Digital-Beamforming Array Antenna Technologies for Future Ocean-Observing Satellite Missions

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***Abstract*—Existing passive microwave radiometers that are used for ocean observations are limited in spatial resolution and geographic coverage, due to the limitations of traditional antenna technologies using mechanically-scanning reflectors and horn-type feeds. Future ocean observation missions call for new solutions, such as digitally-beamforming array feeds (DBAFs) as well as stationary and more complex reflectors. Our studies demonstrate that DBAFs can overcome the physically fundamental limitations of traditional horn feeds, and are capable of meeting all the challenging requirements for the next-generation instruments.**

I. Introduction

Passive microwave observations of sea surface temperature and ocean vector winds represent fundamental geophysical means for understanding, monitoring and predicting the global climate. The next generation ocean-observing satellite missions require high spatial resolution and global coverage including the coastal water from Ku down to C-band (see Table I); however these requirements cannot be met with traditional technologies. Starting in 2009, the European Space Agency (ESA) has initiated and supported a number of studies exploring new micro-wave radiometer concepts and antenna designs that could potentially meet these challenging requirements. The recent review of the overall progress has identified densely packed DBAFs (commonly referred to as ‘dense’ phase array feeds, PAFs, or ‘dense’ focal plane arrays, FPAs) as the top promising antenna technology. This technology has been introduced in the late 90s for the applications in radio astronomy to enhance the survey speed of radio telescopes [1], [2]. In the last years, several PAF-based instruments have been developed world-wide, and a few of them have already become operational [3], [4], [5]. For the herein considered application, it is a new concept, which has the potential to achieve high resolution and improved accuracy over the global coverage, while also correcting for the weather effects, such as rain, as well as mitigate radio frequency interference. This paper presents the expected performance characteristics of a multi-beam conical-scan radiometer system employing a $64 + 63 = 127$ element DBAF (two polarizations) and operating at C-band. The results obtained for conventional horn feeds are also presented that quantify the fundamental bounds between the main system characteristics and horns physical dimensions.

TABLE I
Radiometric requirements for future missions.

Freq., [GHz]	Band width, [MHz]	Polari-zation	Radiometric resolution, [K]	Bias, [K]	Spatial resolution, [km]	Dist.to coast, [km]
C (6.9)	300	V, H	0.30	0.25	20	5-15
X (10.7)	100	V, H, S_3, S_4	0.22	0.25	20	5-15
Ku (18.7)	200	V, H, S_3, S_4	0.25	0.25	10	5-15

II. Antenna requirements

Existing spaceborne microwave radiometers typically use conical-scan reflector antennas. Such systems, operating at C-band (6.9 GHz) or at higher frequency, provide a spatial resolution of around 50 km, whereas less than 20 km is desirable (see Table I) [6]. Furthermore, accurate radiometric measurements are currently possible at not closer than around 100 km from the shoreline, because of the signal contamination by the antenna side-lobes illuminating the land. There is a strong desire to reduce it down to 5-15 km. The required 20 km resolution, i.e. 3 dB footprint, at C band leads to a large antenna aperture of around 5 m in diameter that is considerably larger than any radiometer system antenna flown hitherto. Moreover, the required short distance-to-land can only be achieved by using a dense PAF having a large number of antenna elements. To determine the optimum number of elements and their excitations, we have developed a dedicated procedure maximizing the beam sensitivity, while minimizing the distance-to-land (MSMDL) [7]. In [7], this procedure was applied to the PAF for a stationary push-broom radiometer. In this paper, we extend it to the conical-scan case.

A. Limitations of horn feeds

Horn antenna feeds used in radiometer systems are typically designed to produce an illumination pattern with strong taper toward the edge of the reflector to trade high beam efficiency, and low cross-polarization power against low side-lobes to achieve a short distance to land. Figures 1(b-e) show typical radiometer parameters at C-band, which were obtained for the conical scanner (see the description of antenna geometry in [6]). The antenna was analyzed with the Gaussian beam model of the feed having a varying illumination taper (IT) and aperture diameter of the corresponding horn feed. The positions and aperture diameters of the horns in the focal plane are depicted on Figure 1(a) by circles of different sizes corresponding to three taper values at C, X and Ku bands. The main radiometer parameters are shown for the horn aperture ranging from 2.2 to 5.4λ corresponding to IT $= (-10 \ldots -60)$ dB. As seen, the cross-polarization power can only be minimized by strongly tapering the feed pattern, but this leads to the increased footprint size and distance-to-land, and hence difficulties to satisfy the requirements (more horn/receivers may be needed). The shortest distance-to-land that can be achieved with this tapering approach is ~ 20 km for IT $=$ 25 dB, for which the realized cross-polarization power is at least 3 times higher than the desired 0.34%.

