Development of small satellite for X-Band compact synthetic aperture radar

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Abstract. JAXA/ISAS, University of Tokyo, and Keio University have been developing an X-band compact synthetic aperture radar (SAR) system and carrying out satellite system design. Many SAR satellites are operating on orbit. Generally, weight of SAR satellites vary from three hundred to a few thousand kilograms. Compact SAR satellite has several issues. For example, high power management during mission operation, thermal management of high power amplifier, EMC related with high power consumption and target pointing with high accuracy. Considering above issues, we carried out system design of the X band compact SAR satellite and have obtained feasibility of the system. Engineering model or flight equivalent model of x band compact SAR equipment such as an antenna, a high power amplifier, a mission data recorder and a x band data transmitter have been developing and there characteristics are measured. Integration and testing of a demonstration satellite will start from the beginning of 2019 and first demonstration satellite will be launched within 2019.

1. Introduction

There are many users of image data of earth observation from space with optical sensor and synthetic aperture radar (SAR). Generally, S-band, L-band and X-band are applied to SAR, and weight of SAR satellites vary from three hundred to a few thousand kilograms. In general, a SAR system for small satellite requires an antenna with a several square meters of area. It is difficult to load a large SAR antenna on a satellite body. There are several kinds of SAR antenna, which are categorized in three types.

(1) A body mount antenna on a large satellite structure with 3-5m length such as TerraSAR-X and NovaSAR-S [1],
(2) A deployable parabolic antenna with 3-4m diameter as TecSAR and ASNARO-2 [1],
(3) A deployable active phased array antenna with distributed TX/RX modules which is applied to ALOS and RadarSAT [1].

Types 1 and 2 are not suitable for small or micro satellites launched as piggyback satellites. In the case of type 3, the active phased array antennas with TX/RX modules are exposed to space environments and are not applicable to small satellites. Figure 1 shows examples of SAR satellites. If a compact SAR satellite of 100kg class with high resolution is realized, usage of SAR satellite will be more expanded.

A small satellite is easy to manufacture, handle and launch. On the other hand, SAR is useful to observe ground during nighttime and cloudy weather. Therefore, a SAR mission with microsatellite could be a great contribution. In order to load SAR antenna on a small body of the micro satellite, new
type of SAR antenna is proposed. To achieve high resolution with small antenna, X band is selected. JAXA/ISAS, University of Tokyo, and Keio University have been developing X-band compact SAR system funded by ImPACT Program of Council for Science, Technology and Innovation (Cabinet Office, Government of Japan). Performance of the SAR system is planned to be evaluated by a flight equivalent model, and total system including ground facilities is studied by the University of Tokyo and Keio University. Preliminary design of a satellite system with the compact SAR is carried out by the ImPACT Program, and a demonstration satellite has been developing with another scheme and planned to be launched within 2019.

Figure 1. Example of SAR satellites [1].

2. Small SAR system
X-band SAR, of which the center frequency is 9.65GHz, is selected to achieve 1 m resolution from 300km altitude [6]. SAR antenna is constructed with six deployable panels and one fixed panel on the satellite center body. The SAR antenna size is 70 x 490 cm. Dimension of the satellite of launch configuration with stowed SAR antenna panels is around 75 x 75x 75cm. Flexible thin solar cells are installed on the back side of the SAR antenna panels. Figure 2 shows an overview of the satellite of on-orbit and launch conditions.

Many feeder waveguides are allocated in the SAR panel as shown in figure 4(a) and many radiating slots are arranged as shown in figure 4(b). All electric instruments such as SAR amplifier,
SAR control electronics, mission data storage and data transmitter are located in the satellite center body. Figure 3 shows a system block diagram of small SAR system. Flexible thin solar cell is located on the backside of the SAR antenna panels in order to generate power.

![System Block Diagram](image)

**Figure 3.** Block diagram of X-Band SAR system [1].

### 2.1. SAR antenna panel

Many feeder waveguides are installed in the SAR panel as shown in figure 4(a) and many radiating slots are arranged as shown in figure 4(b) [2] [3] [7] [8]. This configuration of antenna panel works as a passive SAR antenna.

![Antenna Panels](image)

**(a)**

**Figure 4.** SAR antenna panel: (a) antenna panel with feeder, (b) radiating slots of antenna panel.

We have developed an electrical model, structural model and an engineering model of one antenna wing, which consists of four panels including center panel which total size is 2.8m x 0.7m. Using these models, antenna deployment performance was evaluated as figure 5 with air bearing system. The flatness of panel surface after deployment was measured by photogrammetry measurement to confirm the antenna surface accuracy. Antenna pattern was measured by near field RF measurement facility as shown in figure 6. Structural antenna panel model of one wing stowed on the satellite mass dummy body was offered to acoustic vibration test as figure 7, and sinusoidal vibration test, which was carried out as satellite system as shown in figure 8 [4].
Figure 5. Panel deployment test with air bearing system.

Figure 6. Near-field RF measurement: (a) test facility and SAR panel, (b) SAR antenna panel of one wing.

Figure 7. Acoustic vibration test.

