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Development Status of Compact X-band Synthetic Aperture Radar Compatible with a100kg-class SAR Satellite and Its Future Plan

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ABSTRACT

We have proposed a novel SAR system compatible with a 100kg-class small satellite. This SAR development is funded for four years (2016-2019) by Japanese government. At present we are developing engineering model (EM). This paper describes the EM test preliminary results and the future plan. The specifications of SAR observation are single polarization SAR with 1m ground resolution at minimum. A size of the satellite is 0.7m x 0.7m x 0.7m on a rocket. A size of the deployed antenna is 4.9m x 0.7m. Novel parallel-plate slotted array antennas made of honeycomb panel have been developed. Six outputs from GaN HEMT power amplifiers are combined in a waveguide resonator and 1 kW RF transmitting power is fed to the antenna trough non-contact choke flanges at deployable hinges (patented).

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 kilograms or more can afford SAR sensors. Medium SAR satellites such as SAR-Lupe[3]（Germany, total mass 770kg, 2006）, TecSAR[4]（Israel, 300kg, 2008） have been launched. NovaSAR-S[5]（United Kingdom, 400kg）and ASNARO-2 (Japan, 500kg）are planned to be launched. These large or medium satellites cost hundreds million US dollars including launching cost.

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 3-10m that is useful for earth observation and monitoring. If this satellite is injected to a low earth orbit with 300km altitude, the ground resolution can be 1m although life time of the satellite is short.

Section 2 discusses on a SAR system scaling law and the specification of a SAR system that is compatible with 100 kg class small satellite. Section 3 describes the technology developments and preliminary test results of the engineering model. Description on SAR system and satellite integration is shown in section 4. Section 5 and 6 are for future plane and conclusion.

2 SIZING of SAR SYSTEM

In order to realize a SAR system that is compatible with a small satellite, a SAR scaling law should be considered, paying attention to satellite resources (RF power and antenna size), and SAR performances (resolution and image quality). The details are described in[1,2,6] .

$$\sigma_{NE}{}^{\circ}\delta_r = (8\pi R^3 k T_o v_{st})(NFL_s)\frac{\lambda}{P_{TX-ave}A^2\eta^2} \quad (1)$$

where σNE_o (a noise equivalent sigma zero) is a 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 a ground range resolution, R is a distance between the satellite and the observation target, k is the Boltzmann constant, $T_0 = 290$K, v_{st} is a satellite velocity, NF is a noise figure of the receiving system, L_s is a system loss, P_{TX-ave} is an average transmitting RF power, λ is an observation wavelength. A and η are an area and an aperture efficiency of the antenna.

The left-hand side of Eq.(1) is a performance index, namely a product of its ground resolution and the image noise. The right-hand side corresponds to the resources required to realize its performance such as a RF power, an antenna area, a noise figure, and RF loss. Note that the required resource term is inversely proportional to an average RF power and a square of antenna area and is proportional to an observation wavelength. A RF power and antenna area required to obtain a constant

SAR performance $\sigma NE_o\delta_r$ (resolution times noise) become smaller as observation wavelength is shorter. If we accept a coarse ground resolution, then the image quality can be improved.

We have designed a X band SAR compatible with 100kg class satellite as shown in Table 1. The RF peak power is selected to be less than 1000 W that is realized by GaN solid state amplifiers, instead of vacuum tube TWTAs.

For a better image quality with σNE_o = -20 dB, a ground resolution of 10 m can be achieved. Furthermore a ground resolution of 3 m is realized if one accepts image degradation of σNE_o = -15dB, which is still enough for sight recognition.

Another version of small SAR satellites is high resolution SAR with low altitude orbit. A ground resolution of 1m can be obtained where the orbit

Table 1. Specification of SAR System Compatible with 100kg Class Satellite

Item	SAR Mode	
	Strip Map	Sliding Spot Light
Altitude	600km	300km
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（TBD) Hz	
NESZ (beam center)	-15dB	-22dB
Ambiguity (beam center)	>15dB	

altitude 300km, RF bandwidth 300MHz, and RF peak power 1000W. This orbit has only a short life and is limited to on-demand, responsive missions for disaster management.

