization canceler in our demodulator system. However, as a secure way, we develop communication hardware with small cross-talk as much as possible.

XPD (Cross polarization discrimination) defined as a power ratio of main polarization signal to cross polarization power is an index to evaluate the cross-talk effect. When XPD is higher than the required signal-noise-ratio E_s/N_o for the communication channel without cross-talk, the cross-talk effect is not dominant in the communication link. Here, E_s is energy per one symbol and N_o is thermal noise spectrum density. The required E_s/N_o is 18-21dB for non-linear hard limiter channel of various 64APSK modulation of DVB-S2X standard [12].

It is reported that XPD of X band degrades in atmospheric propagation with rain condition [15-17]. Theoretical XPDs at the frequency of 8,185 MHz have been derived by ITU-R model [17] as 27dB, 23dB, 16dB under the conditions of clear weather, rain attenuation exceeded for 1% and 0.1 % of time, respectively. In the situation of 0.1% of time, the degradation of XPD in atmospheric propagation becomes more critical than the thermal noise effect in the non-linear hard limiting channel of various 64APSK.

In addition to atmospheric propagation, the on-board transmitting antenna and the ground receiving antenna may degrade XPD. In this research we develop the on board transmitting antenna and the ground receiving antenna with XPDs which are four times as high as XPD due to atmospheric propagation. This means that XPD due to atmospheric propagation in clear day is 27dB [17] and XPDs due to the on-board antenna and the ground antenna should be higher than 33dB, respectively. Total system XPD becomes 25.5dB (1.5dB degradation by the on-board and the ground antenna). In this research the target of XPDs of the on-board antenna and the ground antenna are higher than 33dB. When these conditions are satisfied, the total XPD 25.5dB at a clear day including atmospheric effect, the on-board and the ground antenna effects may degrade the required E_s/N_o by approximately 0.7-1.3dB in cases of 64APSK.

2.4 Link Calculation and Down Link Speed

The transmitter outputs down link signals with 64APSK5/6 (Modcode198, 1443Mbps), 64APSK11/15 (186, 1270Mbps), 32APSK32/45 (178,1040Mbps), 16APSK26/45 (154,675Mbps), QPSK(132,180Mbps). For example, 64APSK5/6(198,1443Mbps) means 64APSK modulation with Modcode 198 defined in DVB-S2X [12]. Its coding rate is 5/6 and its effective communication speed is 1443Mbps at 300

Table 2. Link Calculation

Orbit Altitude	km	628		
Elevation	deg	20	45	60
Center Freq.	MHz	8200		
Symbol Rate	Msps	300		
TX Power	dBW	-0.5		
Cable Loss	dB	2		
TX Ant. Gain	dB	17		
Prop. Loss	dB	174.2	169.6	168.1
Atmo. Loss	dB	0.5		
RX Ant Gain	dB	56.6		
Pointing Loss	dB	0.5		
Sys Noise Tem	K	55		
Received C/No	dB	107.1	111.7	113.2
Received Es/No	dB	22.3	26.9	28.4

Req.Es/No		
64APSK 5/6(198) (1443Mbps)	dB	20.4
64APSK11/15(186) (1270Mbps)	dB	18.0

Msymbol/sec. DVB-S2X standard [12] describes the required E_s/N_o for bit error rate of 10^{-5} based on non-linear hard limiter model as a power amplifier model.

We calculate the link budget of our down link. Table 2 shows the summary of the link budge for three elevation angles. Table 2 also shows these required E_s/N_o values. The link with 64APSK 5/6 have 4dB margin at elevation of 45deg when we neglect degradation of cross-talk of dual polarization channel. Degradation due to dual polarization may be as high as 1dB as described in 2.3.

We have two channels, right-hand circular polarization and the left-hand circular polarization. Total speed of the down link is 2.88 Gbps. It will be the highest down link speed that has ever reaches in X band.

3. ON-BOARD SYSTEM

3.1 On-board Instruments and Transmitter

On-board system consists of the transmitter, the deep space protection filter, and the transmitting antenna. Figure 2 describes the system block diagram. Figure 3 is photographs of the transmitter and the on-board antenna with the polarizer.

