Compact X band Synthetic Aperture Radar

on 100kg Small Satellite

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Abstract: We are developing a small synthetic aperture radar (SAR) that is compatible with 100kg class satellite. A constellation of such small SAR satellites is promising for shot revisit time of earth observations. The SAR antenna is a deployable honeycomb panel antenna with slot array, that can be stowed compactly. RF instruments are on a satellite structure and feed through waveguides. RF signal feeds through a choke flange at a hinge. The current status of the hardware development will be presented.

Key words small satellite, synthetic aperture radar, X band, slot array antenna, choke flange

1. Manuscript Format

Synthetic Aperture Radar (SAR) is a well known remote sensing technique with reliable capabilities that offer advantages over an optical sensor. However, SAR sensors require relatively large antennas with several meters and high RF power of hundreds watts or more. Up to now, only large or medium size satellites with hundreds kilo-grams or more can afford SAR sensors. These large or medium satellites cost hundreds million US dollars including launching cost.

In this paper, we propose a synthetic aperture radar sensor compatible with 100kg class piggy-back satellites. A 100kg satellite may cost roughly ten million US dollars. Furthermore it can be injected into an orbit as a piggy-back, resulting in total mission cost of less than twenty million US dollars.

Section 2 discusses on a SAR system scaling law and the specification of a SAR system that is compatible with 100 kg small satellite. Section 3 describes technology developments for a compact SAR system. Feasibility study on SAR system and satellite integration is shown in section 4.

2 Sizing of SAR System

We can make a constellation of these small SAR satellites because of the low cost per a satellite. The purpose of this SAR satellite constellation is to observe targets with a short revisit time. Targets that may change in a short time may be exposed on the earth surfaces. X band is suitable for such SAR observations. In order to realize a X band SAR system that is compatible with a small satellite, a SAR scaling law should be considered, paying attention to satellite resources such as RF power and antenna size, and SAR performances such as resolution and image quality. The details are described in [1-3].

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

where σ NEo (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＝290K, vst is a satellite velocity, NF is a noise figure of the receiving system, Ls is a system loss, PTX-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 p erformance 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 σNEo δr (resolution times noise) become smaller as observation wavelength is shorter. If we accept a larger amount of noise, a ground resolution can be finer. This point is a good contrast with optical imaging in which its resolution is determined independently from its

Table 1.
Specification of SAR System Compatible with 100kg Class Satellite for Ground Resolution 3m &10m

Parameter	3m resolution	10m resolution
Frequency (GHz)	9.65	9.65
Altitude (km)	618	618
Off Nadir (degrees)	21	21
Pulse Bandwidth (MHz)	127	38
σ°NE(dB)	-15	-20
Resolution (m)	3	10
Swath Width (km)	28.55	28.55
Antenna Size (m)	4.6x0.7	4.6x0.7
Peak Power (W)	581	592
Transmit Duty Cycle	0.29	0.278
System Noise Temperature (K)	589	589
Noise Figure (dB)	4.8	4.8
System Loss (dB)	4.5	4.5
Antenna Efficiency	0.6	0.6

signal-to-noise ratio.

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 600 W that is realized by a GaN solid state amplifier, instead of vacuum tube TWTAs.

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

3. Technologies for Small SAR Satellite

3.1 Configuration of small SAR satellite

In this section, we consider a configuration of small SAR satellite compatible with piggy-back launch.

In general a SAR system requires an antenna with several m2 area. There have been several types of SAR antennas : 1) body mount antenna on a large satellite structure with 3-5m length (TerrSAR-X, NovaSAR-S), 2) deployable parabolic antenna with 3-4m diameter (SAR-Lupe, TecSAR, ASNARO-2), 3) deployable active phased array antenna with distributed TX/RX modules (ALOS, RadarSAT). The case 1 and 2 are not applicable for piggy-back launch that requires stow small size than 0.7m x 0.7m x 0.7m. In the case 3 the active phased array antennas with 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 a conceptual 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 m2. Its stowed size is 0.7m x0.7m x0.7m and the solar cells are installed at the rear side of the antenna. Figure 1 shows the conceptual configuration.

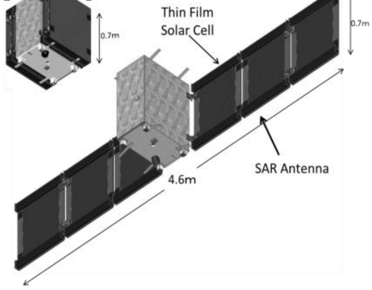

Fig.1. 100kg – class SAR satellite. Left is configuration stowed in rocket. Right is deployed configuration.

3.2 Deployable plain antenna

As shown in table 1, the SAR system requires an a ntenna of several meters in orbit. A stow size of the satellite in a rocket should be less than 0.7x0.7x0.7m3 for piggy back launch. One of the most feasible candidates is deployable plain antenna. A single-layer slot array antenna[4] is friendly with a plain honeycomb structure and a relatively high aperture efficiency.

