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Compact X-Band Synthetic Aperture Radar for 100 kg Class Satellite

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SUMMARY We proposed a new architecture of antenna, transmitter and receiver feeding configuration for small synthetic aperture radar (SAR) that is compatible with 100 kg class satellite. Promising applications are constellations of earth observations together with optical sensors, and responsive, disaster monitoring missions. The SAR antenna is a deployable, passive, honeycomb panel antenna with slot array that can be stowed compactly. RF (radio frequency) instruments are in a satellite body and RF signal is fed to a deployable antenna through non-contacting choke flanges at deployable hinges. This paper describes its development strategy and the present development status of the small spaceborne SAR based on this architecture.

key words: *synthetic aperture radar, 100 kg class small satellite, X band, deployable honeycomb slot array antenna*

1. Introduction

Synthetic Aperture Radar (SAR) is a well-known remote sensing technique [1], [2] with reliable capabilities. Large or medium size satellites with hundreds kilo-grams or more can afford SAR sensors. Medium SAR satellites such as SAR-Lupe [3] (Germany, total mass 770 kg, 2006), TecSAR [4] (Israel, 300 kg, 2008) have been launched. NovaSAR-S [5] (United Kingdom, 400 kg) and ASNARO-2 (Japan, 500 kg) are planned to be launched. SAR-Lupe is provided with solid parabolic antenna of which size is 3.3 m x 2.7 m. TecSAR is provided with umbrella-type deployable parabolic antenna of which stowed size is about 2 m long. ASNARO-2 is provided with deployable solid parabolic antenna of which stowed size is 1.5 m x 1.5 m x 2 m. These large or medium satellites cost hundreds million US dollars including launching cost.

On the other hand, there is a strong social demand to realize small, low cost SAR satellites. If 100 kg class small SAR satellites with 1–10 m ground resolution are realized, they will be utilized for earth observations and monitoring missions such as surveillance and observation for natural disasters. Especially, constellation missions with SAR sensors and optical sensors can realize nearly real time ground monitoring in all-weather condition.

To respond these social demands, 100 kg class SAR satellites are recently proposed. Conceptual study of Panel-SAR [6] (Netherlands) proposes deployable active phased array antenna for SAR observation, which is essentially similar to classical medium and large SAR satellites. Real hardware development of ICEYE is not initiated yet. ICEYE satellite [7] (Finland) is being developed for a limited SAR mission, sea ice detection with low resolution. ICEYE satellite is also provided with conventional active phased array panel antennas. Active phased array antennas with phase shifters or TX(transmitter)/RX(receiver) modules are exposed to harsh space environments. Complicated design and manufacturing processes with thermal, structure, and RF issues are required and drastic cost-down seems impossible.

Authors proposed [8] a new concept of 100 kg class SAR satellite which is provided with deployable, passive, slot array plane antenna fed with microwave through non-contact waveguides at deployable hinges. The antenna and the feeder system is passive, compact and simple. It is possible to reduce drastically cost and satellite size.

This paper describes its development strategy and the present development status of a small spaceborne SAR system that is compatible to 100 kg class satellite. Section 2 describes the strategy of our small SAR system. Section 3 discusses SAR system scaling law and the specification of the SAR system. Sections 4, 5, and 6 describe the SAR antenna, the high power amplifier, and the power and data management, respectively. Section 7 is the conclusion remark.

2. Strategy for Small SAR System

In order to explain our development strategy for small SAR system, mass and power allocation of SAR satellites are overviewed. Figure 1 is a conceptual block diagram of SAR system. A SAR system consists of a digital unit for signal generation and receiving, an RF unit for signal generation and receiving, a high power amplifier for signal transmitting, a SAR antenna, a data recorder unit and a data link, a power supply system and a heat management system for a high power amplifier.

Table 1 shows major specifications, power consumption, mass budget of a typical large SAR satellite with

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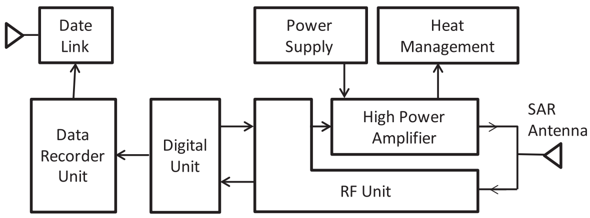


Fig. 1 System block of SAR.

