X-Band SAR Antenna Design for a CubeSat Formation-Flying Remote Sensing Mission

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***Abstract*— This paper presents the design of the receiving antenna of an upcoming formation-flying synthetic aperture radar (FF-SAR) based on the CubeSat standard and on a pre-existing spaceborne SAR of opportunity. The receiving antenna operates at X-band and is compliant with the imaging modes of the FF-SAR, namely a stripmap mode for signal-to-noise ratio improvement (IM1) and a High-Resolution Wide-Swath mode for the monitoring of large areas (IM2). A large reflector has been designed to meet the high-gain requirement in IM1, while the wide coverage needed in IM2 is ensured by a reconfigurable patch array feed. Full-wave analysis shows that the designed receiving antenna achieves 37.42 dBi gain in IM1 and 12.1 degree half-power beamwidth in IM2.**

***Keywords*— reflector antennas, antenna feed, patch array, bistatic SAR, formation-flying SAR, nano-satellites.**

I. Introduction

In the recent past, numerous remote sensing missions have been deployed on nanosatellites, especially CubeSats. As a matter of fact, the number of nanosatellites launched is increasing every year and almost one-thousand nanosat missions have been successfully put into orbit in the past five years [1]. As compared to large satellites, nanosatellites offer several advantages, including the feasibility of launching large constellations of platforms, even in a cooperating mode, at a limited cost. Compactness, light weight, and modularity have also contributed to the breakthrough brought by nanosatellites in space-based Earth Observation and remote sensing.

Formation-flying synthetic aperture radar (FF-SAR) refers to a new concept of distributed bistatic SAR system where the signals emitted by a SAR transmitter are opportunistically exploited for remote sensing applications by multiple cooperating receiving platforms. With respect to monostatic SAR, FF-SAR enables new imaging modes (IMs) by properly combining the Earth-reflected signals received by each platform.

In this paper, we focus on the RF front-end of the single receiving unit of an upcoming FF-SAR mission (a prototype receiver is currently under development) and describe the design of the receiving SAR antenna. The antenna operates at X-band and is suited to two operational modes of the FF-SAR, namely signal-to-noise ratio (SNR) improvement and high-resolution wide-swath (HRWS) imaging [2]. A deep review of antennas for small satellites, including CubeSats, is discussed in [3].

The remainder of this paper is organized as follows. Section 2 introduces the FF-SAR concept and the IMs considered for the SAR antenna design, which is then discussed in Section 3. Simulated antenna performance, including radiation patterns, are presented in Section 4. Finally, concluding remarks are highlighted in Section 5.

II. Imaging Modes of the FF-SAR Receivers

Most past SAR missions, e.g., TanDEM-X, based on formations of satellites were aimed at improving imaging performance in advanced interferometric applications, e.g., single-pass interferometry, differential interferometry, tomography and Ground Moving Target Indication. Such improvements were achieved by combining the different SAR images made available from each satellite.

Conversely, FF-SAR refers to the recent and completely different concept of distributed SAR systems, that operate in a bistatic acquisition geometry where multiple cooperating receiving platforms collect the Earth-reflected signal emitted from a SAR sensor. The simpler architecture of the FF-SAR w.r.t. monolithic SAR allows for mounting the receiving units onboard nanosatellites, e.g., CubeSats. The transmitting SAR can be one of the formation satellites or a pre-existent system which is then exploited as an illuminator of opportunity. In FF-SAR, the final bistatic SAR image is obtained combining the signals received by the formation satellites.

More specifically, the FF-SAR mission under investigation is conceived to opportunistically exploit the microwave signals transmitted by pre-existent SAR missions operating in X-band, e.g., the ongoing Cosmo-SkyMed or the upcoming PLATiNO-1 [4]. This solution allows to combine the advantages of distributed SAR with those of a bistatic passive radar as well as to overcome the performance of a single monolithic SAR by merging both monostatic and bistatic data obtained by illuminating common covered areas [5]. The flexibility of the cluster in terms of number of receiving platforms and their spatial spacing allows for scalable performance, in contrast with monostatic SAR [6]. As a matter of fact, the distributed SAR significantly improves the scalability, reliability and modularity of the overall system w.r.t. monolithic SAR: for instance, payload failures can be more easily faced and mission goals preserved by replacing single cluster elements with little performance degradation.