Figure 8. Sinusoidal vibration test.

2.2. X-band Power Amplifier (XPA)
Recently advanced solid-state amplifiers with GaN HEMT devices has been developed. At present we apply internal matching, 200 W pulse amplifier packages to our system. Our GaN amplifier modules are provided with higher duty cycle ratio of 25%, paying attention to its thermal design. The final amplifier stage of each amplifier module consists of two 200W rated-power devices in parallel, where one device amplifies 100W, half of rated-power output. In this case the device junction temperature is
below 150 °C and the device package temperature is below 90 °C, which satisfies reliable operating temperature of the device. Two 100W outputs are combined in the micro-strip circuit to achieve 200W output. Then outputs of six amplifier modules are combined with a waveguide resonator combiner and obtain 1000W peak output. The power amplifier modules and the power combiner are integrated directly on the satellite panel of aluminium alloy with 5kg mass. At operation of 1000W RF output, and duty cycle 25%, 1100W heat is generated at the amplifier system. This heat is stored at the aluminium alloy panel during SAR operation preventing thermal stress of the device. Figure 9 is a photograph of X band Power Amplifier (XPA) on aluminum satellite panel [4][9].

2.3. Mission Data Recorder (MDR)
A SAR-Electronics Unit (S-ELU) handles transmitting signal generation, receiving signal processing (frequency conversion and analogue-to-digital conversion) for SAR sensor. The S-ELU for small satellites has been developed based on an airborne SAR instrument, which supplies SAR data with average rate of 1.5Gbit/sec. In the SAR observation mode, this SAR data is transferred to Mission Data Recorder (MDR) through serial RapidIO (sRIO) interface. MDR consists of commercial 16 NAND flash memory devices and the total memory capacity is 768Gbyte. Figure 10 shows flight equivalent model of Mission Data Recorder (MDR) [4].

2.4. X Band High Speed Transmitter (XTX)
The observed data is transmitted to ground station through high-speed X band link. We are developing dual polarization channel X band link with total 2-3Gbit/sec capability. Allocated radio frequency for earth observation is 8025-8400MHz (375MHz bandwidth). However, next band 8400-8450MHz is deep space down link band, which must be protected against possible interference. We select 64APSK modulation with 300Msymbol/sec. We apply DVB-S2X standard to this high speed down link. A ground-receiving antenna with 10m diameter is being developed. Existing 10m antenna for Ku band at JAXA’s ground station is improved to X band receiving antenna. Figure 11 is photograph of X Band High Speed Transmitter [4][10].

3. Satellite system design
System design of a technology demonstration satellite was conducted under the assumption of piggyback or sub-satellite launch in FY2019. As for the orbit, a sun synchronous orbit with 600km altitude is choose. In order to realize the micro satellite with compact SAR, several issues have to be overcome as follows.
(1) High power consumption of the SAR equipment,
(2) Reducing thermal deformation of the SAR antenna panels,
(3) Pointing ground target with high accuracy, and
(4) EMC problem caused by high power management. The heat management during SAR mission is described in subsection 2.2.

(1) A lithium ion battery is applied to supply power higher than 1000W to the SAR mission equipment during short period of mission. (2) Directing the SAR antenna panels to the Earth during night time to obtain infrared thermal energy from the earth and reduce thermal deformation of the SAR antenna
panel. (3) Control the satellite attitude with high accuracy for SAR mission in pointing observation. (4) Preventing EMC problem caused by high power consumption, EMC testing was carried out to investigate risk of EMC [5].

3.1. Power Management
During the SAR mission, a power of more than 1300W is consumed within a few minutes by the mission equipment such as X-band SAR amplifiers and control electronics. Solar cell is not suitable for supplying high power. Therefore, a lithium ion battery having capability for high discharge rate of over 3C has been selected. Power Control Unit and Power Distribution Unit, are integrated into one unit named PCDU to reduce footprint. PCDU supplies four kinds of bus power to the bus equipment, as +50V unstable, +28V stable, ±12V stable and 5V stable. The +50V and +28V power are also supplied to the SAR mission equipment. During mission operations, SAR power is supplied from the battery. Power capacity of the battery is defined considering depth of dis-charge during safe mode of the satellite system. Figure 12 shows a power profile during seven revolutions with one SAR mission [5].

3.2. Earth orienting during night time
In order to keep SAR performance, it is important to minimize alignment error caused by mechanical and thermal deformation of SAR antenna panels. The deployable SAR antenna panels have mechanical alignment error caused by thermal deformation. Especially, alignment error becomes large under low temperature condition during eclipse. To reduce alignment error, SAR panels need to be oriented toward the earth during eclipse and to obtain infrared heat input from thermal radiation from the earth. This requires attitude control system to have earth pointing attitude during night time, where +Z axis orients to the earth, and sun pointing attitude during day time orienting -Z axis to the sun. Therefore, attitude control subsystem is required to maneuver the satellite attitude twice per revolution around its pitch axis. Figure 13 shows the concept of attitude maneuverer [5].