3 TECHNOLOGIES for SMALL SAR

3.1 Configuration of Small SAR Satellite

In general a SAR system requires an antenna with several m^2 area. There have been several types of SARantennas : 0) body mount antenna on a large satellite structure with 3-5m length (TerrSAR-X[7], Nova SAR-S[5]), 1a) deployable (passive) parabolic antenna with 3-4m diameter (SAR-Lupe[3], TecSAR[4], ASNARO-2), 1b) deployable passive plane antenna (Seasat[8], ERS-1[9]), 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 2 shows architectures of deployable SAR antenna and feeding system, excluding 0) body mount antenna.

The types of body mount antenna 0) and parabola antenna 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.

Possible configuration of a 100Kg SAR satellite compatible piggy back launch is satellite outlook shown in Fig.1. All electric instruments are installed in the satellite body and several passive antenna panels are deployed to compose antenna area of several m^2. Its stowed size is 0.7m x 0.7m x 0.7m and the solar cells are installed at the rear side of the antenna. Figure 1 shows the conceptual configuration.

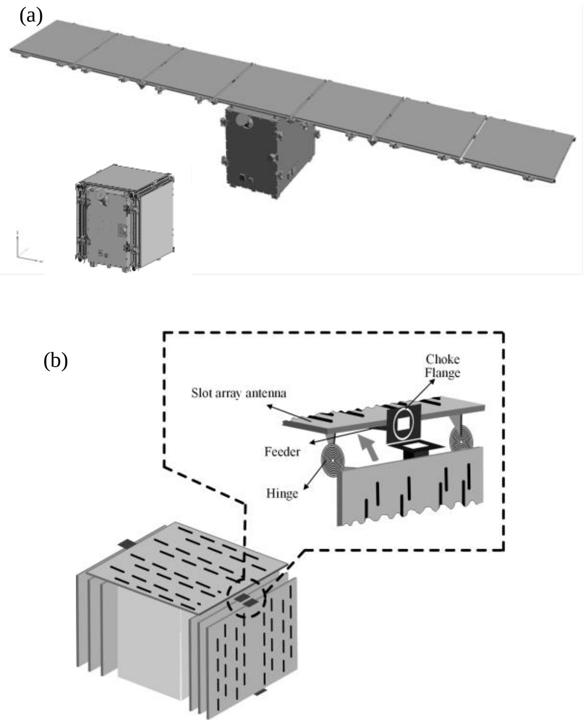
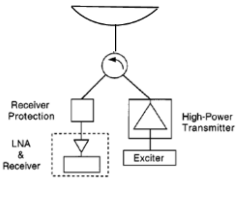
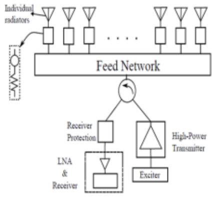
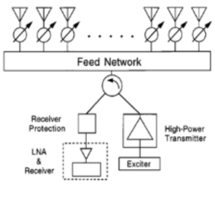
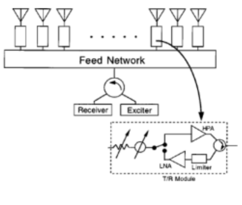


Fig.1 (a) Outlook of small SAR satellite. 0.7x 0.7 x 0.7m^3 in stowed configuration. Antenna size is 4.9m x 0.7m. (b) Non-contact waveguide feeding with choke flange at hinge.

Table 2: 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

3.2 *Deployable Plane Antenna*

As shown in Table 1, the SAR system requires an antenna of several meters in orbit. A stowed size of the satellite in a rocket should be less than 0.7x0.7x0.7m^3 for small launchers. One of the most feasible candidates is passive, deployable, honeycomb panel antenna with slot array [13, 14]. This antenna is friendly with a plane honeycomb structure and relatively high aperture efficiency.

Figure 2 shows structure of an antenna panel. Its size is about 70cm x 70cm x 0.6cm. 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 a dielectric honeycomb core and metal skins, which work as a parallel plate guide for RF. The front surface with two dimensionals array of radiation 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.

