Hybrid Analog-Digital SAR Instrument with Reflector antenna and Overlapped subarray feed for Earth Observation

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Abstract—**As part of the ESA studies of new instrument for Earth Observation, the design of a SAR architecture based on overlapped array antennas was launched last year. The objective of the activity is to develop a test unit of a reflector based SAR antenna fed by an array organised in overlapped subarrays, supporting novel multichannel wide-swath SAR architectures and exploiting multiple beams in both azimuth and range/elevation directions.**

In the study, a hybrid analogue/digital beamforming on reception with analogue beamforming approach on transmission is analyzed. The antenna system consists of a large oversize reflector with a feedarray capable of generating multiple beams on receive for digital processing. In the paper, a description of the hybrid SAR Instrument is presented, describing the characteristics of the system, the Antenna, the considered feedarray options and the main characteristics and system performances.

***Index Terms*—Synthetic aperture radar, Antenna Arrays, Feeds**

I. Introduction

SCIENTIFIC needs for Earth monitoring in the next years require that future SAR applications have large sensitivity and short revisit time, which translates into large swath widths with high resolution and higher quality than current state-of-the-art SAR systems.

For conventional SAR systems, simultaneous large swath widths and high resolutions are contradicting requirements and to solve this a possible solution consists on transmitting using a broad beam and on receiving with multiple narrow beams [1]. The individual receiver signals are processed to reconstruct a sharp Rx beam which can be scanned along the desired swath-width on ground by a Digital beam forming (DBF) technique known as Scan on Receive technique (SCORE) to maximize the directivity to the actual angle of arrival of the radar signal [2]. DBF-SAR architectures based on multiple receiver channels have been proposed in the recent years as the basis for a kind of future SAR systems. The addition of staggered PRI SAR operation technique eliminates the presence of the inherent blind ranges appearing during radar transmission instances and thus allows to map a wide continuous swath [3].

To achieve the demand of highly sensitive SAR sensors, a large deployable mesh reflector antenna fed by an array of feed elements is a promising candidate [4]. The alternative of Direct Radiating Arrays (DRAs) for highly directive antennas are generally more complex and expensive than reflector antennas and Array Fed Reflectors offer intermediate performance [5].

In order for an Array Fed Reflector to scan a certain field of view, it is necessary a number of different feeders in the focal plane of the antenna that by sequential switching cover the angular region. In this work, the SAR system region of interest is approximately ±12º corresponding to a footprint of 400km for the intended orbit height of 700Km. To obtain the required system performances (in terms of noise equivalent σ^0, NESZ, spatial resolution and radar ambiguities) a wide transmit beam is formed illuminating the target area, which is scanned with a set of simultaneous receive spot beams [5].

While previous array fed reflector based SAR system are based on digital Rx beamforming techniques with large amount of electrically small feed elements, the main contribution of OLAF (Ovelapped Array Fed) SAR Instrument concept is to implement a hybrid analogue/digital Rx beamforming technique in order to both relax the number of RF channels in the feedarray and achieve efficient reflector illumination by each individual feeder/channel. The analogue beamforming will be implemented by novel subarray overlapping techniques.

Reflector antennas with feeders formed by overlapped subarrays permit to limit the dimension of the phased array and to generate a significant part of the overall antenna gain with the reflector. Overlapped subarrays may be used to generate directive beams enabling low spillover losses with the possibility of having contiguous overlapped beams with a low

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required cross-over level, typically 1dB.

The paper is organized as follows. In Section II the Hybrid beamforming SAR Instrument and its principles of operation are presented. In Section III the multifeed antenna system and the impact of the multiple beam feedarray are presented. In Section IV the two feeder options that have been considered are shown. In Section V the performances analysis of the selected antenna feeder option are presented.