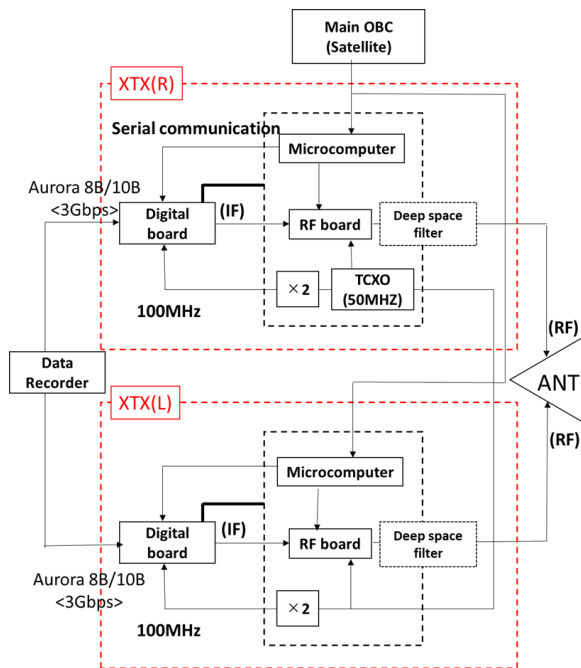


Fig.2 System Block Diagram of On-Board Instruments.

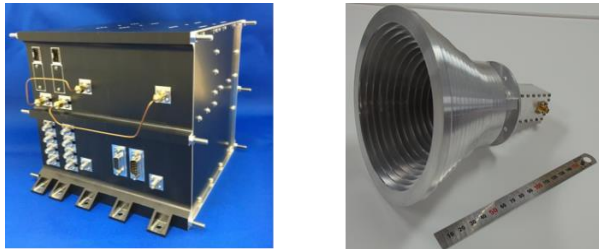


Fig.3 Photograph of transmitter (left) and antenna with polarizer (right)

The transmitter consists of two channels for right-hand and left-hand circular polarization. Each channel consists of a digital unit and an RF unit. There is a common power and control unit. The digital unit has a field programmable gate array (FPGA) with BGA instrumentation. The mission data recorder MDR sends high speed data with maximum 3Gbps speed to each channel. Data from the data recorder are mapped in I-Q constellation with various modulation 64APSK-QPSK at 300 Msps. Then I and Q channel signals are pulse-shaping-filtered with a square-root-raised-cosine FIR filter. Then the digital I and Q data are sent to the digital-to-analogue converter and the intermediate frequency (IF) of 1.2GHz is generated.

The analogue I and Q signals are sent to the RF unit. A PLL generates a stable local frequency 7GHz from a

crystal oscillator. The IF1.2GHz signal is up-converted to X band. Then the modulated X-band signal is amplified by driver amplifiers and the GaN HEMT two-stage power amplifier. The X band output signal is 29.5dBm. Then the X band output signal is sent to the band pass filter for deep space band protection.

Fig.4 is spectrum of the transmitter with modulation of 64APSK 5/6 (Modcode 186), symbol rate 300Msps. The dotted line is observed spectrum of the transmitter output without deep space filter. The broken line is transmission characteristics (dB) of the deep space filter. Solid line is spectrum of the transmitter with the deep space filter, which is obtained by subtracting the broken line from the dotted line. The deep space filter suppresses successfully out-of-band spectrum at 8400MHz by 58dB to protect the deep space band.

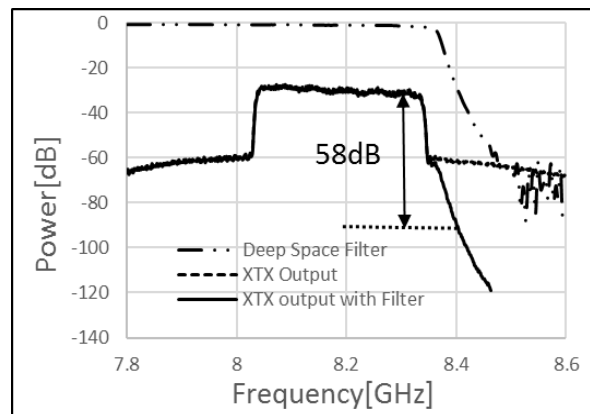


Fig 4 Spectrum of transmitter of 64APSK5/6, symbol rate 300Msps with filter (solid line) and without filter (dotted line). Broken line is transmitting characteristics of deep space filter.

