Proto-Flight Model of SAR for 100kg class Small Satellite

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ABSTRACT

This paper presents the proto-flight model results of X band synthetic aperture radar for small satellites including the RF power amplifier, high speed data storage/transmission system, and the ground SAR response test results. The specifications of SAR performance are single polarization SAR with 3m ground resolution for strip map mode. 1 m ground resolution can be achieved with sliding spot light mode under condition of limited value of NESZ at 600km altitude orbit. The data down link is high speed X band down link with 2-3 Gbps. In May, 2019, 2.5Gbps down link with 64APSK modulation in dual polarization channels was demonstrated by RAPIS-1 Satellite. We will launch the first demonstration SAR satellite in 2020 as collaboration with a private company.

Index Terms— *SAR, small satellite, X-band, slot array antenna, 2.5Gbps data down link*

1. INTRODUCTION

Synthetic Aperture Radar (SAR) is well-known remote sensing technique that is effective in day and night for any weather condition. Conventionally, however, SAR observation requires large or medium size satellites with hundreds kilo-grams or more. Medium SAR satellites such as SAR-Lupe[1] (Germany, total mass 770kg, 2006), TecSAR[2] (Israel, 300kg, 2008), and NovaSAR-S[3] (United Kingdom, 400kg) have been launched. These large or medium satellites cost hundreds million US dollars including launching cost. Recently small satellites with 100kg or less are being applied to SAR observation aiming at SAR satellite constellation. In 2018 January, ICEYE-1 (Finland, 70kg) was launched and demonstrated 10m ground resolution SAR observation in X band [4].

Table 1 SAR Observation Specification

	SAR Mode	
	Strip Map	Sliding Spot Light
Altitude	618km	618km
Resolution	3m	1m
Center Frequency	9.65GHz	
Swath	10 km	10 km
Chirp Band Width	75MHz	300MHz
Polarization	V/V	
Antenna Size	4.9 m×0.7 m	
Ant Efficiency	50%	
TX Peak Power	1000 W	
TX Duty	25%	
System Loss	0.6 dB	
System Noise Figure	2.6 dB	
Off Nadir Angle	15～45 deg	
Pulse Repitition Frequency	3000 ～ 7000 (TBD) Hz	
NESZ (beam center)	-20dB	-16dB
Ambiguity (beam center)	>15dB	

In this paper, we describe a synthetic aperture radar sensor compatible with 100kg class satellites. When this small SAR satellite is injected to typical earth observation orbit with 500-600km altitude, its ground resolution is expected to be 3m that is useful for earth observation and monitoring. Optional 1 m ground resolution can be achieved with sliding spot light mode under condition of limited value of NESZ. The main specification of SAR observation is shown in Table 1. Table 1 shows a relatively conversative swath of 10km for the preliminary design. We confirm that even swath of 20km can satisfy the SAR performance with measured antenna pattern described in the next section.

2. SATELLITE SYSTEM AND ANTENNA

The SAR satellite has 130kg mass and the size is 0.7m x 0.8m x 0.9m on a rocket. A size of the deployed antenna is 4.9m x 0.7m. Fig.1 shows the configuration of SAR antenna. A waveguide is embedded at the center of the rear surface in order to feed RF to the antenna panel through coupling slots. The antenna panel consists of a dielectric honeycomb core and metal skins, which work as a parallel plate guide for RF. The front surface with two dimensional arrays of radiation