Table 1 Typical power and mass allocations of spaceborne and airborne SAR system.

	Large Sat	Medium Sat	Small Sat	Airborne
Satellite Mass(kg)	2000	500	150	-
SAR Band	L	X	X	L,C,X,Ku
Resolution (m) (Alt 600km)	3	1	3〜10	0.3-1
Resolution (m) (Alt 400Km)			1	
RF Average Power (W)	520	200	250	10
SAR DC Power (W)	6000	1000	1100	200
TX DC Power (W)	5000	900	1000	
SAR Total Mass (kg)	900	200	75	20
Antenna	500	50	35	5
RF (TX/RX)	130	60	15	6
Digital Unit	200	40	15	4
Data Down Link	20	10	8	-
Others, Cable	50	40	2	5

2000 kg mass, a medium SAR satellite with 500 kg mass, small aircraft/UAV (unmanned aerial vehicle) SAR, respectively. In a typical small aircraft/UAV SAR for low altitude, mass and total power of SAR system is about 20 kg and 200 W, respectively. On the other hand, a typical large SAR satellite requires 900 kg mass and 6,000 W power of SAR system. An antenna and a high power amplifier play dominant roles in mass and power of SAR system, respectively.

A dominant performance index of a digital unit is processing speed that is mainly determined by a ground range resolution, namely a chirp frequency band width. There have already been commercial, light-weighted airborne SAR products with 0.3 m ground resolution. It is possible to develop a spaceborne digital unit with about 15 kg applying non-space components and technologies.

On the other hand, requirements of antenna size and power of high power amplifier depend on the altitude. Since satellite altitude is 30–600 times higher than aircraft altitude, a spaceborne SAR requires large antenna area and high power of transmitting signal. Critical points of small SAR satellites are antenna mass and its stowed size, high power amplifier, power system, and heat management system relating to high power amplifier. Table 2 summarizes our strategy for small SAR satellite. Following sections describe the critical points for small SAR satellites.

Table 2 Strategy for small SAR satellite.

	Large SAR Satellite	Small SAR Satellite
SAR Antenna	・Active Phased Array (complex,large stow size) ・Parabola(large stow size)	・Deployable, passive plane antenna ・Non-contacting waveguide feeding at hinge
TX/RF Instrument	・distributed TX/RX on ant. ・centralized TWTA	・Centralized TX with GaN SSPA+ power combiner
Power System	・Independent solar panel ・Large space battery	・Share antenna/solar panel ・Rapid-dischargiable battery
Thermal System	・Complex management of distributed TX module on antenna panel	・Install GaN amp module directly on structure panel that works as heat-sink and radiator.
Digital Processing	・Space qualified parts (FPGA, memory, DAC)	・Space qualified parts + commertial parts
Data Down Link	・1.2 Gbps in X band 8PSK ・RHCL/LHCP 2 channel ・200Msps	・1.5-4Gbps in X-band ・64-256 APSK, ・RHCL/LHCP 2 channel ・350Msps

TWTA: traveling wave tube amplifier
FPGA: field programmable gate array
DAC: digital-analog converter
APSK: amplitude phase shift keying
SSPA: solid state power amplifier
RHCP/LHCP right/left handed circular polarization

3. Scaling Law and Design of Small SAR System

In order to realize a small SAR system, SAR scaling law should be considered, paying attention to satellite resources and SAR performances. The details are described in [1], [2], [8].

$$\sigma^0_{NE}\delta_r = (8\pi R^3 kT_o v_{st})(NFLs)\frac{\lambda}{P_{TX-ave}A^2\eta^2} \qquad (1)$$

where σ^0_{NE} (noise equivalent sigma zero) is radar cross section per unit area for which signal-to-noise ratio is unity. This value is widely used as an index of SAR image quality. δ_r is ground range resolution, R is distance between the satellite and the observation target, k is the Boltzmann constant, T_o = 290 K, v_{st} is satellite velocity, NF is noise figure of the receiving system, L_s is system loss, P_{TX-ave} is average transmitting RF power, λ is observation wavelength. A and η are area and aperture efficiency of the antenna.