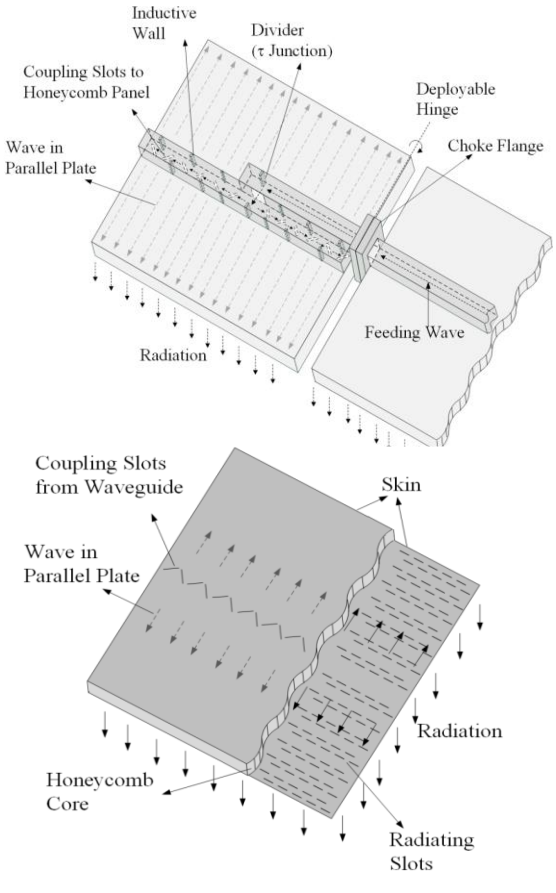


Fig.2 Structure of antenna panel. Upper part is outlook with feeding waveguide. In lower part feeding waveguide is omitted to explain antenna function.

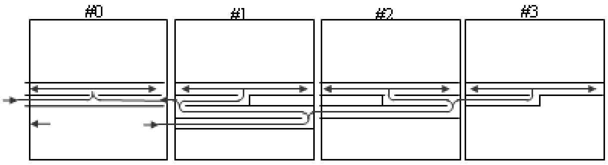


Fig.3 Waveguide feeder network is embedded in antenna panels. Panel #0 is on satellite body. Left wing is symmetric and omitted in this figure.

Fig.4 Photograph of engineering model of antenna panel #3. 70cmx70cm.

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 3 is the waveguide feeding networks for an antenna wing. Panel #0 is on the satellite body and the other wing is symmetric configuration. Figure 4 is the photograph of the engineering model of antenna panel #3 (70cmx70cm).

3.3 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[15]. 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. For a newly developed choke, RF loss is below 0.05dB at all regions of our frequency band and the possible misalignment. Note that reflection at the gap is less than -25dB.

3.4 Engineering Model of One Antenna Wing

We are developing electrical model, structural model and engineering model of one antenna wing which consists of four panels with size of 2.8m x0.7m. Figure 5 is a photograph of near field RF measurement and photogrammetry measurement of engineering model at A-Metlab Facility, Kyoto University. Figure 6 shows the antenna directivity of several panel configurations such as single panel (#3), two-panels (#2+#3), three-panels (#1+#2+#3) and four-panels (#0+#1+#2+#3) . The panel identification number is indicated in Fig.3. The peak directivities at the center frequency 9.65GHz are 36.7dBi for one-panel, 39.6dBi for two-panels, 41.6dBi for three-panels, and 42.4dBi for four-panels, respectively. These values are almost proportional to number of the panels in decibel, indicating that effective in-phase excitation of antenna panels is achieved and antenna arraying can works as designed.

