ON THE DESIGN OF A NOVEL STRIX SMALL SATELLITE EXPLOITING A PASSIVE FREQUENCY SCANNING ANTENNA TO IMAGE WIDE SWATHS AT HIGH RESOLUTION

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ABSTRACT

Frequency Scan for Time-of-Echo Compression (f-STEC) and other frequency scanning Synthetic Aperture Radar (SAR) imaging techniques are attractive alternatives to Digital BeamForming (DBF) for high-resolution and wide-swath (HRWS) observations. However, f-STEC hardware implementation using active phased array antennas (APAA) and true time delay lines (TTDL) result in complex and costly SAR instrument configurations and are therefore unsuitable for small SAR satellites. In this study, we propose an approach utilizing a fully passive frequency scanning antenna to implement a frequency scanning SAR system for StriX, the small SAR constellation developed by Synspective. The paper presents the design of the small SAR system and its estimated key performance metrics. Our results demonstrate that it is possible to achieve a 2-D spatial resolution better than 6 m^2 over a swath width of 100 km with a 1.2 GHz system bandwidth in X-band.

***Index Terms*—** f-STEC, HRWS, Frequency Scanning SAR, Frequency Scanning Antenna, Small SAR Satellite, StriX

1. INTRODUCTION

Synspective is a leading private developer and operator of small SAR satellites, handling the development, operation, and data analysis of small SAR satellites. The company, based in Japan, aims to realize a constellation of 30 satellites, called StriX, by the end of the 2020s. To date, as of July 2025, Synspective has developed and launched six satellites. Figure 1 shows an image of a StriX satellite. Table 1 summarizes the performance of the StriX satellite in terms of swath width, resolution, and noise equivalent sigma zero (NESZ).

There is a tradeoff between resolution and swath width, where, in general, the compromise for improving the resolution it to narrow the swath. One recent trend is to narrow the swath to 5-10 km or less to achieve sub-meter resolution. This approach, realized by many small SAR satellites, is compatible with parabolic antennas with narrower beams and larger bandwidth. Another approach, which has been studied extensively, is to achieve both high-resolution and wide-swath observations using multi-channel technologies and DBF techniques, such as SCan-On-REceive (SCORE) [1,7]. However, implementing DBF on small SAR satellites is a challenge, and further requires a costly and complex hardware/software including on-board DBF processors.

Frequency scanning SAR is a newly proposed technique that has attracted attention in recent years as an alternative to DBF [2]. Scanning the beam in the analog domain eliminates

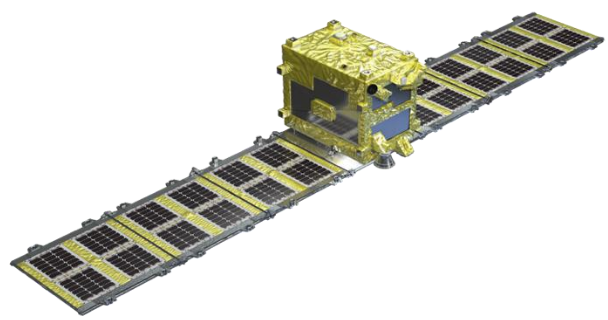


Fig. 1. Image of StriX-alpha, the first small SAR satellite developed by Synspective.

Table 1. Specifications of StriX satellites at an off-nadir angle of 30 deg.

Mode	SM	SL	ST1	ST2
Swath Width	30 km	10 km	10 km	10 km
Ground Range res.	3.6 m	0.9 m	0.9 m	0.9 m
Azimuth res.	2.6 m	0.9 m	0.5 m	0.25 m
NESZ	-21.7 dB	-15.7 dB	-17.4 dB	-17.4 dB

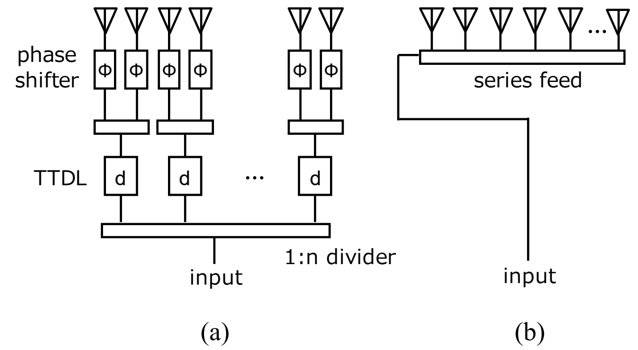


Fig. 2. Comparison of frequency scanning antenna implementation methods. (a) Phased array with phase shifters and TTDLs. (b) Series-fed array antenna.

the need for DBF processing. It also has the unique advantage of compressing the return echo duration, i.e., the required receive window length, suppressing the range ambiguities and lowering the peak-to-average transmit power ratio [3].