The left side of Eq. (1) is a performance index, namely a product of the ground resolution and the image noise. The right side corresponds to the required resources such as RF power, antenna area, noise figure, and RF loss. Note that the required resource term is inversely proportional to average RF power and square of antenna area and is proportional to observation wavelength. RF power and antenna area required to obtain constant SAR performance $\sigma_{NEo}\delta_r$ (product of resolution and noise) become smaller as observation wavelength is shorter. Figure 2 shows ground resolution converted to σ^o_{NE} = −20 dB as a function of SAR satellite mass for previous and planned SAR satellites with various observation band.

X band SAR satellites are advantageous to achieve high

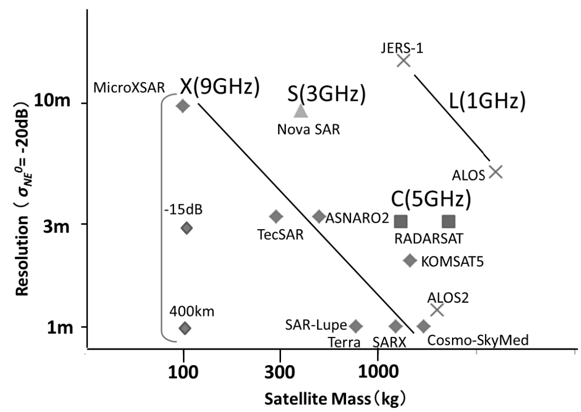


Fig. 2 Mass of SAR satellites and ground resolutions with σ^0_{NE} = −20 dB. Observation band is L (1 GHz): ×, S (3 GHz): ▲, C (5 GHz): ■, X (9 GHz): ◆. MicroXSAR mission (our proposal) has higher resolutions than 10 m. Resolution 3 m for σ^0_{NE} = −15 dB, 600 km altitude. Resolution 1 m for 400 km altitude.

Table 3 Specification of SAR system compatible with 100 kg class satellite.

Item	SAR Mode	
	Strip Map	Sliding Spot Light
Altitude	600km	400km
Resolution	3m	1m
Center Frequency	9.65GHz	
Swath	25 km	10 km
Chirp Band Width	75MHz	300MHz
Polarization	V/V	
Antenna Size	4.9 m×0.7 m	
Ant Panel Efficiency	50%	
TX Peak Power	1000～1100 W	
TX Duty	25%	
System Loss	3.5 dB	
System Noise Figure	4.3 dB	
Off Nadir Angle	15～45 deg	
Pulse Repitition Frequency	3000 ～ 8000 Hz	
NESZ (beam center)	-15dB	-18dB
Ambiguity (beam center)	>15dB	

resolutions with smaller satellite mass. Also X band is suitable for recognition of ground surface objects.

We selected X band as SAR observation frequency. Higher observation bands than X band are subject to large rain attenuation. Also technologies of GaN devices as high power amplifiers are not well matured yet in higher frequency band. We have designed X band SAR (MicroXSAR mission) compatible with 100 kg class satellite as shown in Table 3. The RF peak power is selected to be 1000 W that is realized by GaN solid state amplifiers, instead of vacuum tube TWTAs.

For a standard image quality with σ^0_{NE} = −20 dB, ground resolution of 10 m can be achieved in case of 618 km altitude. Furthermore ground resolution of 3 m is realized if one accepts image degradation of $\sigma^0_{NE} = -15$ dB, which is still enough for sight recognition mission.

Another version of small SAR missions is high resolution SAR with low altitude orbit. A ground resolution of 1 m can be obtained where the orbit altitude 400 km, RF bandwidth 300 MHz. This orbit has short life due to air drag and is limited to on-demand, responsive missions for natural disaster management.