In Fig.4, level difference between the in-band region (8025-8340MHz) and the out-of-band region around 8000MHz is about 30dB. This undesired floor is caused by the third-order non-linear intermodulation at this frequency region. This undesired floor may determine error vector magnitude (EVM) as an index of system performance without additive thermal noise.

The output from the transmitter and the band pass filter is down converted to IF frequency and is digitized by the oscilloscope. The digital data is demodulated by Keysight SystemVue DVB-S2X library. Figure 5 is a demodulated constellation of 64APSK 5/6 without additive thermal noise. The constellation is relatively clear and the measured EVM (error vector magnitude) is about -29dB, which is tightly connected with the undesired floor level.

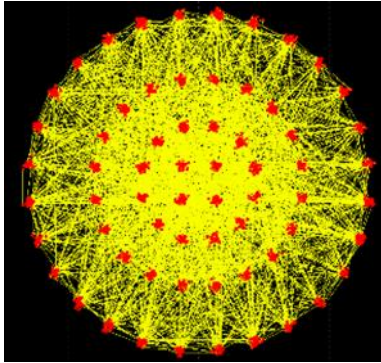


Fig.5 Demodulated constellation of 64APSK 11/15 with 300Mpsps. Measured EVM is about 28dB.

3.2 On-board Antenna

We utilize two channel of right-hand and left-hand circular polarization in order to double down link communication speed. It requires an on-board transmitting dual band medium gain antenna with high XPD. We have developed a corrugated horn antenna with a septum type polarizer. It is well known that a circular corrugated horn antenna is suitable for wide band medium gain antenna with high XPD characteristics [18]. Hybrid mode of TE_{11} mode and TM_{11} mode in a circular corrugated horn antenna provides with linear polarization that has identical distribution in E-plane and H plane. The antenna gain is 17dBi for right-hand and left-hand circular polarization. The size is 140mm in diameter and the length is 104mm. It is not practically difficult to obtain high XPD ($XPD > 40dB$) of a corrugated horn antenna.

Therefore XPD of the on-board system is mainly determined by a polarizer, which is a transducer from two coaxial connector ports to a square waveguide. An adequate polarizer is a septum polarizer for this purpose [19]. We have designed the septum polarizer with ANSYS HFSS simulator [20] and manufactured ones. We measured the total XPD and the gain of the corrugated horn antenna with the septum polarizer. The measured gain of the dual circularly polarized wave antenna is 17dBi, and the measured 3dB angle width is 12.7° . We measured the axial ratio of the corrugated horn antenna to determine its XPD. The pyramid horn antenna transmits linear polarized wave. The corrugated circular horn antenna receives two circular polarization components. The azimuthal angle of transmitting pyramid horn antenna rotated 360° on a boresight axis per 1° . At each azimuthal angle, we measured the receiving antenna gain. The measured

values of axial ratio are converted to XPD values. Figure 6 shows the measured and the design values of XPD as functions of frequency. Figure 6 indicates 37dB~43dB XPD in the bandwidth.

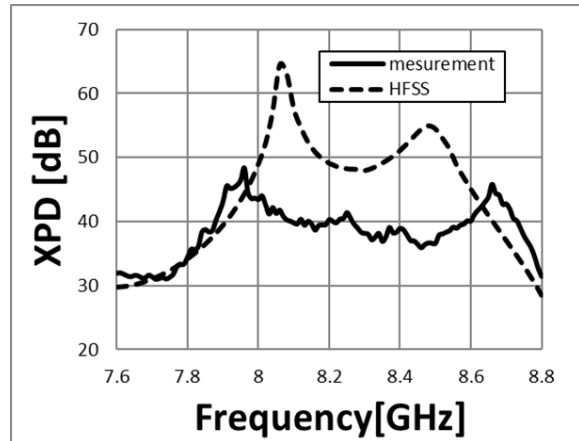


Fig.6 Cross Polarization Discrimination (XPD) as function of frequency. Dotted line is simulation. Solid line is measured value.

4. GROUND SYSTEM

4.1 Ground Antenna

Our down link system requires very high XPD performance since the system utilizes dual polarization channel for high frequency efficiency. Mostly conventional ground stations have XPD of 20-25dB that is not enough for demonstration of our new down link system.