Figure 2 is the antenna structure. The plain slot array antenna consists of dielectric honeycomb core plate and metal skins, which work as a dual plate guide for RF. Its size is about 70cm x 70cm x 0.6cm. The front surface with a slot array works as an antenna radiator. Waveguides are installed at two sides of the rear surface in order to feed positive-direction and negative-direction traveling wave into the dual plate through slots at the waveguide wall. Right-hand and left-hand circular polarizations are radiated through the slots at the skin. It means that one aperture surface can work as a dual polarization antenna. 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.

A first experimental model of the antenna with single polarization (RHCP) has been developed [5] as a collaboration with Ando and Hirokawa laboratory, Tokyo

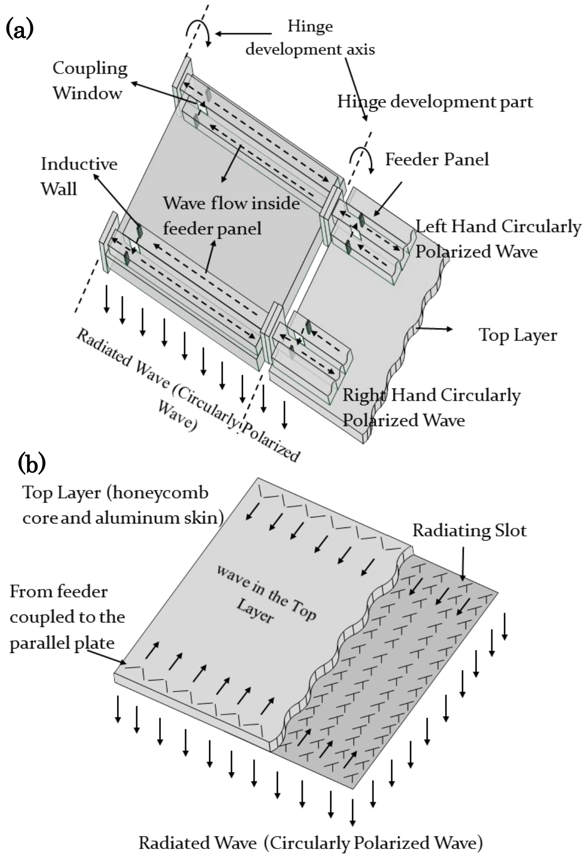

Fig. 2. (a) Antenna panel from feeder side.
(b) Antenna panel without feeders

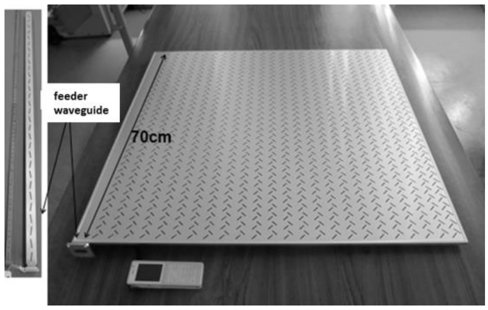

Fig.3 Right: One-layer honeycomb panel slot array antenna (70cmx70cmx0.6cm). There is a feeder waveguide. Left: Feeder waveguide before installed in antenna. There are periodic coupling slots at bottom wall.

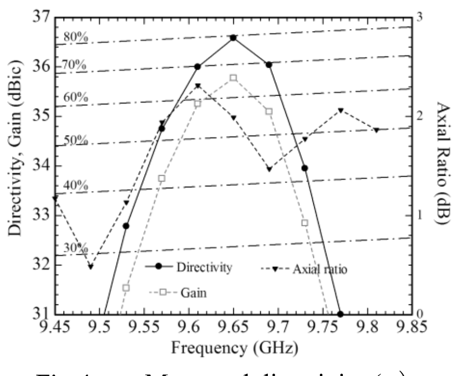

Fig.4 Measured directivity (●), antenna gain(□), axial ratio(▼) of one-layer honeycomb panel slot array antenna.

Institute of Technology. The antenna is one-layer slot array antenna with 70cm x70cm x 0.6cm honeycomb panel, whose center frequency and bandwidth are 9.65GHz and 130MHz, respectively. The photograph is shown in Fig. 3. Near field measurements and far field measurements have been performed and a preliminary result is shown in Fig.4. The antenna aperture efficiency of about 55% is achieved.

3.3 RF feed with non-contact waveguide apertures

The next problem is to feed RF to each deployable antenna panel. There are conventional RF feed 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 a choke flange for waveguides to this problem in order to realize RF feed with non-contact waveguide apertures [6]. A choke flange has 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, a wall current flows smoothly with an effective 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 waveguides.

We have measured the effect of choke connection [6]. A rectangular waveguideWR-90 with a test flange is faced to another waveguide with a cover flange UBR100. There is a spatial gap between two flanges. We have measured the RF loss due to a gap by means of a network analyzer. Δx, Δy, and Δz are gap with repect to the wide – wall direction, the narrow – wall direction, and the axial direction, respectively.