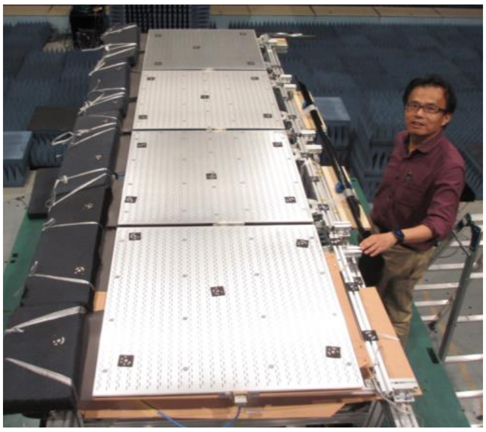


Fig.5 Near field RF measurement and photogrammetry measurement of engineering model (one wing, four panels, 2.8m x0.7m) at A-Metlab Facility, Kyoto University.

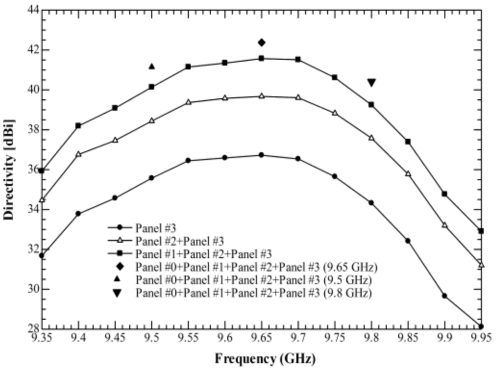


Fig.6 Antenna directivity as function of frequency by near field measurement. Antenna configurations are single panel, two-panels, three-panels and four-panels (2.8mx0.7m).

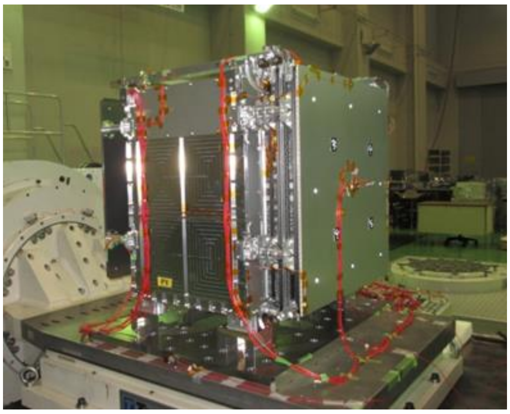


Fig.7 Structure model vibration test of antenna wing stowed on satellite body.

Figure 7 is a photograph of structure model vibration test of antenna wing stowed on satellite body. We have confirmed that the structural model of the SAR antenna wing and the satellite body satisfy requirement of rigidity and strength for launchers. We also performed deployment tests of one wing antenna model with air bearing system. The surface shape after deployment is measured by photogrammetry measurement to confirm the antenna surface accuracy. Figure 8 is a photograph of the deployment test. The stow-deployment configuration is “wrapped-round” type, the merit of which is that the hinge mechanical parts do not stick out from the radiation surfaces.

In order to satisfy our SAR system performance, the surface deformation of antenna wings is designed to be less than 1mm rms, or $\lambda/30$. We have checked manufacturing surface errors, the thermal deformation in orbit so on so forth by means of numerical analysis

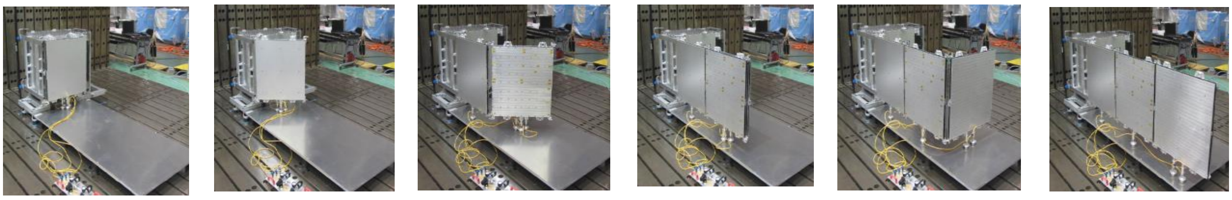


Fig.8 Deployment test of one-wing antenna structural model with air bearing system. We measure surface shape after deployment by photogrammetry measurement.

and several panel-level tests. Repeatability of deployment angle of the panel hinges is successfully confirmed to be a order of 1/100 deg at the deployment test of Fig.8 even before and after the vibration test of Fig.7.