II. SAR Instrument

The feedarray antenna is composed of N (arranged in the elevation plane) times M (arranged in the azimuth plane) overlapped feeders. Based on system performances 34 feeders are required in each of the 3 azimuth arrays. The number of elevation feeders has been derived as a result of the needed scanning angle to map the required 400Km on ground (23º to 45 º off nadir angles) and the number of azimuth arrays is due to the required azimuth Doppler Bandwidth to be received, imposed by the required 5m azimuth spatial resolution.

In reception each feeder provides the illumination that optimizes the reflector efficiency, approximately a taper of 12dB at the reflector edge. In transmission all the elements of the feedarray are coherently excited and generate a narrow beam that creates a suboptimal illumination of the reflector that causes a wide antenna beam.

In transmission the signal is distributed with analogue power dividers to the M=3 azimuth arrays, and from these to the N=34 feedarray elements. On receive each channel receives simultaneously the H and V polarized signals which are amplified and digitized; the system operates at L-band so direct conversion receivers can be considered for this task. The received signal is routed to the digital processor.

Multiple simultaneous elevation Rx beams allow extending the imaged swath beyond the limit of range ambiguities by acquiring echo signals from different portions of the swath. The simultaneous echoes that arrive at the antenna plane at the same time can be properly separated considering the desired signals incidence from different directions (or equivalently from different imaged swath regions).

OLAF has N=34 feed/channels in elevation and M=3 rows of these channels in azimuth. The number of simultaneous received beams is given by the largest value of the pulse repetition frequency (PRF) which makes the unambiguous swath length smaller. Considering mission geometry requirements the number of beams to cover the 400km ground swath is equal to 5, which is the number of signals from different ground regions reaching the antenna at the same time instance. Table 1 shows the main OLAF system requirements.

Figure 1 shows the block diagram of the hybrid digital/analogue OLAF SAR Instrument. The block diagram includes the oversize reflector, Rx and Tx channels and the digital processing units. The RF architecture of the Rx/Tx modules the SSPAs and LNAs included in the 'equivalent feeder (EF) RF subsystem' shown in Fig.2. The term equivalent feeder (EF) has been used to define the RF element or subarray that illuminates the OLAF reflector. The calibration network has been omitted from the diagram for clarity. It is planned as a passive network that allows to inject a signal to track variations of the Rx and Tx paths.

TABLE I
OLAF System Requirements

Parameter	Value	Comment
Frequency Band	1215-1300 MHz	
Orbit height	700km	mission reference orbit height
Incidence angle	≥17º	
Angular range	15º-45º	
Polarisation	Dual and quad	simultaneous linear H and V pol in reception
Swath Width	400 km	for dual-pol mode
	200 km	for quad-pol mode
Range Resolution	5m	Single look complex resolution
Azimuth Resolution	5m	Single look complex resolution
NESZ	<-28dB	Noise equivalent sigma 0
PTAR dB	< -25 dB	point target-to-ambiguity ratio
DTAR	< -22 dB	distributed target-to-ambiguity ratio
Reflector	12m≤ D ≤15m	
elevation beams	30≤ N ≤60	Simultaneous
azimuth beams	2≤ M ≤6	Simultaneous

The block diagram in Fig. 2 includes one receive channel per polarization, composed of filter and possibly a limiter at the inputs to reduce crosstalk coming from the transmit path. The SSPA is sequentially switching the V or H polarization ports of the feeder as required at system level. The SSPA units are driven by the RF power distribution network that split to the 3 different azimuth/elevation dividers. In the block diagram each