4. SAR Antennas for Small Satellite

4.1 Architecture of SAR Antenna and Feeding System

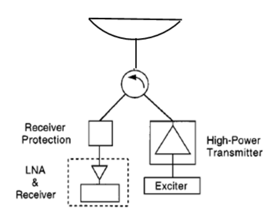
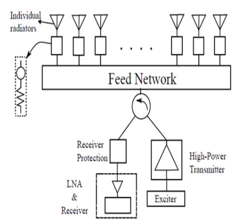
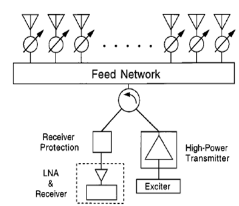
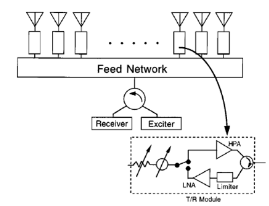
In this section, we discuss architectures of small SAR antenna and feeding system. In general a SAR system requires an antenna with several m^2 in area. There have been several types of SAR antennas: 0) body mount antenna on a large satellite structure with 3–5 m length (TerrSAR-X [9], Nova SAR-S [5]), 1a) deployable (passive) parabolic antenna with 3–4 m diameter (SAR-Lupe, TecSAR, ASNARO-2), 2a) deployable active phased array with centralized TX/RX module (RadarSat-1 [10]), 2b) deployable active phased array antenna with distributed TX/RX modules (ALOS 1, 2 [11], RadarSAT-2 [12]). Table 4 shows architectures of deployable SAR antenna and feeding system, excluding 0) body mount antenna.

The types of non-deployable antenna 0) and 1a) are not applicable for small satellites that require small stowed size. In the case 2a) and 2b) the active phased array antennas with phase shifters or TX/RX modules are exposed to harsh space environments. Complicated design and manufacturing processes with thermal, structure, and RF issues are required and drastic cost-down seems impossible.

The last type is passive plane antennas 1b) in Table 4 which are not provided with any amplifiers in deployable panels. TX/RX subsystems are installed in the satellite body. The world first SAR satellite Seasat-A [13] in 1978 was provided with L band patch antenna array on deployable panels. The feeders were hollow coaxial conductors and flexible coaxial cables at deployable hinges. ERS-1 [14] in 1991 was provided with C band waveguide slot array antennas without any amplifiers in deployable panels. Their antenna sizes are relatively large (about 10 m) since their observation frequency is low (L and C band). The significant merit of this type is its simplicity of antenna which can afford cost down. Possible configuration of a 100 kg-class SAR satellite is deployable passive, plane antenna of X band with centralized TX/RX instruments. The summary is shown as case 1b) of Table 4. The satellite outlook is shown in Fig. 3.

There are no electronics RF instruments on the antenna. All electric instruments are installed in the satellite body. Since the antennas are thin planes, the stowed size can be very small as 0.7 m x 0.7 m x 0.15 m for one wing of 3 panels. The three passive antenna panels are deployed to compose antenna area. Left wing, right wing and the center panel on the satellite body works as a SAR antenna with 4.9 m x 0.7 m area.

Table 4 Architecture of SAR antenna and feeding system for small SAR.

	deployable Passive Antenna		deployable Active Phased Array Antenna	
	1a) Parabola	1b) Passive Plane Antenna	2a) Centralized TX/RX	2b) Distirbuted TX/RX
Examples	TecSAT, ASNARO2	Seasat-A, ERS-1, MicroXSAR	RadarSAT-1	RadarSAT-2,ALOS-1,2
Characteristics	X large stowed size X mechanical complexity △ medium cost X no scan mode	◯ compact stowed size possible ◯ no instruments on panel ◯ low cost X no scan mode	X medium stowed size △ instruments on panel △ medium cost ◯ scan mode	X large stowed size X instruments on panel X high cost ◯ scan mode
system				

LNA: low noise amplifier
HPA: high power amplifier

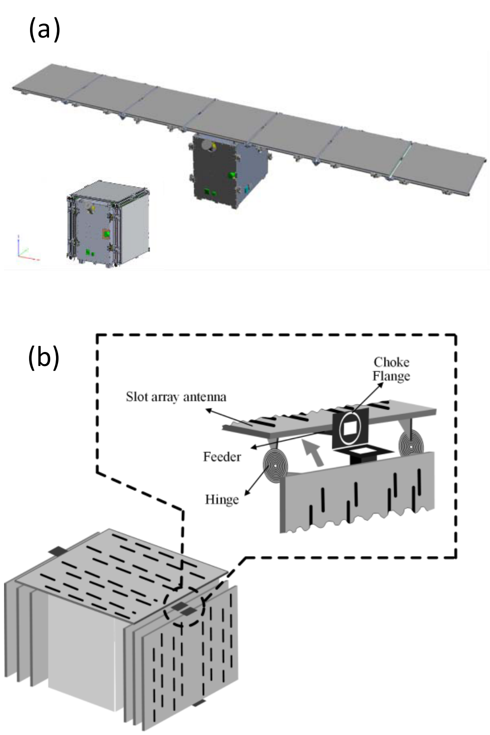


Fig. 3 (a) Outlook of small SAR satellite. 0.7 m x 0.7 m x 0.7 m in stowed configuration. Antenna size is 4.9 m x 0.7 m. (b) Non-contact waveguide feeding with choke flange at hinge.

