

Concept and Performance of a Stripmap-F-STECC Mode to Image Wide Swaths at High Resolution with the Novel StriX Small Satellite

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Abstract

To image wide swaths at high resolution is still challenging for small, NewSpace synthetic aperture radar (SAR) satellites. In order to overcome this limitation, Synspective, supported by the German Aerospace Center (DLR), has recently led an innovative feasibility study on the exploitation of a fully passive frequency scanning antenna according to the frequency scan for time-of-echo compression (f-STECC) technique in the small satellites of the StriX constellation. Within the joint research, a first, dedicated operational mode, denoted as stripmap-f-STECC (SM-f-STECC), suitable for small satellites in standalone operation, was developed and analyzed. The obtained results are very promising: in SM-f-STECC, for the first time, a small satellite in the 100-200 kg class would be able to generate high-quality SAR images with a swath width up to 100 km and a 2-D spatial resolution below 5 m². The continuous coverage in the azimuth direction of a conventional stripmap mode is preserved.

This paper presents the SM-f-STECC mode for the novel StriX satellite with frequency scanning capability: the rationale is explained and the SAR imaging performance numerically analyzed.

1 Introduction

Small, NewSpace synthetic aperture radar (SAR) satellites are going to offer a novel, unique, tool for Earth observation (EO) applications, thanks to their ability to provide global access with high temporal and spatial resolution [1]. In regard to SAR image quality, a small satellite, in standalone operation, can achieve very high azimuth resolution over relatively small areas by exploiting the platform mechanical agility to increase the synthetic aperture in spotlight-like operational modes. Larger areas can be imaged at a high/medium resolution in stripmap (SM) mode. Specifically, swath widths up to 30 km can be imaged at a 2-D spatial resolution of about 3 m × 3 m [2], [3].

The inability to image wide swaths at high resolution with a satisfactory quality represents a limitation, especially for security applications, emergency management, and archiving purposes [4]. In order to overcome this limitation, Synspective, supported by the Microwaves and Radar Institute of the German Aerospace Center (DLR), has recently led an innovative study on the exploitation of the frequency scan for time-of-echo compression (f-STECC) technique by the small satellites of the StriX constellation [5].

The f-STECC technique, also known as frequency scanning (F-Scan), denotes an analog beamforming, used both on transmission (Tx) and reception (Rx): within each pulse repetition interval (PRI), the imaged swath is scanned in the elevation direction, from the far to the near range, by means of a frequency-dependent pencil beam with steering direction controlled by the frequency of the Tx signal [6], [7]. The scanning mechanism produces a temporal overlap between the signals received from the far and near range of

the imaged swath, i.e., an *echo compression*, so that long pulses can be transmitted without sacrificing the swath width. Under the availability of a relatively large signal bandwidth, it allows to image wide swaths at high range resolution; excellent radiometric performance and range ambiguity suppression are also expected [6], [7].

The f-STECC technique has been widely analyzed in the last years to implement advanced operational modes. However, in order to guarantee a great flexibility in the mode design and enhance the achievable imaging performance, architectures based on active phased array antennas, eventually with multiple azimuth Rx channels, are typically considered for the realization of the frequency scanning functionality [8], [9], [10]. These solutions are suitable for multi-purpose, full-fledged, big SAR satellites, but can be challenging for small satellites [5].

In order to exploit, for the first time, the f-STECC technique in small SAR satellites to image wide swaths at high spatial resolution with overall high image quality, Synspective has investigated the realization of a compact, lightweight, inexpensive, fully passive frequency scanning antenna based on a series-fed array [5]. In parallel, the design of a simple operational mode, denoted as SM-f-STECC, obtained by combining f-STECC with a conventional (single azimuth channel) SM mode, has been analyzed in a joint research study with the DLR.

This paper presents the SM-f-STECC mode for Synspective's novel small satellite with frequency scanning capability: the rationale is explained and the SAR imaging performance numerically analyzed.