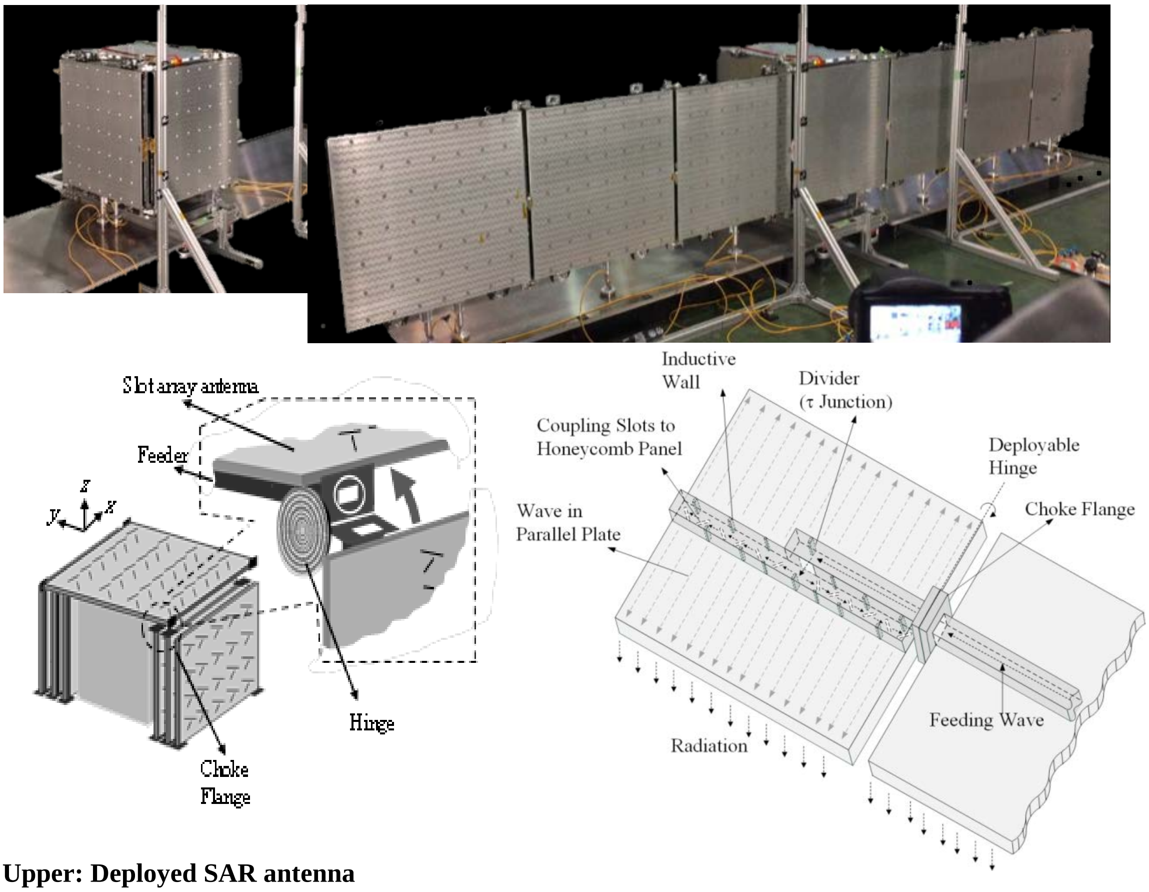

Fig. 1 Upper: Deployed SAR antenna
Lower Left: Non-contact waveguide feeding with choke flange
Lower Right: Honeycomb antenna panel with slot array and embedded waveguide

slots works as an antenna radiator for vertical polarization SAR mode. In order to achieve 1m ground resolution, the antenna bandwidth should be about 300MHz. This antenna is a traveling wave array antenna. Therefore, length of an array branch should be less than about 30cm. We have developed a proto-flight model of full antenna configuration with 7 antenna panels (size of 4.9m x0.7m). Also near field RF measurement of the full antenna configuration has been performed at A-Metlab Facility, Kyoto University. Figure 2 shows the relative antenna gain and the phase of the far field pattern from the measured near field data as functions of elevation angle and azimuthal angle. The side love level of the elevation pattern is -13dB with a uniform excitation. However the side lobe level of the azimuthal pattern is slightly higher than - 13dB due to phase unbalance between each panel antenna. We will perform phase adjustment for each panel antenna in order to improve the side lobe level. However the SAR specification shown in Table 1 is satisfied with the measured antenna pattern described in Fig. 2. The peak directivities at the center frequency 9.65GHz are 36.7dBi for one-panel, 42.4dBi for four-panels and 44.5dBi for 7-panel full configuration, respectively. These values are almost proportional to number of the panels, indicating that effective in-phase excitation of antenna panels is achieved as designed. The aperture efficiency of 7-panel full configuration is about 70%.