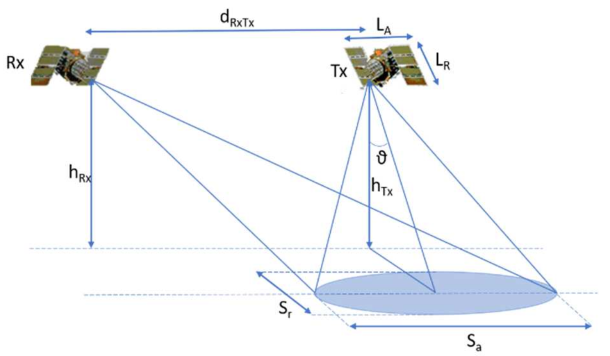


Fig. 1. Geometry of the bistatic FF-SAR. The transmitter of opportunity is a side-looking SAR operating at X-band, while the receiving platforms follow the transmitter on the same orbit and are properly squinted to cover the region illuminated by the transmitter.

TABLE I. SYSTEM PARAMETERS OF THE FF-SAR MISSION

Symbol	Parameter	Value
d_{RxTx}	Along-track baseline	100 km
h_{Rx}	Rx height	410 km
h_{Tx}	Tx height	410 km
L_A	Tx antenna size (azimuth)	3.4 m
L_R	Tx antenna size (range)	0.7 m
ϑ	Looking angle	20 – 40 deg
S_r	Range swath	15 km (IM1) Up to 100 km (IM2)
S_a	Azimuth footprint	5 km
N_{sat}	Number of receivers	3
G_{Rx}	Receiving antenna gain	> 34.8 dBi (in IM1)

Additionally, combination of the received signals enables a number of IMs which are not feasible with monostatic SAR and allows to improve the imaging performance achievable by the single receiving units if operating independently each other.

Here we focus on two different IMs, namely:

- SNR improvement (IM1), where the signals received from each element of the formation are properly combined to improve the SNR of the final bistatic image w.r.t the single receiving unit. If the number of satellites is sufficiently large, the obtained SNR is larger than that offered by a monostatic SAR.
- High-Resolution Wide-Swath (HRWS, IM2), which ensures a significantly larger range swath without degradation of the spatial resolution, thus overcoming the pulse repetition frequency limit of monostatic SAR. This is achieved by properly processing the Doppler spectrum of the received signals.

More details about the processing chain of the received signals can be found in [2].

III. PROPOSED DUAL-MODE RECEIVING SAR ANTENNA

For the design of the receiving SAR antenna, we here refer to the bistatic geometry that is shown in Fig. 1 and whose parameters are listed in Table I. The transmitting source of opportunity is a side-looking spaceborne SAR operating at X-band, e.g., COSMO-SkyMed or the upcoming PLATiNO-1 [4]. The formation of receivers moves on the same orbit of the transmitter and follows it at a distance of about 100 km. Each receiving satellite is equipped with a SAR antenna which is pointed toward the area illuminated by the transmitter and collects the Earth-reflected signal. Additionally, here we consider a formation of three satellites.

TABLE II. RECEIVING ANTENNA REQUIREMENTS

Parameter	Value
Volume	≤ 3U
Mass	≤ 3.2 kg
Frequency	9.6 GHz – X-band
Pointing	20 – 40 deg
Bandwidth	≥ 80 MHz
Polarization	VV
Gain	> 34.8 dBi in IM1
HPBW range	≥ 1.79 deg in IM1 ≥ 11.1 deg in IM2
HPBW azimuth	≥ 0.61 deg

According to Table I, the following requirements apply:

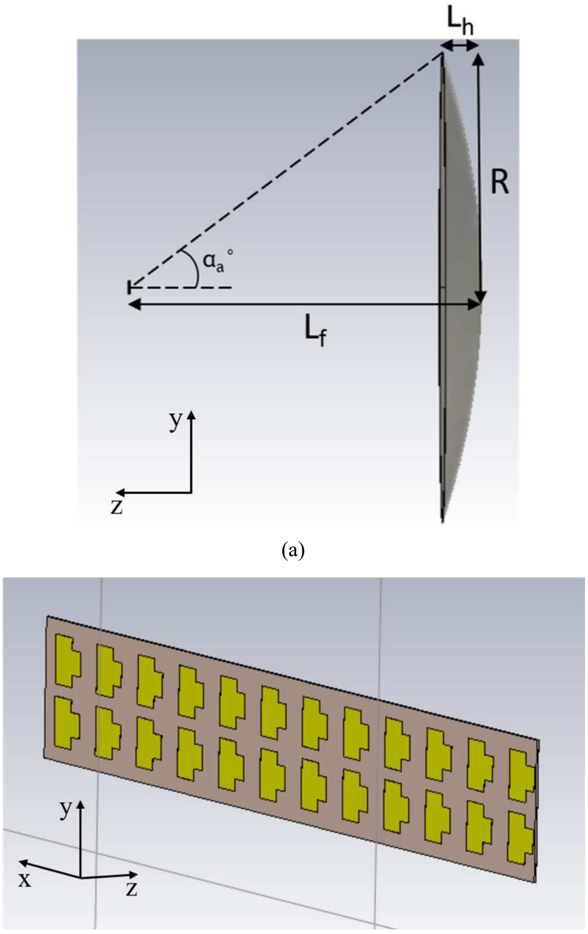
1. in IM1, a minimum range swath of 15 km and a receiving antenna gain larger than 34.8 dBi should be ensured in order to offer a better SNR and noise equivalent sigma zero (NESZ) than an equivalent monostatic SAR;
2. in IM2, the coverage area should be as large as 100 km in the range direction.

