The Multiple Imaging Modes Design of A Low Cost X-band Space-borne SAR Payload

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ABSTRACT: Taiwan has started a series of SAR payload design activities for short-revisit environment monitoring, disaster management and resource survey over its land cover targets and the surrounding seas/oceans. Cost reduction of the space-borne SAR payload under planning will be achieved by using a self-reliant array-fed reflector antenna and GaN HEMT basis PA modules. A one-piece elliptical paraboloid, made of lightweight composite material, will be attached to the satellite body as the reflector. It is deployable to trim down the satellite envelope during launch phase. The multiple feeds system in conjunction with the distributed PA modules, not only performs the spatial power combining for radar detection, but also provide the beam diversity. Five continuously arranged switched beams cover a total swath of about 50~90 km in range direction. In addition, many other switched broad beams are feasible as well. Flexible and complex imaging mode operations (normal Stripmap mode, broad Stripmap mode, ScanSAR modes and Spotlight mode) become realistic with these multiple beams having various directions and various widths.

1. INTRODUCTION

Taiwan often suffers miserable disasters (i.e., mud/land slide, flooding, etc.) from monsoons and typhoons as well as earthquakes. To apply knowledge and technology of remote sensing effectively for mitigation and contingency of the disaster is one of the urgent issues for Taiwan. Since 2004, Formosat-2 has provided a rich imagery database in the clear sky weather. Another frequent revisit orbit SAR satellite is very urgently needed for Disasters Management (DM) and Earth Observations (EO) operations.

For developing the Synthetic Aperture Radar (SAR) mission in Taiwan, SAR data application was surveyed and user conferences were hold from 2009. After that, a small satellite SAR mission was defined and it has been analyzed for a few years for seeking a payload development solution in Taiwan [1-2]. The X-band SAR satellite mission objectives were formerly scoped to provide DM supports in Taiwan, and EO in the cloudy and disaster weather. The advices from the expert committee are listed below.

Table 1 Mission guidelines for Taiwan SAR satellite

Mission parameters	Trade-off between user requirements and technology
Frequency	X-band (or C-band)
Ground resolution	1m is the best, 3~8 m is acceptable
Observation period	Daily revisit is the best,13-day revisit is secondary
Incident angle	30°~45° is necessary, 20°~50° is goal
Swath	100km is the best, 20km can be reluctantly accepted
Polarization	Full-pol. is the best, dual-pol. is acceptable
Radiometric Sensitivity (NESZ)	≤ -17dB (clear sky)

Recently, the requirements of marine and ocean monitoring were emphasized by domestic users. NSPO modified the mission requirements as in Table 2. The ScanSAR mode is employed mainly for performing ocean surface monitoring near Taiwan. The Stripmap and Spotlight modes will be employed mainly for supporting disaster management services and operations especially over the landmass targets of Taiwan.

Table 2 Key mission requirements

Parameters	Requirements
Central frequency	9.45 GHz
Altitude	~ 500km
Incidence angle	30°~45° (up to 50°)
Polarization	Dual (HH/HV and VV/VH)
Multi-beam antenna	At least 3 beams

Ground range resolution	Spotlight	1m
	Stripmap	3m
	ScanSAR	< 20m
Swath	Spotlight	~20 km
	Stripmap	~20 km
	ScanSAR	50~100 km
Radiometric sensitivity (NESZ) in clear sky	Spotlight	≤ -15 dB
	Stripmap	≤ -17 dB
	ScanSAR	≤ -23 dB

Hence the space-borne SAR payload system requirements can be flowed down as in below.

Table 3 X-band SAR payload system requirements

Key Parameters	Requirements
Chirp bandwidth	≤ 300MHz
PRF	≤ 4KHz
Pulse width	≤ 50μs
Pulse duty cycle	15~20 %
Peak Tx power	≥ 2.2KW
Receiver noise figure	≤ 5dB
Antenna gain	≥ 44.5dBi
Antenna elevation beamwidth	≥ 1.2°

2. System Architecture

Three payload subsystems (i.e., SAR Electronics, Antenna, and High Power Amplifier) were divided for the easiness of development. The preliminary subsystem requirements understood at that time were documented in [3]. The system architecture comprises the array-fed reflector antenna and the High Power Amplifier assembly is shown in Figure 1. As long as the space-borne SAR providing enough signal intensity to the antenna along the round trip slant range, fully covering Taiwan can be realized either by beam scanning or by satellite roll maneuvering. Many inputs and outputs designed in the antenna support the two dual-polarization imaging operations (i.e., either HH+HV or VV+VH) for various land covers targets and multi-beam capability. An on-going project has been initiated in 2013 mid-year to build the GaN power amplification modules. In addition, a development project of the large reflective-type antenna assembly is in progress since 2015. The SAR Electronics, which will provide transmission and receiving of RF signals and data handling, is also under development.