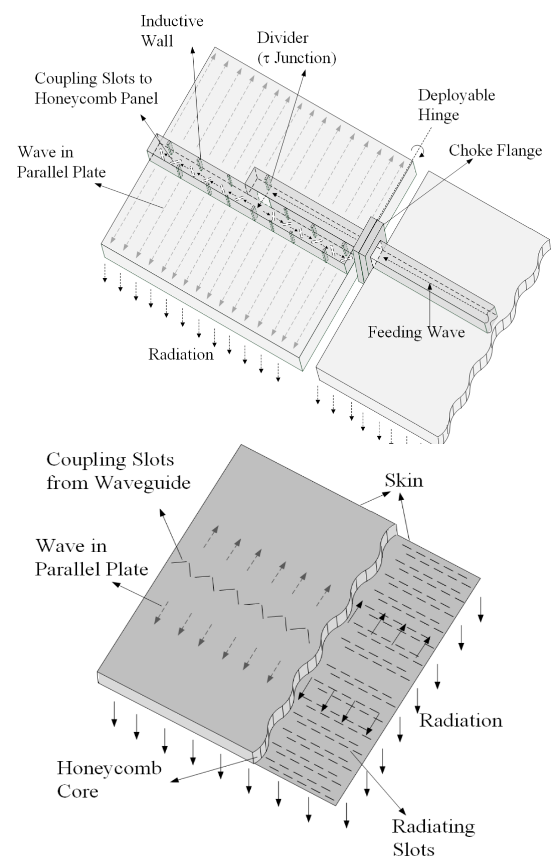


Fig. 4 Structure of antenna panel. Upper part is outlook with feeding waveguide. In lower part feeding waveguide is omitted to explain antenna function.

4.2 Deployable Plane Antenna

As shown in Table 3, the SAR system requires an antenna of several meters in orbit. A stowed size of the satellite in a rocket should be less than 0.7 m x 0.7 m x 0.7 m for small launchers. One of the most feasible candidates is passive, deployable, honeycomb panel antenna with slot array [15], [16]. This antenna is friendly with a plane honeycomb structure and relatively high aperture efficiency.

Figure 4 shows structure of an antenna panel. Its size is about 70 cm x 70 cm x 0.6 cm. The 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

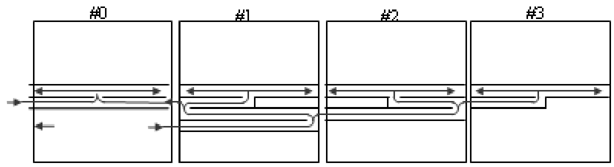


Fig. 5 Waveguide feeder network is embedded in antenna panels. Panel #0 is on satellite body. Left wing is symmetric and omitted in this figure.

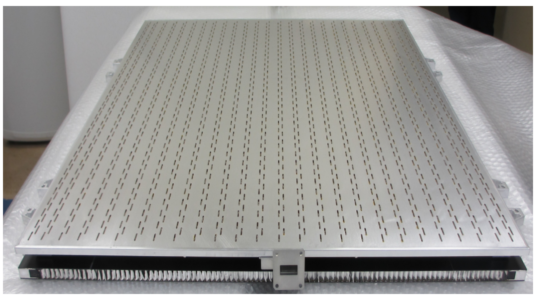


Fig. 6 Photograph of bread board model of antenna panel #3.

a dielectric honeycomb core and metal skins, which work as a parallel plate guide for RF. The front surface with two dimensional array of radiation slots works as an antenna radiator for vertical polarization SAR mode. In order to achieve 1 m ground resolution, the antenna bandwidth should be about 300 MHz. This antenna is a traveling wave array antenna. Therefore, length of an array branch should be less than about 30 cm.

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. Figure 5 is the waveguide feeding networks for an antenna wing. Panel #0 is on the satellite body and the other wing is symmetric configuration. Figure 6 is the photograph of the antenna panel #3.