For the bistatic geometry depicted in Fig. 1, such constraints lead to the minimum half-power beamwidth (HPBW) values reported in Table II, where other antenna requirements are listed as well. It is noteworthy that no gain constraint explicitly applies in IM2. However, some comments on this point are reported in Section IV.

Table II reveals that contrasting requirements apply in the two IMs. Actually, in order to achieve high SNR values in IM1, the receiving antenna must exhibit gain values larger than 30 dBi. However, such an antenna will likely exhibit a too narrow beamwidth, compared with that required in IM2. As a matter of fact, solutions based on a single standard antenna are hardly viable. Moreover, the strict physical constraints on volume and mass dictated by the Cubesat standard make solutions based on two different antennas, each designed for a single IM, impractical.

The proposed antenna is shown in Fig. 2, where the range direction approximately lies in the *xz* plane. It is a parabolic reflector [Fig. 2(a)] feeding a reconfigurable 2x12 patch array [Fig. 2(b)], whose receiving characteristics are dynamically adapted to the IM by properly connecting the array elements to the receiver according to the acquisition mode. More specifically, in IM1, only the central 2x2 subarray is connected to the receiver in order to make the whole area of the dish reflector participating to the received signal. This maximizes the receiving antenna gain, but, as it will be shown in Section IV, also produces a very narrow beamwidth, which is incompatible with IM2. Therefore, in order to enlarge the HPBW in the range direction, in IM2 the area of the parabolic dish contributing to the received signal is significantly reduced in the *xz* plane by connecting the whole 2x12 array to the receiver. The absence of grating lobes, which might negatively impact the imaging performance of the FF-SAR, is achieved with an inter-element spacing of $\lambda/2$.

The dielectric substrate between the patches and the ground plane is designed with Rogers RO4003C woven glass-reinforced hydrocarbon ceramic, with a nominal dielectric constant of 3.55 and a loss tangent of 0.0027 at 10



(a)

(b)

Fig. 2. (a) Parabolic reflector. (b) Reconfigurable 2x12 patch array feed.

GHz. This substrate has been successfully adopted in the reflectarray antenna of the NASA MarCO mission [7].

The parabolic reflector has been designed according to KaTENna thanks to its high-gain performance and suitability with 12U CubeSat class [8]. Accordingly, the radius *R* and the focal length L_f of the parabolic dish are set to 0.5 m and 0.75 m, respectively. As a result, we obtained a tapering angle α_a equal to 36.9 degree and L_h equal to 0.083 m, which are compatible with a 3U stowage and with an umbrella-like deployment mechanism [9].

IV. Numerical Performance

In this Section, we show radiation performance of the designed antenna, that has been simulated via a numerical electromagnetic solver based on a Finite-Difference Time-Domain method. According to the receiving antenna operating modes described in Section III, the 2x2 central patch subarray has been fed in IM1, while the whole array has been excited in IM2. Additionally, in order to speed up the simulation, the dish reflector has been assumed of perfect electric conductor with 10 mesh cells per wavelength. Conversely, the patches and the ground plane have been assumed of (lossy) annealed copper.

The 2-dimensional cuts of the radiation pattern in *xz* and *yz* planes are shown in Fig. 3 and Fig. 4 for IM1 and IM2, respectively. Synthetic performance parameters are listed in Table III and Table IV for IM1 and IM2, respectively.