In order to make antenna instrumentation simpler, TX and RX instruments are in the satellite body. Therefore RF should be fed from the satellite body to each panel with equal electric length. We apply choke flanges of waveguides in order to realize RF feeding with non-contacting waveguide flanges. Choke flanges have been

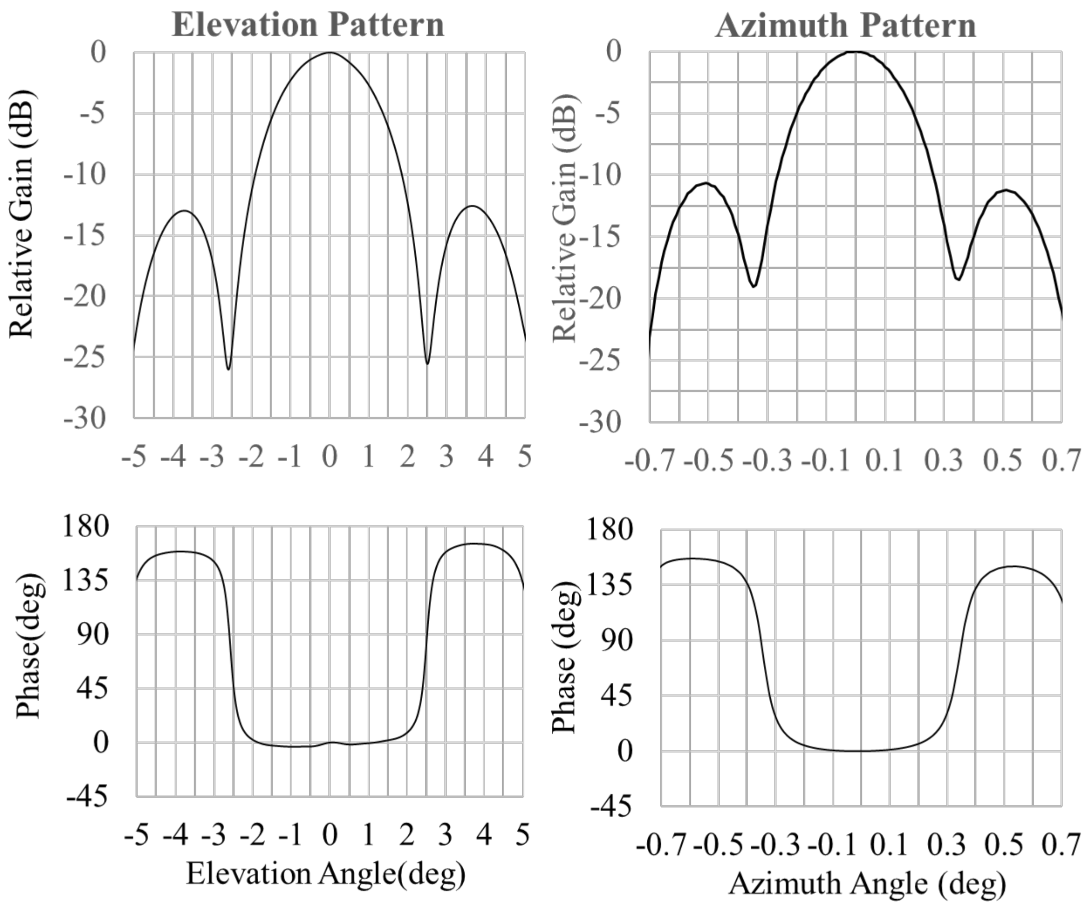

Fig.2 Far field pattern of 7 panel antenna (4.9x0.7m) from near field measurement as functions of elevation angle (left) and azimuthal angle (right). The upper is relative antenna gain pattern. The lower is phase of the far field.

widely used to avoid the degradation of current conduction through waveguide flanges due to manufacturing imperfections or oxidization of the flange surfaces. RF loss can be minimized by the choke connection even though there is a physical gap between two waveguide flanges.

3. ON-BOARD SAR INSTRUMENTS

The RF peak power is selected to 1000 W that is realized by GaN solid state amplifiers, instead of vacuum tube TWTAs. A chirped transmitting signal is amplified in six GaN HEMT 200W amplifier modules to be combined in a wave-guide resonator. The on -duty ratio is 25% to in crease the average power.

A SAR-Electronics Unit (S-ELU) handles transmitting signal generation, receiving signal processing (frequency conversion and analog-to-digital conversion) for SAR sensor. The S-ELU for small satellites is developed based on an airborne SAR instrument. The chirp bandwidth is 300MHz for 1m ground resolution. The received signal is converted to digital signal of 8bit x 720M sample/sec. Data compression rate is about 50%. Receiving duty cycle is about 50% to acquire reasonable signal-to-noise ratio. After time stretching process, the average data rate is 1.5Gbit/sec. In the SAR observation mode, this 1.5Gbit/sec SAR data is transferred to Mission Data Recorder (MDR) through serial RapidIO (sRIO) interface.