4.3 RF Feeder with Non-Contacting Waveguide Flange

The next problem is to feed RF to each antenna panel at the deployable hinges. There are conventional RF feeding methods to deployable antenna such as flexible cables, flexible waveguides and rotary joints. However, they have disadvantages of large RF loss, resistive torque and structural complexity.

We apply choke flanges of waveguides to this problem in order to realize RF feeding with non-contacting waveguide flanges [17], [18]. Choke flanges have been widely used to avoid the degradation of current conduction through waveguide flanges due to manufacturing imperfections or oxidization of the flange surfaces. There is a ditch whose depth and distance from a wide wall of a waveguide are roughly a quarter of the wavelength λ. The ditch works as a quarter-wave resonance short-circuit stub. Although there is a gap at the main waveguide, wall current flows smoothly with low impedance at the gap.

Each antenna panel with a feeder waveguide is connected by a deployment hinge. After deployment, a choke and a cover flange face to each other. RF loss can be minimized by the choke connection even though there is a physical gap between two waveguide flanges.

We have measured the effect of choke flanges [17]. Firstly we tested a standard choke flange whose choke ditch is circular shape. It is assumed that an axial gap distance between two flanges at the hinge is 0–1 mm and a misalignment in the transverse direction is ±0.5 mm. These mechanical accuracies can be realized by standard mechanical hinge design. Measured RF losses due to a flange gap are less than 0.05 dB in a wide range of frequency and misalignment configuration. However, it is found that RF losses increase resonantly in specific frequency, which depends on the flange misalignment. Electromagnetic numerical simulation reveals that two dimensional standing wave is excited at such resonance condition in the gap region between the rectangular waveguide cross section and the choke ditch. We designed egg-shape choke ditch in order to avoid the standing wave condition in the frequency band of our interest. For this newly developed egg-shape choke, RF loss is below 0.05 dB at all regions of our frequency band and the possible misalignment [17]. Note that reflection at the gap is less than −25 dB. We will apply the egg-shape choke flanges at the deployable hinges of the antenna feed waveguides.

5. GaN Power Amplifier and Heat Management

Recently advanced solid state amplifiers with GaN HEMT (high electron mobility transistor) devices have been developed up to X band. A 200 W peak power, internally matched GaN HEMT amplifier is available in the market. The package size is 24 x 17 x 5 mm^3. The typical power added efficiency is 38%.

Duty ratio is also important for SAR performance. Conventional SAR satellites have adopted duty ratio of typically 10%. We are developing GaN amplifiers with duty ratio of 25%, paying attention to its thermal design. We will combine RF outputs from 6 modules of 200W GaN amplifiers with a waveguide resonator combiner to obtain peak power of 1000 W [19]. The inputs of the power combiner are microstrip lines from 200 W amplifier modules. The output of the combiner is a rectangular waveguide. Figure 7(a) shows the outlook of the bread board model (BBM) of the 6-port power combiner.

Heat management of GaN amplifier module is very critical. The recommended channel temperature of GaN HEMT devices for commercial use is less than 200°C and the typical duty ratio is 10% according to the manufacturer's data sheet. We design the high power amplifier for satellites so that the channel temperature should be lower than 150°C based upon MTTF (mean time to failure) analysis. The effective thermal impedance between the channel and the package case is obtained for our operation condition (channel dissipation heat, pulse width, and case temperature). These thermal analyses reveal that a final stage device should operate at about 100 W that is half level of maximum power level since our

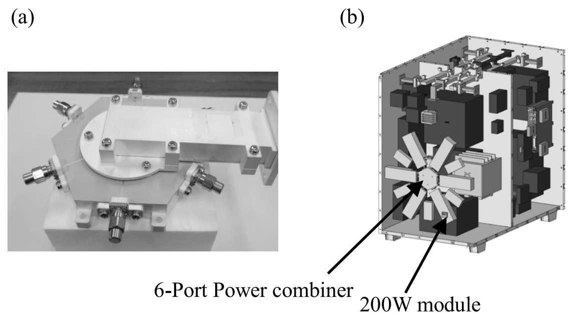


Fig. 7 (a) 6-port power combiner with cylindrical cavity. Inputs are Micro-strip-line and output is waveguide. (b) Configuration of high power amplifier. 200 W modules are fastened directly on aluminum structure panel that works as heat spreader, capacitor, and radiator.