TABLE III. Antenna performance in IM1

Parameter	Value
Pointing (*xz*, *yz*)	(0.1, 0.0) deg
HPBW (*xz*, *yz*)	(1.9, 2.0) deg
Gain	37.40 dBi
SLL (*xz*, *yz*)	(-16.0, -18.9) dB
Edge taper (*xz*, *yz*)	(-7, -5.75) dB

TABLE IV. Antenna performance in IM2

Parameter	Value
Pointing (*xz*, *yz*)	(0.1, 0.0) deg
HPBW (*xz*, *yz*)	(12.1, 1.8) deg
Gain	31.37 dBi
SLL (*xz*, *yz*)	(-27.8,-13.0) dB
Edge taper (*xz*, *yz*)	(-22.35, -5.56) dB

As the performance indicators reveal, in IM1 the antenna achieves a gain of 37.4 dBi, i.e., 2.6 dB larger than the one required with a formation of three satellites. This allows an adequate improvement of SNR w.r.t. a monolithic SAR. Moreover, the HPBWs obtained in both *xz* and *yz* planes are compliant with the required values and ensure the coverage of the ground area illuminated by the transmitter.

In IM2, the reflector dish area illuminating the feed is reduced in the *xz* plane due to the excitation of the whole patch array. This leads to a reduced gain and to a larger beamwidth in the range direction w.r.t. IM1. The achieved HPBW in the *xz* plane allows the FF-SAR to cover range swaths as large as 100 km, as required in IM2. The gain reduction of about 6 dB w.r.t IM1 leads to a similar degradation of performance in terms of SNR and NESZ and might be compensated with a larger number of receiving platforms.

Finally, it is worth mentioning that additional losses related to the deployment mechanism, e.g., losses due to surface ribs, struts, surface mesh, and surface accuracy, have not been considered in this simulation study. Notwithstanding, they can be safely assumed on the order of 1 dB [7], therefore only negligibly impacting the antenna performance.

V. Conclusions

In this paper, we described an upcoming FF-SAR mission (a prototype receiver is currently under development), conceived as an X-band bistatic SAR of opportunity, and focused on the design of the receiving SAR antenna module which is mounted onboard each receiving platform of the formation. The design of the antenna was driven by the requirements of two imaging modes of the FF-SAR, namely 1) a stripmap mode for the improvement of SNR w.r.t. an equivalent monostatic SAR (IM1) and 2) a HRWS imaging mode for large areas monitoring (IM2).

The proposed receiving antenna consists of a 1-m parabolic reflector (to be properly deployed) feeding a reconfigurable 2x12 patch array located at 0.75 m from the reflector. The radiation characteristics of the reflector are dynamically adapted to address the imaging mode requirements by properly connecting the feed elements to the receiver. In IM1, the high-gain (>34.8 dBi) requirement is accomplished by feeding the 2x2 central subarray, while the wide range beamwidth (⩾ 11.1 degree) in IM2 is realized by feeding the whole 2x12 array.

Numerical results obtained with a full-wave electromagnetic solver demonstrate that the proposed solution meets the requirements for both acquisition modes. More specifically, the proposed antenna achieves a gain of 37.4 dBi in IM1 and a HPBW of 12.1 degree in the range direction in IM2.

Finally, a proper deployment mechanism for both the reflector and the patch array is currently under investigation.