3.3. High Pointing Accuracy
There are three kinds of attitude control during SAR observation, strip map mode, sliding spot light mode, and spotlight mode. Large change of momentum is required for pitch axis when the satellite is in spotlight mode. Two reaction wheels are located for pitch control, however, wheels do not have enough momentum to achieve spotlight mode. In order to relax the torque and momentum requirements to the pitch wheels, a sliding spotlight mode was selected for SAR observation with high resolution. To achieve high pointing accuracy against a defined ground target point, the attitude control loop applied feed forward compensation with estimated attitude angle and rate. Figure 14 shows concept of sliding spot light mode, and figure 15 presents control error for required attitude during sliding spot light mode. [5]
3.4. EMC

Equipment for SAR mission consumes total large power more than 1300W, therefore PCDU has a risk of causing electrical and RF influence to the bus power and signal line. In order to research the interference to the system, electrical interface check was performed using breadboard model of PCDU, battery, x-band transmitter and mission data recorder which manage high power and high rate signals. EMC testing was performed and confirmed no significant interference between equipment. Figure 16 is a photograph of EMC test configuration [5].

3.5. System Configuration

System design has been performed with targeting the piggyback launch on 2019. In order to develop the satellite system within short period without risk, existing technologies except SAR mission system are applied such as reaction wheel, torque rod, S-band communication system, star tracker, digital sun sensor, GPS receiver and magnetometer. Battery, power control and distribution unit “PCDU” and satellite structure, thermal control subsystem are newly developed to fit with the micro SAR satellite. Onboard computer and flight software are modified from existing flight code. Based on the above discussion, selection of equipment and design of allocation are running side-by-side to obtain best design result. Figure 17 shows equipment allocation in the satellite center body. Satellite total mass is around 135 kg [5].
4. Conclusion
We have obtained a prospect of solution for main issues related with X-band compact SAR satellite system. Evaluation of the performance of X-band compact SAR system using flight equivalent model will be finished by the end of 2018, and manufacturing of demonstration satellite will be started from the beginning of 2019 based on the system design result aiming launch end of 2019. Table 1 shows the overall rough schedule.

Table 1. Schedule of ImPACT and related satellite system.

| MILESTONE                  | 2016 | 2017 | 2018 | 2019 |
|----------------------------|------|------|------|------|
| Kick off                   |      |      |      |      |
| Phase A Review             |      |      |      |      |
| Phase B Review             |      |      |      |      |
| Final review               |      |      |      |      |
| System Design Review       |      |      |      |      |
| Launch TBD                 |      |      |      |      |

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References
[1] Web DLR: http://www.dlr.de/dlr/eng/desktopdefault.aspx/tabid-10377/565_read-36/#/gallery/350, SSTL: https://www.sstl.co.uk/Missions/NovaSAR-S/NovaSAR-S/NovaSAR-S-Small-satellite-Synthetic-Aperture-Radar, Defense Update: http://defense-update.com/products/t/tecsar.htm, CSA: http://www.asc-csa.gc.ca/eng/satellites/radarsat2/default.asp.
[2] Hirobumi S., Akbar P. R., Ravindra V., Hiromi W., Atsushi T., Jiro H., Zhang, M. and Seiko S., *Compact X-band Synthetic Aperture Radar with Deployable Plane Antenna –Project of a100kg-Class SAR Satellite*, Small Satellites Systems and Services – The 4S Symposium 2016.

[3] Akbar, P. R., Saito, H., Zhang, M. and Hirokawa., *The development of rectangular slot array antenna on board micro XSAR*, IEICE, Technical report (SANE), SANE2014-39, 2014.

[4] Kei-ichi H., Seiko S., Toshihiro O., Shin-ichi N., Ken-ichi A., Shinobu N. and Takashi T., *Preliminary Design for On-demand Micro Satellite for SAR Mission*, IAA#11, IAA-B11-1001, 2017.

[5] Kei-ichi H., Seiko S., Toshihiro O., Shin-ichi N., Shinobu N. and Takashi T., *Preliminary System Design of Micro Satellite for Compact SAR Mission*, Small Satellites Systems and Services – The 4S Symposium, 2018.

[6] Kei-ichi H., Shin-ichi N., Masahiro K., Ken-ichi A., Seiko S., Shinobu N., Takeshi T., *Conceptual design for On-demand small satellite for SAR mission*, ISAST IV, 2016.

[7] J. Hirokawa, et al, *Waveguide-fed parallel plate slot array antenna*, IEEE Trans. antenna & propagation, vol.40, no.2, pp.218-222, Feb. 1992.

[8] Prilando R. A., et al, *Parallel-plate slot array antenna for deployable SAR antenna on board small satellite* IEEE Trans. antenna & propagation, vol.64, no.5, pp.1661-1671, May, 2016

[9] Hiromi W., et al *1000W X-Band Microwave GaN Solid State Power Amplifier for Small SAR Satellite*, Small Satellites Systems and Services – The 4S Symposium 2018

[10] Tomoki k., et al., *2Gbps Downlink System of 100kg Class Satellite for Compact Synthetic Aperture Radar Mission*, Small Satellites Systems and Services – The 4S Symposium 2018