SAR transmitter operates at higher duty ratio of 25% than typical duty ratio of 10% for commercial application. Then two devices' outputs are combined to generate 200 W in one module.

Total heat generation of the high power amplifier is about 800 W. Duration of SAR observation is less than 5minutes per one orbit period (96 min). Six amplifier modules are distributed around the power combiner and are fastened directly to a satellite structural panel. The structural panel is a thick aluminum plate that works as a heat spreader, a heat and capacitor, a radiator. Aluminum has relatively high specific heat (0.9 kJ/K/kg) and thermal conductance (200 W/K/m).

Figure 7(b) shows configuration of the high power amplifier. The mass of the aluminum plate is about 4.4 kg and the temperature of the plate rises by 50 deg after 5 min's SAR observation. The heat stored in the aluminum plate during SAR observation is emitted with time constant of about 50 mins as infrared radiation from an outer radiator surface of the aluminum plate to deep space.

6. Power and Data Management

Firstly we describe the power management. SAR instruments consume about 1100 W DC (direct current) power in 5 min SAR observation period. A wide area of solar cells are available in the rear side of the antenna panels with 4.9 m x 0.7 m area which can generate 500 W. Flexible solar cell films are installed at the rear side of the antenna panels in order to supply a large amount of electric power for SAR system. Multi-layer insulators (MLIs) are installed between solar cells and antenna panels to prevent from thermal deformation of the antenna.

In sunshine period of the orbit the solar cell surface is sun-pointed by attitude control system. The electrical power is stored at batteries. Since SAR observation period is only 5 minutes, the discharge rate of the batteries is as high as 3 C-rate, where C-rate is a measure of the rate at which a battery is discharged relative to its rated capacity. A 3 C-rate means that the discharge current will discharge the entire battery in 1/3 hour. Conventional space qualified batteries cannot afford such high discharge rates. We apply commercial batteries that are robust for high discharge rates.

Secondly the data management is depicted briefly. Chirp bandwidth is 300 MHz for 1m ground resolution at 30 deg off-nadir angle. The received signal is digitized with 8 bit at 720 M sampling/sec. The data compression rate is expected to be 50% and the received window in time domain is about 50%. Then generation rate of SAR data is about 1.5 Gbps and the total data volume for 5 minutes observation is 56 GByte. This data is stored at a solid-state recorder with 1TByte capacity that can store data of 1.5 days' observation. Recently NAND flush memories with 62GByte per one device are available in the commercial market. Storage functions of NAND flush memory are essentially robust space radiation environments. We pay careful attentions to radiation-induced single event phenomena at memory writing and reading.

In a responsive SAR mission for natural disaster, observed data is required to be transmitted to ground station at the 5 mins' communication pass just after the SAR observation. This performance has to be maintained even in bad weather conditions. Required down link is X band (8025–8400 MHz) link with higher bit rate than 1.5 Gbps. Hodoyoshi 4 satellite in 2014 [20], [21] has already demonstrated high-speed X band down link. The data rate is 505 Mbps with 64APSK modulation where occupied frequency band is only 125 MHz. As the next generation, 64-256APSK (amplitude phase shift keying) down link with 350M symbol/sec is being developed with use of full band of 375 MHz in the X band. Here two channels of right-handed and left-handed circular polarization will be utilized to double the link speed.

7. Conclusion

This paper describes a development strategy and the development status of a small SAR system that is compatible to a 100 kg class satellite. The key technologies are SAR antenna and heat management of GaN amplifier.

We select new technologies of deployable, passive, plane slot array antennas and non-contacting waveguide feeding at deployable hinges. The stowed size is small and the cost can be low since the antennas are just honeycomb panels with radiation slots. The rear surfaces of the antenna support flexible solar cell sheets.

All electronics instruments are in the satellite body. A GaN amplifiers are fastened directly on a thick aluminum satellite structural plate that works as a heat spreader, a capacitor, and a radiator. Outputs from GaN amplifier modules are combined into a rectangular waveguide through a newly developed waveguide cavity.

Possible applications of this small SAR satellite are constellation earth observation missions together with optical sensors as well as responsive missions for natural disasters.

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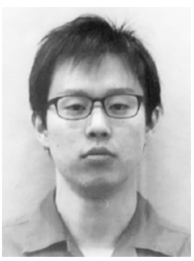

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