The low cost design approaches for building up our X-band satellite payload system are mainly in antenna and high power amplifier. The SAR Electronics are mostly conventional and won't cause too much cost reduction compared with the above-mentioned two subsystems. Aerial validation of some key parameters has been planned for the mission to reduce program risks.

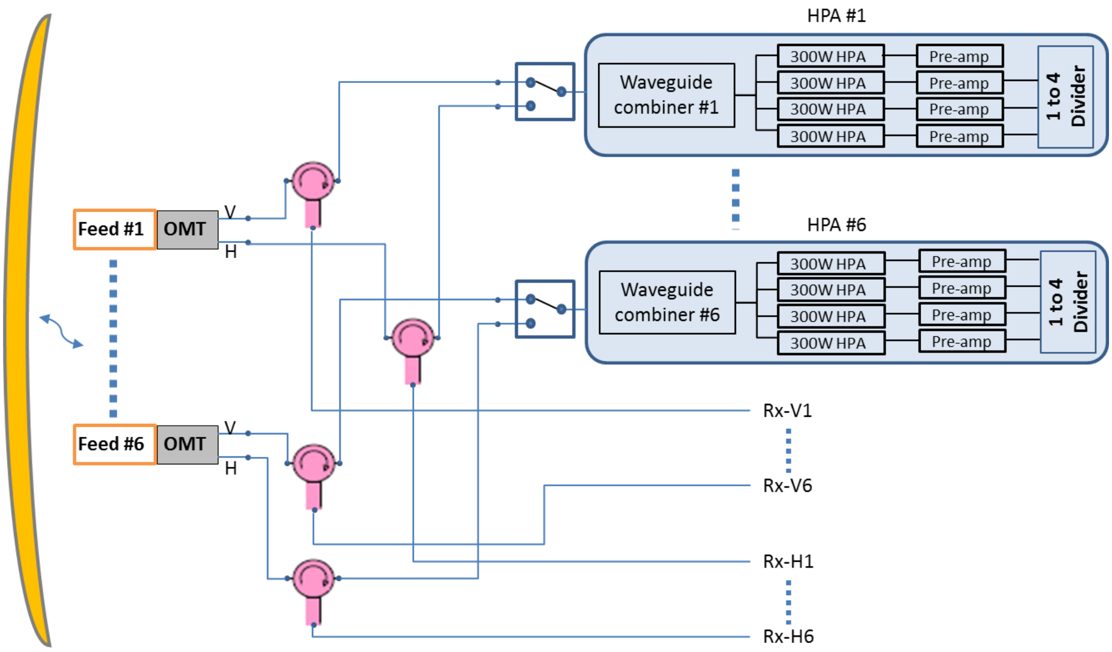


Figure 1 NSPO space-borne SAR payload system architecture

3. High Power Amplifier (HPA)

A solid state power amplification module in 8-to-1 power combining architecture with GaN HEMT devices have been implemented in Taiwan by NSPO/NCTU team. The peak output of the PA module can exceed 300W/600W as shown in [4] by the team. The voltage level supplied to the basic GaN HEMT chips will be around 40 volts, that makes the electric power management system design much easier compared to the costly HVPS (High Voltage Power Supply) required by the TWTA. At present, both 300W and 600W elementary modules are under considerations to construct the 1200W HPAs. Trade-offs between volume, combining efficiency and thermal effect of the GaN HEMT devices will be made after the accomplishment of the HPAs. Commonly, a typical duty cycle of 10% is adopted in a space-borne SAR system. We are going to build the 1200W HPAs with 20% duty cycle which is used in our NESZ system performance evaluations. Special cares on heat dissipation and electrical power generation and distribution designs are foreseen. NSPO has been proceeded the PCM (Phase Change Material) and heat pipe explorations for the HPA thermal issues.