RF loss due to a flange gap is measured for three test flanges. 1) a cover flange UBR100, 2) a standard circular choke flange (CBR100 with gasket), 3) a newly developed egg-shape choke flange [7]. Photograph of 2) and 3) is shown in Fig.5. Measured RF losses are shown in Fig.6 as functions of an axial gap distance Δz. For the cover flange case 1), we observe 1.1dB loss at Δz=0.5mm. For the standard choke flange, the RF loss is effectively reduced. However, a resonant peak appears at Δz=0.8mm. For the newly developed egg-shape choke, RF loss is

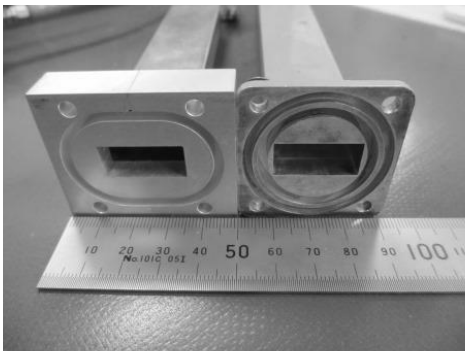

Fig.5 Right: Conventional choke flange with gasket ditch for WR90 waveguide (CBR100). Left: Newly proposed egg-shaped choke flange for WR90 waveguide.

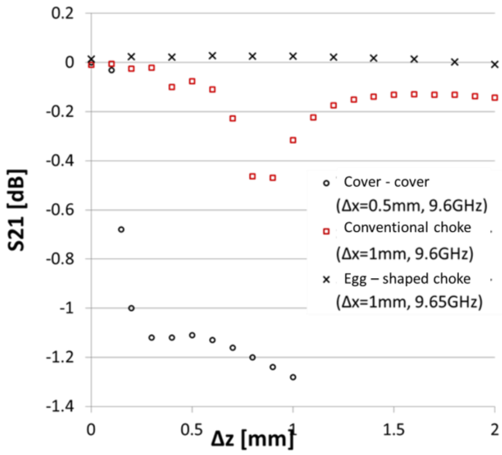

Fig.6 Measured RF losses due to gap between two WR90 waveguides. Horizontal axis is axial gap distance Δz. Verticl axis is RF loss S21(dB). One waveguide flange is cover flange UBR100. Other waveguide flanges are cover flange UBR100 (○) , conventional choke flange CBR100(□), and newly proposed egg-shaped choke flange (╳).

below 0.05dB at all region of Δz=0-2mm. Note that reflection at the gap is less than -25dB. We will apply the egg-shape choke flanges at the deployable hinges of the antenna feed waveguides.

3.4 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. We assume 600 W as a peak RF power, which can be practically generated by GaN HEMT devices.

We have already developed X band amplifiers of AB class and F class for high data rate down link system [8]. The F class amplifier achieved a power-added efficiency of 63%. Based on this development, a pulsed 30W amplifier was developed with a AB class internal matched package device, achieving power-added efficiency of 38%. At present we are going to develop a 130 W pulse amplifier.

Duty cycle ratio is also important for SAR performance. 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 GaN amplifiers with a spatial combiner.

4. SAR System and Satellite Bus

JAXA has developed and launched in 2012 a 100kg satellite, SDS-4 [9]. Based on the SDS-4 heritage, we have been designing a SAR system which is compatible with a 100kg satellite. The preliminary result shows it is feasible to bear the SAR system.

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 (σNEo = -15dB) for sight-recognition application. Another is a coarse resolution (10 meter) mode with standard image quality (σNEo = -20dB). As described in 3.1, the single layer slot array antenna can be a dual circular-polarized (R and L) antenna with a single aperture area. We construct a compact polarimetric SAR which is compatible with a small satellite. The SAR system transmits one circular –polarized (either R or L) signal and receives two circular-polarized (R and L) backscattered signals.

The received data is digitized in four channels (I/Q channels for R/L polarizations) with a rate of less than 150 Mbps. Then data are stored at a solid-state recorder with 50-100Gbyte capacity. The observed data will be transmitted to ground station through a high-speed X band link that has been demonstrated in Hodoyoshi 4 satellite in 2014 [10]. The maximum data rate is 348 Mbps with 16QAM modulation.

In general SAR system consumes relatively large power. Most conventional SAR satellites can operate SAR observation only for 5-10 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.

A solar panel is thin-film solar cell with 210 W capacity, which is installed at the rear side of the SAR antenna panel. The thin-film solar cell loosely couples with the SAR antenna panels. Thermal deformation may be small enough for SAR observations. Duty cycle of SAR observation is about 5%. Power of 460 W for SAR operation is supplied from batteries with a very high discharge rate of about 3C. Dedicated Li-Ion battery with olivine-type cathode will be developed for the peaked power profile.

Heat generation during SAR observation is about 300 W. Since duty-cycle of SAR observation is about 5%, the average heat generation is about 30W 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 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. Conclusion

This paper describes the goal and system description of a piggy-back satellite with a small SAR. The system analysis shows that a ground resolution of several meters is possible with X-band. Possible applications are to form a constellation of tens piggy-back SAR satellites for disaster managements and maritime security, which require short revisit time.

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