In this study, we propose to realize a frequency scanning SAR system using a fully passive frequency scanning antenna and implement f-STEC for a small SAR constellation. The targeted SAR resolution is in the 1m class for a swath width in the 100km class. If satellites equipped with the above frequency scanning SAR system can be added to the StriX constellation, it is expected that high-resolution and wide-area SAR data will be available to the market in larger quantities and at a lower cost than ever before.

In the following sections, an actual design example and its performance evaluation results will be presented.

2. SAR SYSTEM DESIGN

In [2], two different antenna configurations for frequency scanning SAR system are proposed. The first is a combination of phase shifters and true time delay lines (TTDL). The second is a series-fed array antenna. Figure 2 illustrates the comparison of the two different configurations. The advantage of the former method is that the beam direction and scanning characteristics can be electronically changed by switching the phase and TTDLs between antenna elements. However, active phased array antennas including transmit/receive modules with phase shifters and TTDLs are still complex and expensive, which is challenging for small SAR systems with severe resource constraints.

On the other hand, series-fed array antennas have a fixed frequency and beam pointing relationship, because the scanning characteristics are determined by the physical distance between adjacent elements. However, they have the following advantages:

- The antenna configuration is very simple, compact, lightweight, and inexpensive.
- Ideal frequency-dependent linear phase characteristics can be obtained by design. No errors due to quantization or grouping of phase shifter or TTDLs.

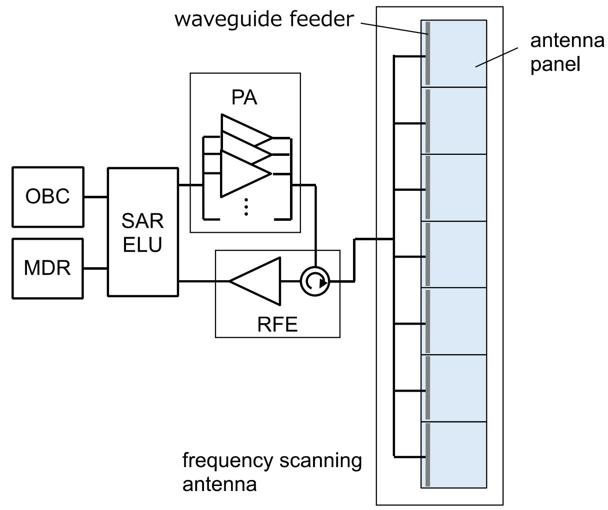


Fig. 3. Block diagram of the proposed frequency scanning SAR system (OBC: On-Board Computer, MDR: Mission Data Recorder, SAR-ELU: SAR Electronics Unit, PA: Power Amplifier, RFE: RF Front-End.)

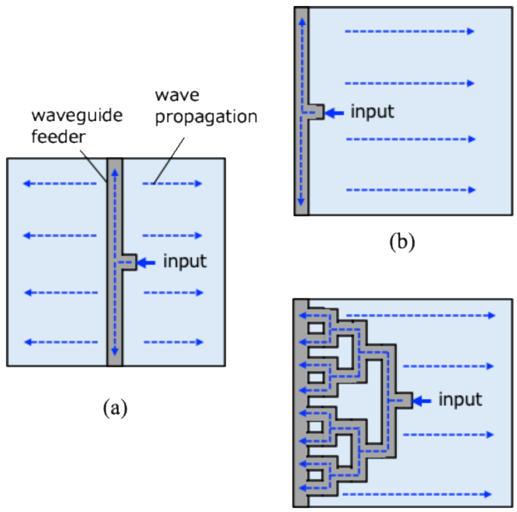
Table 2. System parameters used for the design.

Parameter	Value
Orbit Height (Equator – Poles)	510 – 532 km
Center Frequency	9.8 GHz
System Bandwidth	1200 MHz
Antenna Length	6.2 m
Average Transmit Power	810 W
Number of Azimuth Receive Channels	1

- Large delay. The delay between two ends of the 0.9 m height antenna is about 3 ns in vacuum. This allows for a large scan rate, which will be discussed later.