4. High-gain Large Antenna (HLA)

Normally a SAR antenna will cost the most in a SAR satellite system. Thus, the cost reduction emphasis is on the proper antenna design and realization. In our study process, the space SAR mission was first defined by assuming that the payload antenna was similar to the one used for the TECSAR [5] mission. A 3-m X-band reflector umbrella antenna for the mission definition and the antenna beams analysis result was released in the APSAR 2011 [6] conference. It was found later the deployment mechanism and its machinery of a sizable umbrella antenna can be too complicated and it could be an impossible acquisition item for the future low cost SAR program. Then we took a reflector antenna approach similar to the one onboard the ASNARO-2 satellite [7]. It has three separate pieces before deployment, with a center piece attached to the satellite body and the two other deployable pieces to form a curved antenna main reflector after deployment, together with a second reflector and four feeds to compose a Cassegrain antenna.

NSPO has made the FORMOSAT-3, FORMOSAT-5 and FORMOSAT-7. The future space SAR programs will be carried out on the NSPO existing/developing mircosat and smallsat buses. Besides, using small-class launch vehicles for the SAR satellites, including Pegasus (OSC), Minotaur I (OSC), Minotaur IV (OSC), Delta II (ULA), PSLV (ISRO), Vega (ESA), Epsilon (IHI Aerospace), Dnepr (Yuzhmash) and Rokot (Khrunichev), is part of our cost reduction strategy. The multiple feeds system is envisioned to perform the spatial power combining, which can alleviate the burden of power combining effort with transmission lines and waveguides and provide a variety of beams. During the mission definition phase, we confined the satellite diameter to be less than 2.4 m in order to have the choice to meet more candidate launchers and even keep the piggy-back opportunity.

4.1 Configuration

The HLA (High-gain Large Antenna) is reformed to a single reflector antenna to be on board the NSPO's microsat. The reflector is a deployable elliptical paraboloid made of low cost lightweight composite material (CFRP). The conceptual antenna configuration is shown in Figure 2. The one piece reflector will be folded upon the satellite bus in the stowed configuration to trim down the satellite envelope during launch phase. The hinges for the reflector is on one side of the panel and the feed horn system is mounted on the other side of the panel.

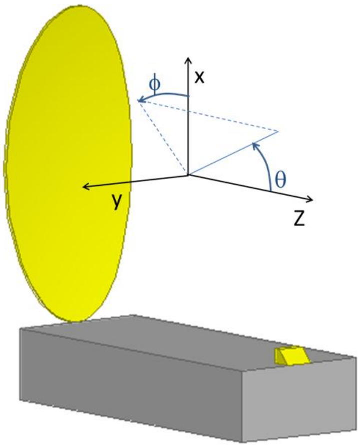
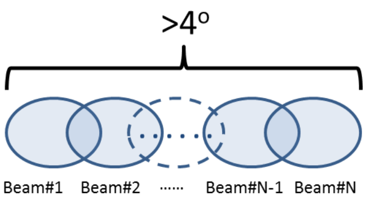


Figure 2 The conceptual configuration of the SAR satellite and HLA

4.2 Requirements

The major requirements of the HLA for the configuration stated above are as follows:

- Reflector size: ≦4m×2m×2m
- Focal length: ≦3m
- Center frequency: 9.45 GHz
- Bandwidth: ≧300 MHz
- Beam:
  1. Multiple switched beams should be available, but one beam is required at the same time.
  2. Every beam
     - Directivity: ≧44.5 dBi
     - $\phi=90^{o}$, 3-dB beamwidth≧0.7^{o}；$\phi=0^{o}$, 3-dB beamwidth≧0.3^{o}
     - Side-lobe Level:
       - ≦-25 dB, ($\theta= 30^{o}\sim55^{o}$ & $\phi=85^{o}\sim95^{o}$)
       - ≦-15 dB, other solid angles
     - Cross-polarization Level：<-25 dB。
     - Polarizations: Vertical (V) and Horizontal (H)
  3. Overlap between adjacent beams (3-dB beamwidth): ≧10%
  4. The total beamwidth of the continuous competent beams in $\phi=90^{o}$ cut: > 4^{o}



- Transmitting: Vertical (V) or Horizontal (H) selectable
- Receiving: Vertical (V) and Horizontal (H) simultaneously
- Return Loss for every feed element: ≦15 dB
- Isolation between all the Tx and Rx beams (i.e., HH,HV,VV,VH) >= 30 dB

4.3 Design and Simulations

As shown in Figure 3, the reflector of the HLA is a parabolic surface with 4 m × 2 m elliptical aperture. The feed system is composed of 6 identical dual polarizations (V and H) horns arrayed in the y-axis and placed at the focal point of 3 m away from the geometry center of the paraboloid. Many efforts were made such that the elementary feed horn has rotationally symmetric patterns about the longitudinal axis, as plotted in Figure 4.