2 SM-F-STECh Mode

The SM-f-STECh mode for the novel small satellite of the StriX constellation is obtained by combining the f-STECh technique in elevation with a conventional (single azimuth channel) SM mode in azimuth. In particular, for the implementation of the f-STECh technique, (i) a linear frequency modulated (chirp) pulse and (ii) a f-STECh beam steering direction linearly dependent on the instantaneous frequency of the chirp are assumed. Accordingly, the following relationships apply [7]:

$$\frac{\tau_w}{\tau_p} = \frac{B_w}{B_p} = \frac{\Theta_w}{\Theta_{im} + \Theta_w} \quad (1)$$

where τ_p and B_p denote, respectively, the duration and the bandwidth of the Tx chirp pulse; Θ_w the dwell angle, i.e., the scanning beam angular sector, used to image a point target; τ_w the dwell time, i.e., the interval during which a point target remains within Θ_w ; B_w the dwell bandwidth, i.e., the range frequency bandwidth seen by a target during τ_w and used to image the point target; Θ_{im} the imaged swath angle, i.e., the angular sector covering the imaged swath. In particular, in SM-f-STECh, Θ_w is assumed to be close to the half power beamwidth (HPBW), Θ_{3dB} , of the scanning beam¹. Note that, for $\Theta_w \approx \Theta_{3dB}$, the f-STECh beam modulation is expected to have a minor effect on the ground range resolution.

For the StriX frequency scanning antenna, the ratio between scanned angle and frequency bandwidth, denoted as scan rate, can be selected at design level but is constant and not reconfigurable once the antenna is built [5].

The f-STECh technique is further characterized by the so-called operation point:

$$O_p = \frac{c_0}{2(R_{far} - R_{near})} \frac{(B_p - B_w)}{B_p} \tau_p \quad (2)$$

where, R_{near} and R_{far} denote the near and far slant range edges of the imaged swath, respectively; c_0 the light speed.

The operation point conveys information about the level of echo compression and the maximum possible pulse repetition frequency (PRF). In particular, for $O_p = 1$, the echo duration is minimized and the instantaneous Rx bandwidth reaches the maximum value, B_p . Moreover, lower operation points are associated with higher maximum PRF values, which are possible for a given scenario, defined by the imaged swath, the range resolution, and the Tx pulse bandwidth.

For the SM-f-STECh mode, a low operation point ($O_p < 0.6$) is assumed. In fact, as in a conventional SM mode, also in SM-f-STECh, in order to optimize the azimuth performance and minimize the required antenna length, it is advanta-

geous to exploit possibly large PRF values to image a desired swath. Additionally, a lower operation point can be exploited to reduce the data rate [11], [12].

3 SAR Imaging Performance

Let us consider the scenario in Tab. I, which relies on SynSpective's novel small satellite with frequency scanning capability [5]: an X-band instrument, based on a planar, rectangular, antenna, 0.9 m high and 6.2 m long, with an average Tx power of 810 W, and an available system bandwidth of 1200 MHz; the orbit height is 532 km; the antenna tilt angle corresponds to the center of the imaged swath. The f-STECh technique is implemented by means of a linearly scanning antenna with a fixed scan rate value in the order of 6 - 10 deg/GHz.

Let us assume a Tx pulse bandwidth of 1200 MHz and a dwell bandwidth of 210 MHz. According to (1), with these parameter values, the f-STECh technique allows to image a swath of about 100 km, centered at 30 deg incidence angle, with a ground range resolution² below 1.4 m at swath center. It is worth to remark that for the considered constant processing bandwidth, B_w , the ground range resolution varies between about 1.6 m and 1.2 m from the near to the far range. A possible equalization solution, based on the variation of the range processing bandwidth, is presented in [13].

Figure 1 shows the f-STECh timing diagram, obtained under the assumption of a low operation point, for $\tau_w PRF = 5\%$ and a guard time of 2 μs . Only the constraints imposed by the Tx event are considered (the nadir echo is assumed to be suppressed by means of the antenna pattern and dedicated techniques). The diagram indicates that a swath of 100 km, centered at 30 deg incidence angle, can be imaged with a maximum PRF of 2583 Hz and an O_p of 0.27. A PRF equal to 2583 Hz is then selected, in order to optimize the achievable azimuth performance over the swath of interest. The value of the main SM-f-STECh parameters can be now derived, as shown in Tab. II.

Based on the considered parameter values, assuming a uniform antenna taper in azimuth and a processing Doppler bandwidth of 2208 Hz, it is possible to achieve a full azimuth resolution of about 2.8 m with an azimuth ambiguity-to-signal ratio (AASR) below -17.6 dB (see **Figure 2**).