3.5 GaN Power Amplifier

Recently advanced solid state amplifiers with GaN HEMT devices have been developed, and they are almost ready to apply in space in X band. At present we apply internal matching, 200 W pulse amplifier packages to our system. Newly 300W amplifier packages will be applied soon. Duty cycle ratio is also important for SAR performance (see Eq.(1)). Conventional SAR satellites have adopted duty cycle ratio of typically 10%. We will develop a GaN amplifier with higher duty cycle ratio of 20-30%, paying attention to its thermal design. We will combine RF output from 6 GaN amplifiers with a waveguide resonator combiner and obtain 1000W peak output.

4. SAR SYSTEM AND SATELLITE BUS

The SAR system is provided with a nominal strip-map mode and a spot-light mode with satellite attitude maneuver. There are two resolution modes. One is a fine resolution (3 meter) mode with degraded image quality (σNE_o = -15dB) for sight-recognition application. Another is a coarse resolution (10 meter) mode with better image quality (σNE_o = -20dB).

The chirp bandwidth is 300MHz for 1m ground resolution and the average data generation rate is 1.5Gbps. Then these data are stored at a NAND flash solid-state recorder with 1Tbyte capacity. The observed data will be transmitted to ground station through a high-speed X band link. A high-speed downlink of 64 APSK, 100Msps has been demonstrated in Hodoyoshi 4 satellite in 2014[16]. Based on this technology, we are developing dual polarization channel X band link with 300Msps aiming at 2-3Gbps.

In general SAR system consumes relatively large power. Most conventional SAR satellites can operate SAR observation only for 5 minutes per one orbit revolution (100 minutes) due to severe constraint of power and heat. Similarly we assume 5 minutes SAR operation in one orbit revolution. The consumption power of our SAR system is estimated to be about 460 W during SAR observation. Solar cells are thin-film solar cell sheets with 500 W capacity, which is installed at the rear side of the SAR antenna panel. Multilayer insulators effectively isolate the antenna from solar heat. Careful thermal and mechanical designs have been performed so that thermal deformation of the antenna is small enough for SAR observations. Duty cycle of SARobservation is about 5%. Power of 460 W for SAR operation is supplied from batteries with a very high discharge rate of about 3C. Li-Ion battery with olivine-type cathode will be developed for the peaked power profile.

Heat generation during SAR observation is about 800 W. Since duty-cycle of SAR observation is about 5%, the average heat generation is about 40W throughout one orbit revolution. Thermal balance for one orbit revolution can be designed taking into account heat capacity effects.

Attitude control accuracy is required to be as good as 0.06°, which is roughly 1/10 of azimuthal antenna beam width 0.6°. Maneuver rate is required to be 1°/sec in order that RF beam keeps pointing to the target for sliding spot-light mode. A SAR antenna may have small rigidity with a hinge structure. Attitude maneuver algorithm is paid to special cares to avoid vibration excitations. A satellite is in sun-pointing mode for power balance in periods except for SAR observation and data down link.

5. FUTURE PLAN

Proposed SAR satellite Technology provides a great business opportunity with promising growth potential.

Results from engineering model testing indicate that compact SAR antenna design developed here can accommodate wide-area observation mode or high resolution mode. Multiple SAR satellites allows frequent revisit, rapid coverage, and InSAR.

Development of value-added applications and services using SAR data is also implemented with potential users and providers in Japan.

Several inquiries are received from US and European private companies as well as space organizations. In compliance with laws, we started information exchange with several entities compliance with laws. We continue pursuing business partnership opportunities with companies with data and analytic capability.

6. CONCLUSION

This paper describes the system and the engineering model test of a X band SAR which is compatible to a 100kg class satellite. When this small SAR satellite is injected to typical earth observation orbit with 500-600 km altitude, its ground resolution is expected to be 3-10m that is useful for earth observation and monitoring. If this satellite is injected to a low earth orbit with 300km altitude, the ground resolution can be 1m. This small SAR project for a responsive observation is funded for 2015 - 2019 by Japanese Government.

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