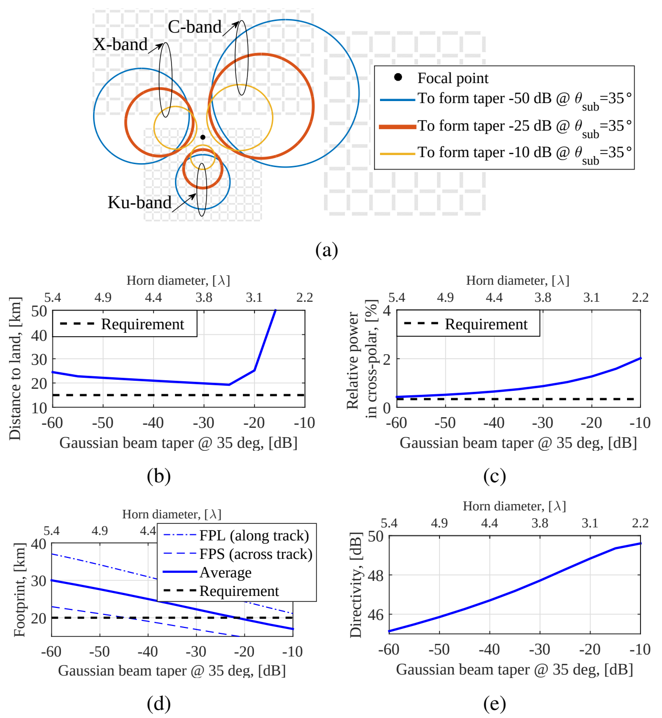

Fig. 1. (a) Simulated locations and aperture diameters of the horn feeds at C, X and Ku frequency bands for three different values of the illumination taper; (b-e) Radiometer characteristics as function of the illumination taper of the Gaussian feed and the corresponding horn diameter.

B. Arrays feed

In [6] it has been found that in order to meet the requirement on spatial resolution for a swath of 1500 km, the conical-scan antenna needs 2 beams at C-band, 21 beams at X-band and 30 beams at Ku-band. The layouts of the considered PAFs along with their relative positions in the focal plane of the reflector are illustrated on Figure 1(a). The total number of elements at C-band is 127 and the overall array aperture area is $(6 \times 5.25)\lambda$. To limit the complexity of the analysis of PAFs, we have used a simplified model of the array, where we assumed that it has identical embedded element patterns. These patterns were modeled for the case of a half wavelength dipole antenna array with 0.75 wavelength inter-element separation distance, located above an infinite ground plane. The resultant radiometer characteristics at C-band are summarized in Table II, where we show the cases of the optimal horn (IT $=$ 25 dB) and two PAFs. The PAF II was optimized by using a conventional Conjugate Field Matching (CFM) approach and the PAF I was designed with the MSMDL approach [7]. As seen, the CFM approach would require 30 more elements for the PAF to achieve a similar performance as that obtained with the customized beamforming method. In future work we plan to re-evaluate the resultant radiometer characteristics with a more accurate array model accounting for the mutual coupling and edge truncation effects, as well as try to further minimize the number of antenna elements.

TABLE II
RADIOMETER CHARACTERISTICS FOR DIFFERENT FEEDS

Radiometer characteristic	**Require-ment**	**Horn feed**	**PAF I, MSMDL**	**PAF II, CFM**
Number of antenna elements (2 polarizations)			64 + 63 = 127	80 + 77 = 157
Distance to land, [km]	< 15	19	14	16
Rel. cross-pol. power, [%]	< 0.34	1.04	0.29	0.19
Beam efficiency, [%]		97	96	95
Footprint (average), [km]	< 20	21	20	21
Footprint ellipticity		1.6	1.4	1.7

C. Conclusions

An advantage of novel phased array feeds with respect to traditional single-horns is their capability of satisfying complex performance specifications by optimally beam-forming the signals received by a large number of array elements. As shown in this paper, an optimal design can lead to a major improvement in the performance of the present and flying technologies. For the conical-scan antenna operating at C-band, the required distance to land of 15 km can be achieved with an array of 127 half-wavelength dipole antenna elements.

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