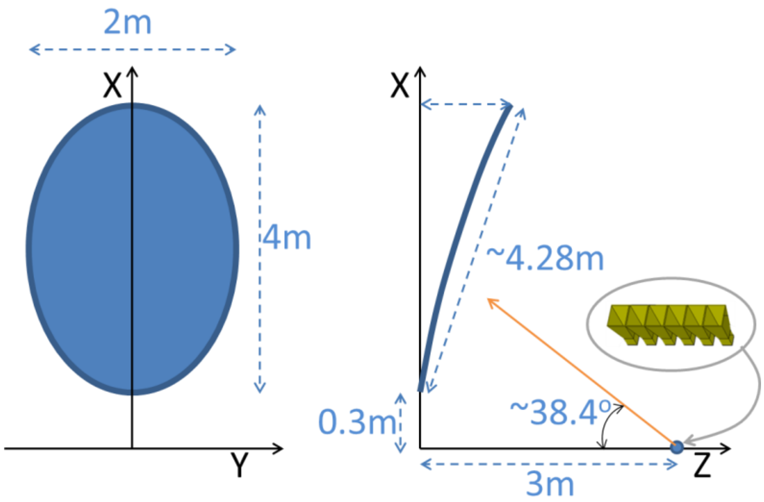


Figure 3 The preliminary design of the HLA

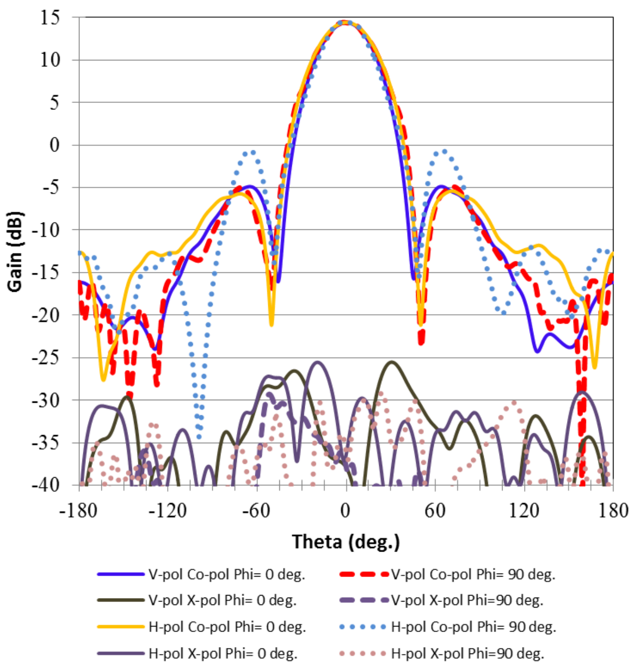


Figure 4 The simulated patterns of the elementary feed horn

Every two adjacent horns form a basic beam. Hence there are five continuously arranged switched 2-feed beams in the range direction, with a total swath of about 4.83°, for Stripmap mode operation. The simulated beams characteristics at 9.45 GHz are summarized in Table 4. In addition, three switched broad beams with 4 horns excited and the broadest beam with all 6 horns excited are practicable and summarized in Table 5. For simplicity, the biased beams on the left-hand side with respect to the central beam are included because of symmetry. The resultant beams at 9.3 GHz and 9.6 GHz are very similar to the ones at 9.45 GHz. The radiation efficiency, aperture taper efficiency, spillover efficiency, cross polarization, aperture blockage and non-ideal feed phase center effect have already been taken into account in the simulation. Only those imperfections due to implementation, like surface error, will further deteriorate the antenna gain by up to 0.5 dB in expectation.