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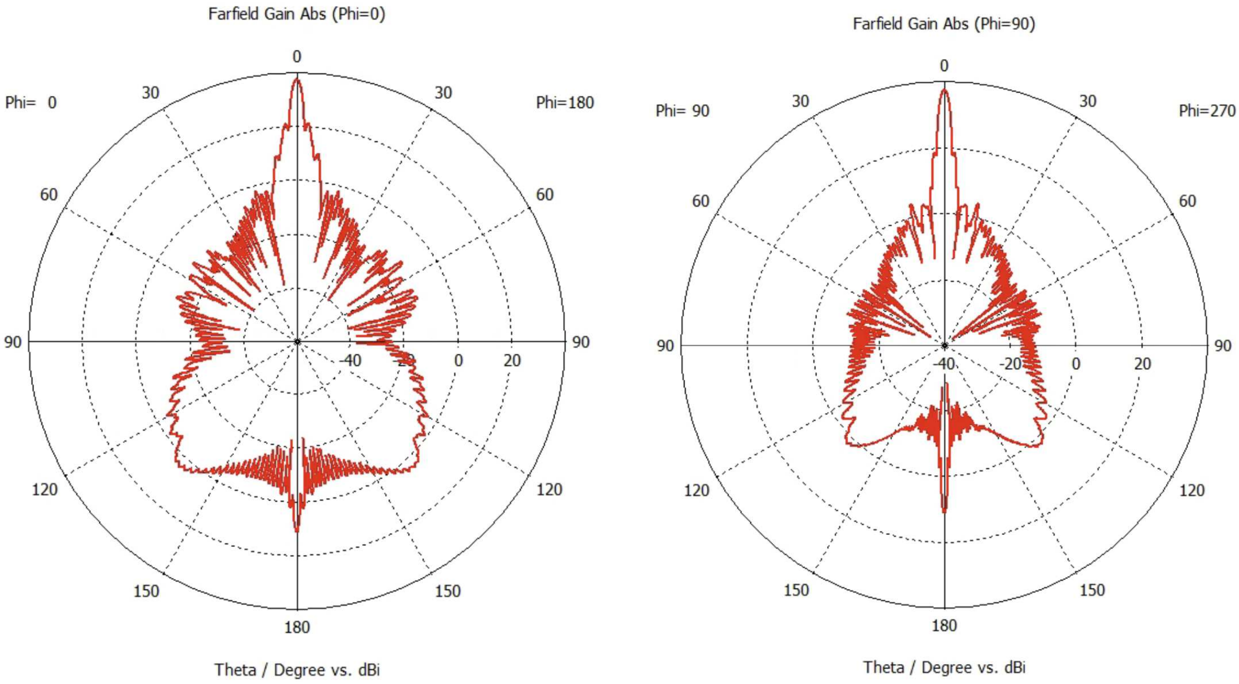
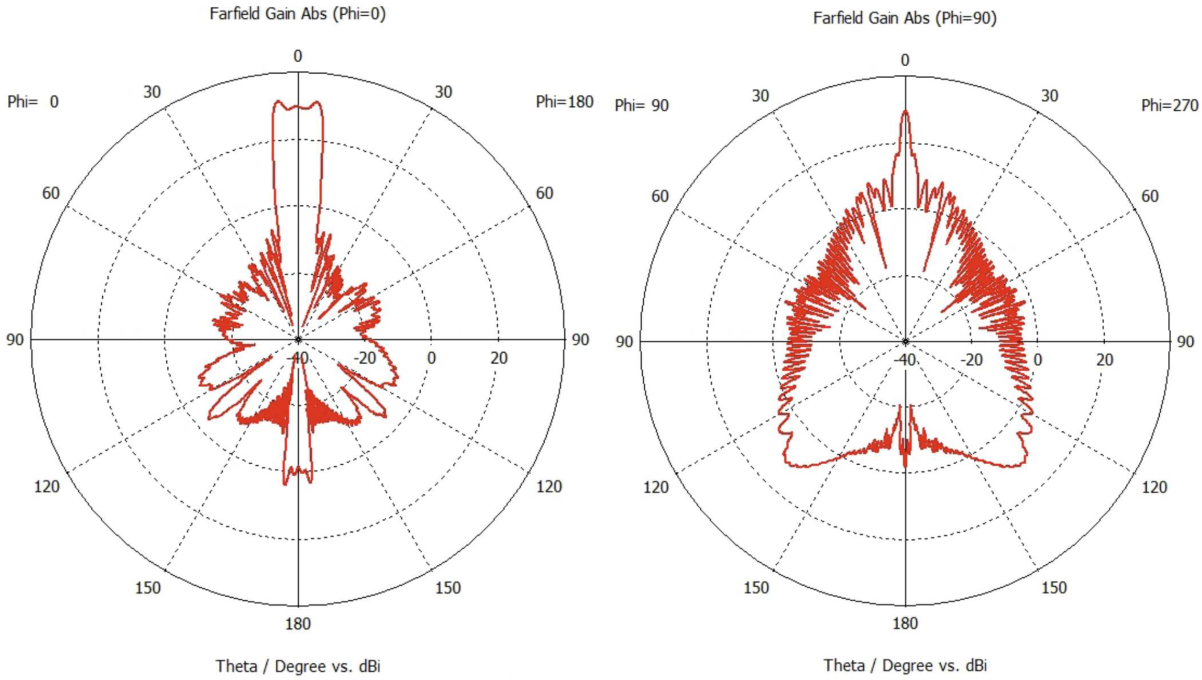


(a) (b)

Fig. 3. Simulated radiation pattern at 9.6 GHz in IM1. (a) *xz* plane. (b) *yz* plane.



(a) (b)

Fig. 4. Simulated radiation pattern at 9.6 GHz in IM2. (a) *xz* plane. (b) *yz* plane.