We have been modifying an existing 10m antenna at JAXA, Usuda deep space station. This 10m antenna was constructed in 1980s for Ku band data link of space VLBI mission "HARUKA". The 10m antenna is a Cassegrain antenna with modified dish surface. We converted this Ku band antenna to X band antenna with high XPD by replacing the primary horn antenna. Figure 7 is a photograph of the 10m antenna.

Candidates of the primary feeder antenna are corrugated horn antennas and dual-mode horn antennas [18]. Corrugated horn antennas have better XPD performances of frequency bandwidth and beam angle width than dual-mode horn antennas. However, the primary feeder antenna is large (220mm in diameter, 450 mm in length). A corrugated horn antenna with such large size costs much. On the other hand, a dual-mode horn antenna

has high XPD performance in the bore sight direction while its XPD degrades in the off-axis direction. However, cross-polarization components from the primary feeder antenna in the off-axis direction are almost canceled out in the far field pattern of the Cassegrain antenna due to axial symmetry. XPD performance of the primary feeder in the bore sight direction is critical in case of a primary feeder of axial symmetric Cassegrain antenna application. Therefore, a dual-mode circular horn antenna was designed and manufactured for the primary feeder in order to realize high XPD performance.

The design value of 10m antenna is 57dBi and aperture efficiency is 67% at the input port of the primary feeder.



Fig.7 10m X band dual polarization Antenna at Usuda Deep Station, JAXA, Japan.

The septum polarizer and coaxial low noise amplifier (LNA) that are cooled down to 18K by a cryogenic cooler are connected to the primary feeder through a 1.5m circular waveguide. The noise temperature of the LNA and the polarizer is measured to be 7K at physical temperature 18K. The 1.5m waveguide with 0.4dB loss at room temperature increases the noise temperature by 28K. The total noise temperature of the 10m antenna hardware is estimated 35K (=28K+7K). The measured system noise temperature is 52-58K when the antenna elevation is 90 deg at winter fine weather day. The sky temperature is estimated to be 15K.

The design value of XPD due to main dish surface accuracy is about 52dB and the measured value of

XPF of the primary feeder is 45dB. The septum polarizer is the same design as one for the on-board antenna. XPD of the septum polarizer was measured to be >36dB at cryogenic temperature 18K. Therefore, total XPD of the 10m antenna is estimated to be >36dB.

4.2 Demodulation System

A conventional method of demodulation and decoding processing of high rate down link is in use of hardware system with FPGAs or gateways [21]. However, required hardware is very high performance and expensive especially for higher bit data rates than several 100Mbps. Especially a hardware demodulator of DVB-S2X with 64APSK and roll-off coefficient $\alpha = 0.05$ is not in market yet as of 2018. We have to wait until the hardware demodulator system becomes matured and inexpensive.

An alternative method is software processing. The merits of software processing are low cost of the hardware and flexibility of the software. The demerit is latency of processing. However, down link of earth observation data does not necessarily require real-time processing. Typically a down link time and an orbit period are 10 and 100 minutes, respectively. It is acceptable that the processing has finished by the next down link time.

In this highspeed communication experiment, the 2ch X-band signals from on-board transmitter are received at the 10m antenna and amplified by the low noise amplifiers. They are down-converted to 1400MHz band. Then these IF signals are digitalized with 1.25Gsample/sec and are stored in the mass memory. After the down link pass, the stored files are transported to a workstation dedicated to software demodulator.

We are developing software demodulator system for this purpose. The first step is demodulation software development on Matlab. Then as second step the Matlab software would be converted to much faster software language with parallel processing.

5. Conclusion

We are developing 2.8Gbps down link in X band (8025-8350MHz) from small earth observation satellites. The modulation and coding is 64APSK of DVB-S2X with symbol rate of 300Msps. Dual polarization channels are applied to the system. We have tested an engineering model of the transmitter, and on-board antenna with high XPD. The ground

antenna with high XPD is also developed. This down link system will be demonstrated in 2019 by JAXA advanced small satellite.

6. Acknowledgement

This research was funded by ImPACT Program of Council for Science, Technology and Innovation (Cabinet Office, Government of Japan).

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