Table 4 The simulated 2-feed beams characteristics of the HLA at 9.45 GHz

Beam@ 9.45GHz	Central (Beam #3)		1st Biased (Beam #2)		2nd Biased (Beam #1)	
Activated Horns	3&4		2&3		1&2	
Polarization	H	V	H	V	H	V
Gain (dBi)	46.57	46.18	46.50	46.11	46.31	45.93
Beam Direction	0°	0°	0.904°	0.908°	1.802°	1.812°
Phi = 0° 3-dB BW	0.512°	0.530°	0.513°	0.531°	0.518°	0.535°
Phi = 90° 3-dB BW	1.202°	1.176°	1.208°	1.185°	1.216°	1.210°
Phi = 0° SLL (dB)	-21.15	-21.84	-21.33	-21.93	-21.76	-22.05
Phi = 90° SLL (dB)	-27.75	-26.52	-26.27	-25.50	-25.41	-24.64
X-pol level (dB)	-41.09	-49.26	-38.99	-48.16	-34.70	-37.67
SLL (dB) θ = 30°～55° & φ = 85°～95°	-58.31	-61.81	-57.42	-60.76	-56.84	-60.40

Table 5 The simulated broad (4- and 6-feed) beams characteristics of the HLA at 9.45 GHz

Activated Horns	2, 3, 4&5		1, 2, 3&4		1, 2, 3, 4, 5&6	
Polarization	H	V	H	V	H	V
Gain (dBi)	43.16	42.68	43.19	42.71	41.26	40.71
Beam Direction	0°	0°	0.948°	0.937°	0°	0°
Phi = 0° 3-dB BW	0.495°	0.518°	0.491°	0.512°	0.4957°	0.519°
Phi = 90° 3-dB BW	3.065°	3.064°	3.038°	3.055°	4.866°	4.919°
Phi = 0° SLL (dB)	-21.99	-23.32	-22.1	-23.22	-21.57	-22.85
Phi = 90° SLL (dB)	-28.67	-26.19	-26.26	-24.2	-30.49	-28.18
X-pol level (dB)	-30.89	-29.48	-32.22	-30.67	-29.77	-29.42
SLL (dB) θ = 30° ~ 55° & φ = 85° ~ 95°	-52.41	-55.91	-51.41	-57.08	-48.54	-54.80

Following the preliminary antenna simulation results, our space SAR system shall be capable of providing five 2-feed beams where every beam combining the power from 2 adjacent feeds can perform 1.2° elevation beamwidth and 45.93 dBi gain (the minimum among all the simulated beams in Table 4) with 2400 W peak transmitting power at 18% duty cycle. The imaging swath and NESZ by operating these 5 beams at different incident angles are derived as in Table 6. Note that the normal operation in our mission design ranges from 30^o to 45^o incident angle. The operations at 50^o are unusual. It can be seen that the requirements listed in Table 2 would be met except the swaths of Stripmap/Spotlight mode at incident angles < 45^o. The swath and NESZ by three 4-feed beams at 45^o incident angles are listed in Table 7, by assuming every beam with 42.68 dBi minimum gain and 4800 W peak transmitting power at 18% duty cycle. The same condition would bring about -14.5 dB NESZ and 83 km swath for 3 m Stripmap mode imaging with the 6-feed broad beam. However, it is not in our operation plan for the time being since an astonishing peak transmitting power of 7200 W is required. Fortunately, the modular architecture of HPA alleviates the burden on power supply circuits and heat dissipating. A possible scenario is to reduce the imaging time per orbit.

Table 6 Achieved swath and NESZ in imaging operations by 2-feed broad beams (Tx = 2400 W)

Swath / NESZ	@ 30° incident angle	@ 45° incident angle	@ 50° incident angle
Spotlight (res. = 1m)	13km / -17.4dB	20km / -15.1dB	24km / -14.0dB
Stripmap (res. = 3m)	13.8km / -22.4dB	20.2km / -20.1dB	24.2km / -19.0dB
ScanSAR (res. ~ 12m)	55.3km / -28.5dB	81.2km / -26.1dB	97km / -25.1dB

Table 7 Achieved swath and NESZ in imaging operations by 4-feed broad beams (Tx = 4800 W)

Swath / NESZ	@ 45° incident angle
Spotlight, 1m resolution	54km / -11.6dB
Stripmap, 3m resolution	54km / -16.6dB
ScanSAR, 8m resolution	84.5km / -20.9dB

5. Concluding Remarks

We presents the most updated design approaches and development status of a low cost X-band SAR payload system in Taiwan. This SAR payload is accommodative to NSPO's microsats and smallsats. The integration of simple curved reflector antenna with multiple feeds and distributed solid-state power amplification modules spatially combines the required power and forms diverse beams for various SAR imaging modes operations. High reliability and flexible operations are achieved by this kind of system architecture. The antenna simulation results and system analysis show that the mission requirements would be satisfied with our current design. Moreover, three payload subsystems are all well under way.

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