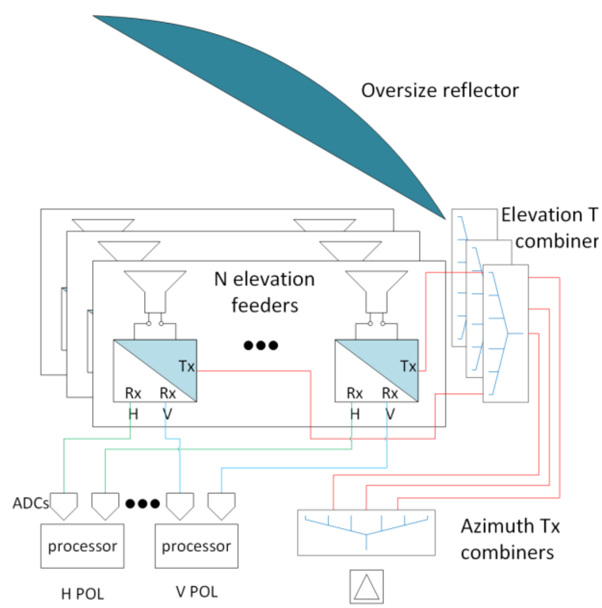

Fig. 1 OLAF SAR Instrument

SSPA is connected to a phase shifter that permits the correction of the phase differences between channels. This block diagram at feeder level permits both dual pol (VV-HH) and quad pol (VV-HH-VH-HV) operations of the SAR instrument.

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Each of the 34 EF's generates an individual spot beam on receive. In transmission a subset of the total available EF's (28x3) are combined in order to generate a single wide Tx beam pattern that cover the full swath size (i.e. 400km in dual polarization).

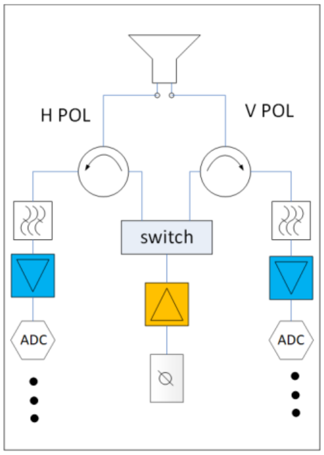

Fig. 2 OLAF transceiver module

In Fig. 3 the radiation patterns of the 34 receive and 1 transmit beams are shown in color lines. The 15m reflector is illuminated with ideal Gaussian beams with an angular spacing of 1º. The black dashed line is the transmit antenna pattern obtained with 28x3 EF's simultaneously on.

The positions of the EF's along the feedarray impact the efficiency of the antenna in terms of EF's pattern spillover. To mitigate this, a GRASP analysis was performed rearranging the EF's orientations and shifting the center of the feedarray from the focal point. The digital combination of several contiguous beams provides an extra processing gain in the near and far range swath edges that compensates the larger efficiency loss.

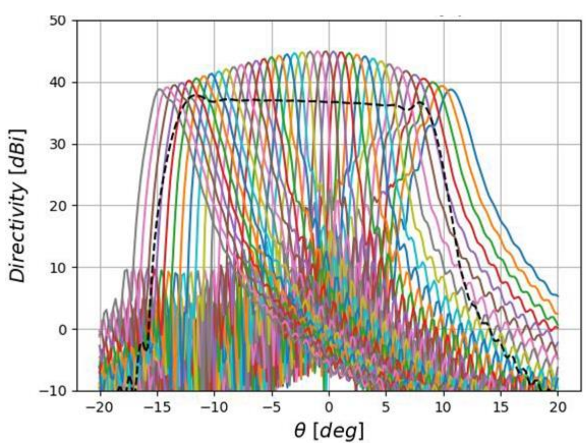

Fig. 3 Set of 34 Rx secondary patterns and single Tx secondary pattern at centre frequency (1257MHz)

III. Antenna

The maximum aperture diameter of 15m was selected to have sufficient directivity at antenna level to compensate the losses due to the reduced illumination efficiency, spillover and pattern defocusing and provide compliance to specification in Table I.

The antenna is an offset reflector which parameters (focal length, clearance and offset angle) have been optimized through GRASP. The *f*/D trade-off exercise concluded that the optimum *f*/D ratio for this SAR system is 0.9 balancing the feedarray size (smaller than for larger *f*/D), and subtended angle. A smaller clearance distance improves the crosspolar performances but it can produce blockage effects. Under these conditions the clearance distance has been fixed to 3000mm to minimize blockage. Main antenna parameters are listed in Table 2 and illustrated in Fig 4.