Mission Data Recorder MDR consists of commercial 16 NAND flash memory devices and the total memory capacity is 768Gbyte. Total dose tolerance of NAND devices is confirmed by Co60 irradiation test. Single event upset errors are corrected by standard error correction code for commercial NAND devices. A commercial FPGA (Field Programmable Gate Array) device is utilized for high speed data flow and standard powerful error correction code. Special cares are paid to thermal heat path and thermal stress of BGA (Ball Brid Array) packaging. In down link communication mode, stored data are transferred to high data rate X band transmitter (XTX). XTX has dual polarization (RHCP/LHCP) channels to increase its down link capability. Stored data are switched to the 2 channels and they are transferred to XTX through Xilinx Aurora data interface. The data rate between MDR and XTX is 2Gbit/sec per one channel and total data rate is 4Gbit/sec.

Figure 3 shows photographs of on-board instruments described in this section.

4. SAR IMAGING TEST WITH POINT SOURCE SIMULATOR

We have performed ground test of SAR observation with a dedicated target signal simulator. Proto-flight model of SAR-Electronics Unit (S-ELU) sends exciter signal with chirp modulation to High Power Amplifier (HPA). A dedicated target signal generator (TSG) generates echo signals from a single point target under assumption of stop-and-go model. The echo signals are input to S-ELU. Then S-ELU performs frequency down-conversion, conversion of analog signal to digital signal. Then the digital data are sent to the data recorder. The conventional SAR imaging processing gives us the range- azimuthal SAR image of point target as shown in Fig.4. We have confirmed 0.81m azimuthal resolution and 0.86m ground resolution at off-nadir angle 30deg with sliding spot light mode.

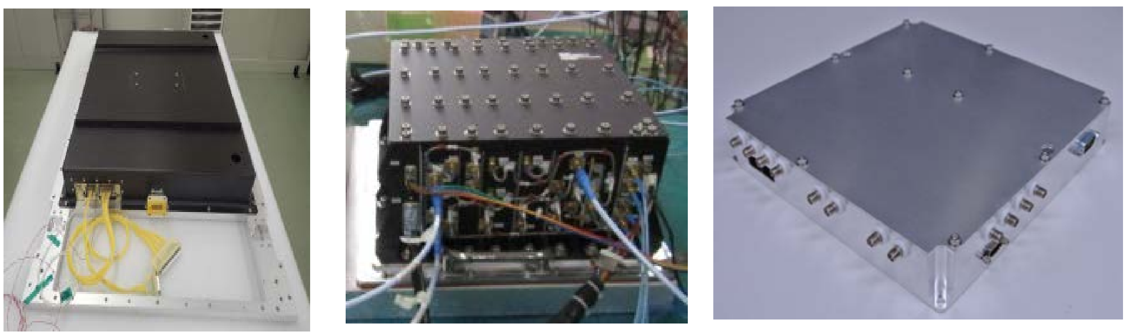

Fig.3 Left : 1kW Xband Power Amplifier installed on satellite body.
Center: SAR Electronics Unit converted from air plane application
Right : 768Gbyte, 2Gbps Mission Data Recorder with NAND memory

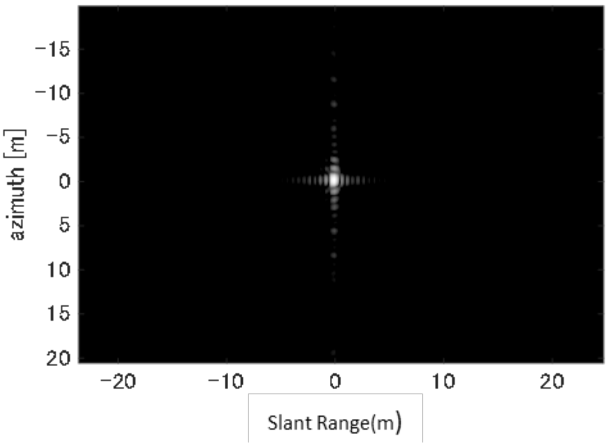

Fig.4 SAR response image of single point source with sliding spot light mode. 2D plot of slant range and azimuthal direction. Azimuthal resolution is 0.81m and slant range resolution is 0.47m (ground range resolution 0.86m at off-nadir angle 30deg).