Based on the above considerations, a series-fed array antenna is adopted in this proposal due to its suitability for installation on small SAR satellites [8].

Figure 3 shows the configuration of the proposed frequency scanning SAR system, and Table 2 shows the system parameters. The system bandwidth is 1200 MHz which is the maximum allocation by the ITU. For efficient development, the satellite system will be as similar as possible to the existing StriX systems (see [4-6] for the detailed design of the existing satellites). The antenna consists of seven rectangular panels, which are stowed during launch and deployed after separation from the launch vehicle in orbit. Adjacent (azimuth) panels are fed by a waveguide power divider network ensuring in-phase power distribution from the power amplifier in the satellite body to the input of each panel. Solar cells are installed on the back of the antenna panel, eliminating the need for dedicated solar paddles. This design is extremely compact and lightweight, and can be manufactured cost effectively and in short time cycles, assuming multiple production.



(c)

Fig. 4. Comparison of antenna panel feeding methods. (a) Center feeding. (b) Edge feeding. (c) Edge and corporate feeding.

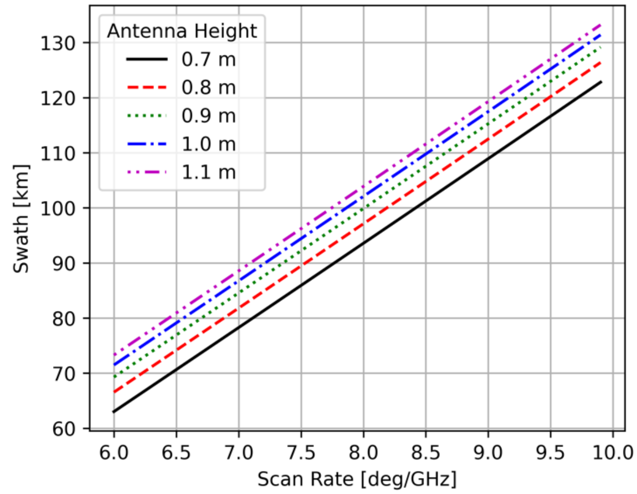


Fig. 5. Ground range swath extent as a function of scan rate with a chirp bandwidth of 1200MHz and orbit height of 510km, for different antenna heights.

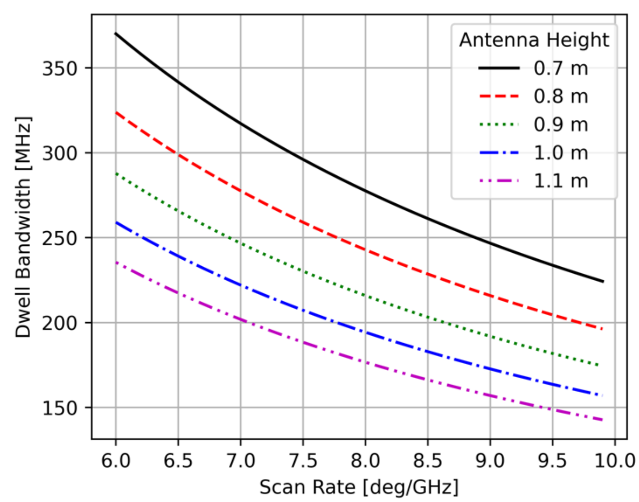


Fig. 6. Dwell bandwidth as a function of scan rate for different antenna heights.

The antenna panel shall be a passive series-fed array antenna with no built-in RF amplifier, phase shifter, or LNAs. The scan direction is in the elevation from far to near range. Since the (mechanical) pointing direction of the antenna beam at a given frequency is fixed with respect to the satellite body, changing the imaged swath is done by body pointing, which changes the satellite attitude.

3. SAR ANTENNA DESIGN

Figure 4 shows a comparison of the feeding schemes inside the panel. Figure 4a is the scheme used in the StriX satellites as reported in [4-6]. The antenna panel consists of a radiation panel of parallel plate waveguides and a feeding waveguide on the back side coupled to the radiation panel. The power supplied from the feeding waveguide excites a quasi-TEM mode inside the radiation panel, causing the quasi-TEM waves to travel outward from the center of the panel where the feeding waveguide is located. Radiation slots are used to couple the electromagnetic traveling wave to the radiating space outside the antenna panel. By properly designing the coupling factor for each slot, it is possible to excite power of the same amplitude and phase across the entire surface of the panel. The whole structure works as a series-fed, leaky wave antenna.