Parameter	Value
RF Center Frequency	9.800 GHz
Antenna Size (height \times length)	0.9 m \times 6.2 m
Average Tx Power	810 W
Available System Bandwidth	1200 MHz
Orbit Height	532 km
Imaged Swath Center (inc. ang.)	30 deg
Antenna Tilt (look ang., inc. ang.)	27.48 deg, 30 deg

Table I Reference SAR system and acquisition geometry.

¹ The HPBW variation over the swath is neglected: the considered HPBW is evaluated in the boresight direction.

² The range compression is assumed to rely on a filter matched to an ideal chirp with bandwidth B_w ; no further weighting is considered.

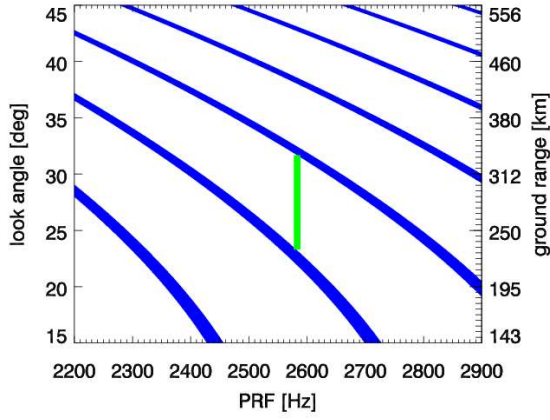


Figure 1 Timing diagram: the blue stripes denote the blind regions associated with the Tx event; the vertical green segment corresponds to the imaged swath. $\tau_w PRF = 5\%$; guard time: $2 \mu s$; orbit height: 532 km.

Parameter	Value
Tx Pulse Bandwidth	1200 MHz
Dwell Bandwidth	210 MHz
Imaged Swath Angle	8.19 deg
Dwell Angle	1.73 deg
Pulse Repetition Frequency	2583 Hz
Tx Pulse Duration	111 μs
Dwell Time	19 μs
Tx Duty Cycle	29%

Table II SM-f-STEAC mode main parameters.

Figure 3 shows the normalized, 2-way, elevation antenna pattern (i.e., the f-STEAC beam) for the SM-f-STEAC mode, when pointing at the near range edge of the imaged swath. The imaged swath angle, Θ_{im} , is marked by the green segment on the top of the plot. A uniform taper is assumed. The pattern values weighting the useful signal and the corresponding range ambiguities are also marked (by green and red symbols, respectively). In particular, due to the scanning mechanism: (i) the useful signal is weighted by pattern values around one, over all the swath; (ii) the range ambiguities suppression induced by the pattern is higher than 45 dB; (iii) the nadir echo suppression higher than 60 dB.

Figure 4 shows the range ambiguity-to-signal ratio (RASR), obtained under the assumption of a uniform backscattering coefficient. As expected, SM-f-STEAC achieves a very good performance: the RASR is below -40 dB over all the swath.

Figure 5 shows the noise-equivalent sigma zero (NESZ) versus ground range: the NESZ is below -17.7 dB over all the imaged swath, with a linear degradation up to 2.3 dB from the near to the far range, induced by the acquisition geometry. A NESZ equalization approach, with low implementation complexity, exploiting a nonlinear chirp and a variable range processing bandwidth, is described in [13]. The reported analysis refers to an imaged scene centered at 30 deg incidence angle. More in general, the results of the

joint research study between SynSpective and DLR show that, in SM-f-STEAC, high-quality SAR imaging performance can be obtained over the access range by properly selecting the Tx pulse bandwidth.

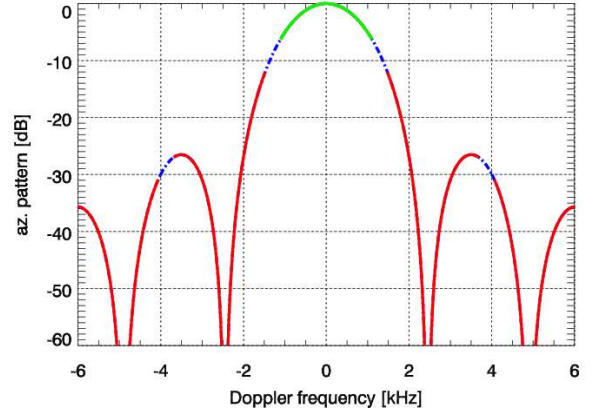


Figure 2 Two-way azimuth (power) pattern versus Doppler frequency. The pattern values weighting the useful signal and the azimuth ambiguities are highlighted in green and red, respectively.