5. SAR DATA DOWN LINK SYSTEM AND ITS DEMONSTRATION

The observed data is transmitted to ground station through high-speed X band link. We have already demonstrated high speed down-link of 64 APSK, 100Msps with Hodoyoshi 4 satellite in 2014 [5,6]. Based on this technology, we are developing dual polarization channel X band link with total 2-3Gbit/sec capability [7,8]. Figure 5 is photographs of this communication system.

Allocated radio frequency for earth observation is 8025-8400MHz (375MHz bandwidth). However, next band 8400-8450MHz is deep space down link band that should be protected against possible interference. We select 64APSK modulation with 300Msymbol/sec to observe the protection regulation. We apply DVB-S2X standard to this high speed down link.

Digital processing of the transmitting signal including DVB-S2X standard formatting, I-Q mapping, route Nyquist filtering is performed by a commercial FPGA. A commercial, high-performance digital-to-analog converter is applied to generate 1.2 GHz IF signal. Special cares are also paid to thermal heat path and thermal stress of BGA (Ball Brid Array) packaging. This IF signal is frequency up-converted to X band and is amplified up to 1W at RF section. Nonlinearity, especially third-order inter-modulation of the final power amplifier is critical issue of the RF section. Figure 6 is demodulated constellation pattern of 64APSK (coding rate 11/15), DVBS-2X, 1.27Gbps/channel. Error vector magnitude is about -27dB rms. In order to secure the dual polarization channel link, Cross Polarization Discrimination (XPD) factor is important for communication link system to avoid interference between dual channels. Dominant factors are XPD of atmosphere propagation and XPD of onboard and ground antenna. We have developed the corrugated horn antenna and the septum polarizer for this purpose. The antenna gain is 17dBi and XPD is higher than 33dB.

A ground receiving antenna with 10m diameter is being developed. Existing 10m antenna for Ku band at JAXA, Usuda is converted to X band receiving antenna. The antenna gain, system noise temperature, and XPD is 56.5dBi, 55K (zenith), and >35dB, respectively.

Fig.5 Left : High Speed X band Transmitter. Center : Medium Gain Antenna (MGA), Right : 10m Ground Station Antenna

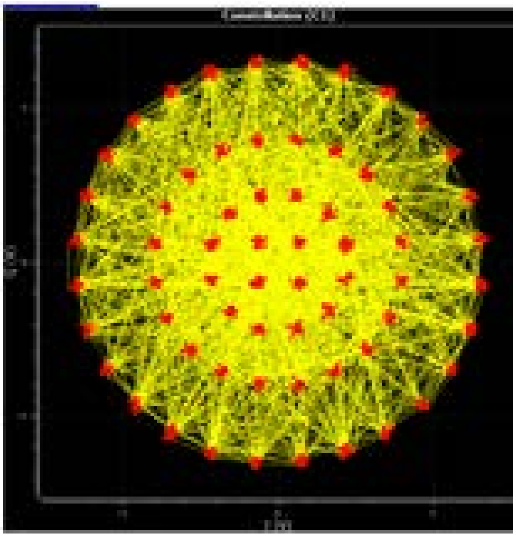

Fig.6 Demodulated constellation of 64APSK, 1.27Gbps/ch.

Received RF signals at the ground station are frequency down converted and are stored at a dual channel, high speed, data recorder. Since there is no real-time demodulator of 300Msps, 64APSK modulation at present in market, non-real time software demodulation system is being developed as a part of our project.

This high speed down link system has been demonstrated by the Mini-satellite, RAPIS-1 of "Innovative Satellite Technology Demonstration Program" in Japan and was launched in 2019, January 19th. We have received simultaneously the signal of 64APSK 11/15 (data rate 1, 270Mbps) in both of RHCP channel and LHCP channel. The data are stored in the dual channel data recorder. As a preliminary result, dual channel signals are successfully demodulated. The total data rate 2,540Mbps in X band for earth observation band is demonstrated. This down link speed is the world-highest one in the X-band for earth observation band as far as the authors know. We will continue receiving experiments of dual channel 64 APSK 5/6 (data rate 1,443Mbps) down link aiming at total 2,886 Mbps speed.

6. CONCLUSION

We describe the proto-flight model test results of compact SAR. The SAR system includes several unique points such as the non - contact choke flange feeding, the honeycomb panel slot array antenna, and the. 2-3 Gbps ultra - high speed down link in X band. The first demonstration flight of this SAR system will be in beginning 2020 as collaboration with a private company Synspective [9] .

7. ACKNOWLEDGEMENT

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