Series-fed antennas inherently have frequency scanning characteristics, therefore typically the feeding waveguide is placed at the centerline of the panel, cf. [6], such that effect of beam shift is cancelled out on both sides of the panel. On the other hand, the feeding waveguide can be placed at the edge of the panel to obtain a frequency scanning characteristic as shown in Figure 4b [5]. The (quasi-)TEM mode has linear dispersion characteristics and is particularly suited for achieving linear scan characteristics.

Figure 4c shows a configuration in which a corporate power feed structure is added to avoid unwanted phase differences inside the feed waveguide. In order to use a frequency scanning antenna in a wide bandwidth, the structure of Figure 4c should be adopted to improve the aperture efficiency of the radiating panel.

Next, we discuss scan rate, which is an important index for designing a frequency scanning SAR system. The scan rate is expressed as:

$$K = \mathrm{d}\theta / \mathrm{d}f \quad (1)$$

where θ is the beam direction of the antenna at a certain frequency f.

Figure 5 shows the relationship between swath and scan rate, and Figure 6 shows the relationship between dwell bandwidth and scan rate. The larger the scan rate, the wider the beam scanning angle range for a given frequency bandwidth, therefore the wider the swath. Although this may be desirable in frequency scanning SAR systems to expand the swath, there is an upper limit to the swath that can actually be observed due to timing constraints. Also, the larger the scan rate, the smaller the dwell bandwidth (the bandwidth which a point within the swath can acquire), and as a result, the resolution of that point becomes worse. Therefore, the actual scan rate should be determined in consideration of the above constraints.

For a passive series-fed array antenna, the relationship between the beam direction θ and the frequency f is expressed by

$$\sin\theta = \frac{s}{d}\lambda(f)\left(\frac{1}{\lambda_{eff}(f)} - \frac{1}{\lambda_{eff}(f_0)}\right) \quad (2)$$

where s is the feed length difference between adjacent elements, d is the distance between elements, λ is the vacuum wavelength, λ_{eff} is the effective wavelength inside the antenna, and f_0 is the center frequency. Equation (2) shows that the scan rate can be controlled by changing either s, d, or λ_{eff}. To achieve the desired scan rate, it is essential to select an appropriate radiating element that can control these parameters.

4. PERFORMANCE EVALUATION

Table 3. Optimized parameters and SAR performance estimation.

Parameter	Value
Look Angle	25.0 – 33.2 deg
Antenna Height	0.9 m
Scan Rate	8.3 deg/GHz
Transmit Duty Cycle	44 %
Pulse Repetition Frequency	2298 – 2399 Hz
Ground Range Resolution	1.07 – 1.4 m
Azimuth Resolution	3.7 – 3.85 m
Swath Width	99.4 – 103.9km
NESZ	-18 dB
RASR	-41.7 dB
AASR	-17.6 dB

The performance and timing analysis was performed based on the parameters in Table 2, utilizing the f-STEC imaging mode [3,8] and taking into account the above-mentioned constraints. Variations in the orbit of 22 km, due to the oblateness of the Earth, were considered. To image the given swath, the optimum scan rate was found to be 8.3 deg/GHz. The obtained performance results are shown in Table 3: resolution, swath width and pulse repetition frequency are given with their variation over the swath and orbit height. NESZ, range ambiguity-to-signal ratio (RASR) and azimuth ambiguity-to-signal ratio (AASR) values are given for the worst case.

The analysis confirms that a swath of about 100 km can be imaged at a ground range resolution of about 1 m, with sufficient NESZ and ambiguity level.

5. CONCLUSION

A new design of an f-STEC imaging mode for small SAR satellites using passive frequency scanning antennas was presented. The system design and SAR performance were analyzed, and it was shown that it is possible to achieve a 2-D spatial resolution below 6 m^2 over a swath width of 100 km with sufficient image quality performance. The design method of the frequency scanning antenna, which is the key to realize the system, was also presented, and the optimal value of the scan rate was clarified.

The new system is expected to contribute to the provision of SAR images with wide swath and high resolution by implementing it on Synspective’s StriX satellites, which are less expensive and more suitable for mass production than large SAR satellites.

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