TABLE II
Optical Parameters

Reflector	value	Feed Array	value
Diameter (D)	15m	Tx EF's (per azimuth row)	28
Focal length (*f*)	13.5m	Rx EF's (per azimuth row)	34
f/D	0.9	No. of azimuth rows	3
clearance	3m	Feed-array length	8m
offset	10.5m	Separation between EF's	1λ (240mm)
Offset angle	41º		

Antenna performances have been calculated with data coming from the feeder simulation pattern and integrated into GRASP. Effects of spillover, blockage and optical aberrations (astigmatism, coma) are inherently included in the computations. The GRD output from GRASP was used as input to the system simulator to compute Instrument performances.

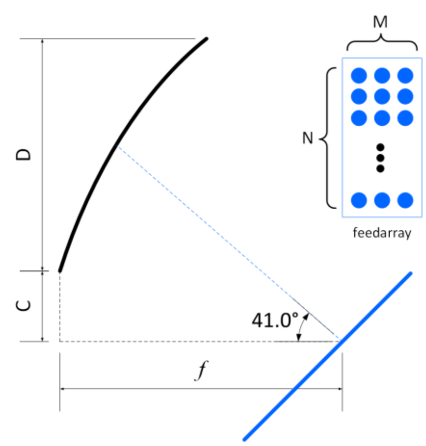

Fig. 4 OLAF antenna configuration

IV. Feeders

Two different overlapped feedarray options have been traded-off in the project. The first option is based on overlapping by beamforming network and is based on the CORPS concept described in [6,7,8]. In the application to OLAF, the BFN is a multiport network in which each beam port feeds three radiating elements, and each radiating element is shared between three different EF's following a triangular lattice. Since the beam forming is shared and common to all the

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feeding array, these three small radiators also receive contributions from the neighboring inputs, overlapping the effective radiating areas of the subarrays.

Fig. 5a shows a sketch of a part of the beamforming network designed for OLAF showing one split (1:3) network in stripline technology covering the complete 1215-1300MHz bandwidth.

The second feedarray (Fig. 5b) is based on a leaky wave antenna with a metamaterial surface overlay (MTS) [9]. The patch antenna elements are located over a ground plane and the presence of the overlay grid-etched superstrate makes a leaky wave to propagate between the radiating elements plane and the superstrate. The patterns between contiguous elements are overlapped with no beamforming network connecting the radiators. The main weak points are the reduced bandwidth of the design due to frequency sensitivity and the high mutual coupling between EF, approximately 20dB.

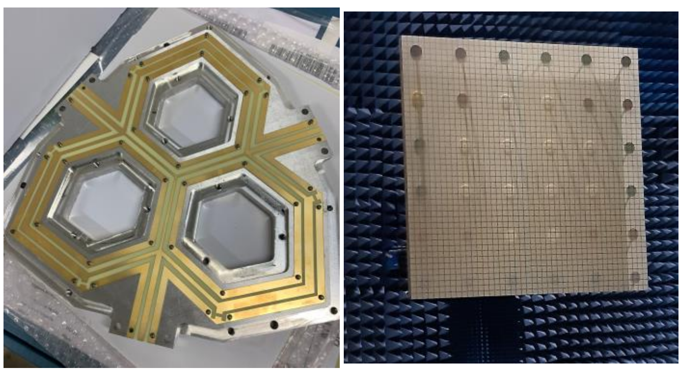

Fig. 5: (a) CORPS overlap BFN; (b) leaky wave overlapped array

Prototypes have been built for both feeder concepts to check the critical performance parameter of each radiating element; the insertion loss in the CORPS design and the mutual couplings in the leaky wave overlay design. The measurements have been used to compute patterns at Instrument antenna level and derive SAR Instrument Performances.