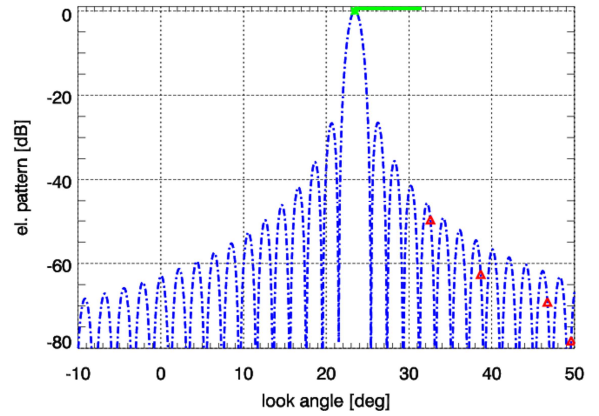


Figure 3 Normalized, two-way, elevation antenna (power) pattern, pointing at the near range edge of the swath. The pattern values weighting the signal from a resolution cell in the near range edge of the swath is highlighted by the green x symbol, the corresponding ambiguities by the red Δ symbol, for $PRF = 2583$ Hz. The green segment on the top highlights the swath location.

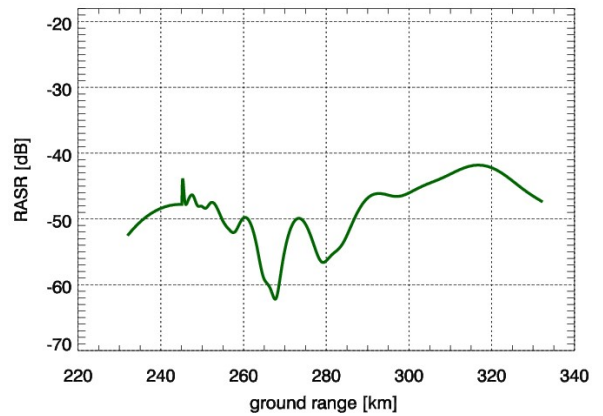


Figure 4 RASR vs. ground range in SM-f-STEAC mode. Backscattering coefficient: uniform.

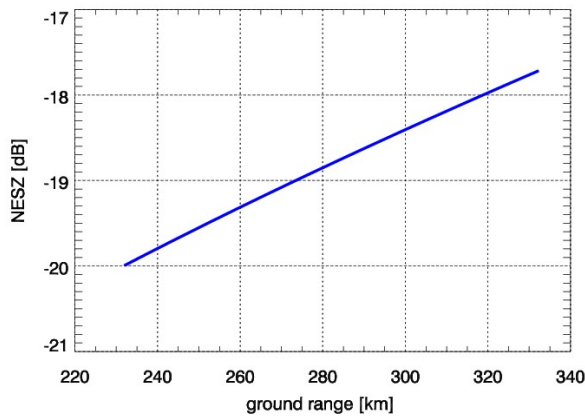


Figure 5 NESZ vs. ground range in SM-f-STECh mode. The reported variation is induced by the slant range and incidence angle variation across the swath (other parameters, such as the radar wavelength, are assumed constant).

4 Conclusion

The reported analysis indicates that in SM-f-STECh mode, the novel StriX small satellite with frequency scanning capability will be able to achieve SAR imaging performance well beyond the state-of-the-art: for the first time, a small SAR satellite in the 100-200 kg class will be able to image a swath extension up to 100 km in the range direction, at an azimuth full resolution around 2.8 m and a ground range resolution below 1.6 m, with NESZ, RASR, and AASR below -17.5 dB, keeping the continuous coverage of a conventional SM mode.

It is worth to remark that the obtained performance relies on StriX's large antenna size (0.9 m × 6.2 m). For this, Synspecive's simple and lightweight frequency scanning antenna is essential.

As future development, the combination of the f-STECh technique with a conventional spotlight mode is under consideration.

The on-orbit demonstration of the first StriX satellite with frequency scanning capability is planned by 2031.

5 Literature

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