The tests on the CORPS beamformer confirmed the 1dB insertion loss for each multiport combiner with isolation levels of 35dB, and the tests on the MTS confirmed the impact of the 20dB mutual coupling in the element pattern which caused dips/ripple of 1-2dB in the pattern broadside direction (Fig. 6).

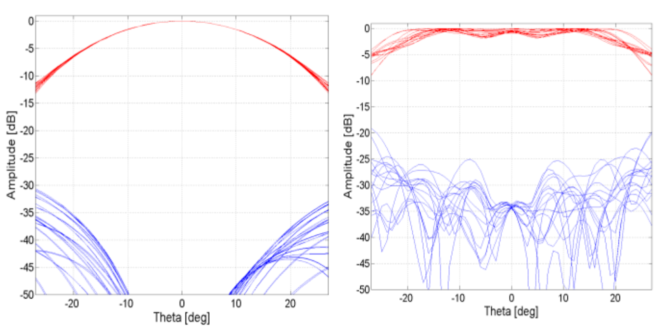

Fig. 6: CORPS feed pattern (left) and MTS feed pattern (right) at center frequency (1257MHz)

Taper specification of the EF pattern was -12dB, in line with the CORPS solution while the MTS solution shows a taper of 5dB, insufficient to give optimum illumination to the reflector.

V. RF AND SAR PERFORMANCES

The RF performances at antenna level have been calculated for each feeder in the focal plane. Each feeder in Rx generates one spot beam as shown in Fig 3. All antenna calculations have been performed with GRASP software. The main parameters evaluated for each feeder are the taper at reflector edge angles, the spill-over losses and the pattern deformation and crosspolar level. Data from prototype measurements was also incorporated into the antenna and system simulations.

Worst case spill-over losses produced by both feeders are 1.79dB for CORPS and 2.83dB for the leaky wave MTS.

Degradation of the antenna radiation patterns of the central feeder element (closer to the antenna focal point) and the elements located in the edges of the feedarray have been also traded-off. The CORPS solution shows lower degradation than the MTS. Finally, both CORPS and MTS show on axis crosspolarization levels better than 25dB.

Instrument performances are illustrated in Fig. 7 in terms of SAR sensitivity (NESZ) over the swath. It shows that a solution based on CORPS feedarray is compliant while a solution based on MTS shows a severe noncompliance. These results correspond to the dual pol (VV & HH) mode. In conclusion and based on both RF and Instrument performances, the solution adopted has been the CORPS design [10].

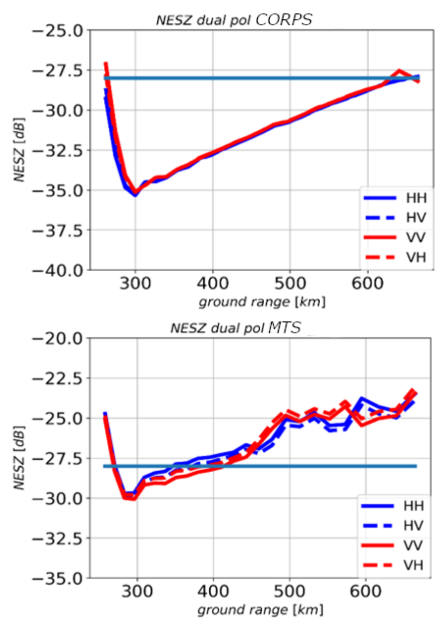

Fig. 7: Instrument NESZ for solution with CORPS(a) and MTS(b) feedarray designs. Horizontal blue line shows the required -28dB NESZ

VI. CONCLUSIONS

A new SAR instrument concept based on array fed reflector has been presented with analog beamforming on transmit and hybrid analogue/digital beamforming on receive. Based on system needs (close spacing between feeders), a solution based on overlapped feed arrays is selected. Two feedarray solutions have been studied, one based on overlap by BFN (CORPS) and other based on overlap by radiation (MTS), and the guidelines of the trade-off performed between both have been outlined, covering both RF and Instrument system aspects.

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