Design of a Push-Broom Multi-Beam Radiometer for Future Ocean Observations

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Abstract—**The design of a push-broom multi-beam radiometer for future ocean observations is described. The radiometer provides a sensitivity one order of magnitude higher than a traditional conical scanning radiometer, and has the big advantage of being fully stationary relative to the satellite platform. Thanks to a dense focal plane array and a dedicated optimization procedure, the instrument can accurately measure in C, X and Ku band and as close as 15 km to the coast line.**

Index Terms—reflector, dense focal plane array, radiometer, power, deployable reflector.

I. INTRODUCTION

Current spaceborne radiometers for ocean observation operating at C- X- and Ku-band, like AMSR-E and WindSat for example, provide a spatial resolution of around 55 km, 35 km and 20 km at the three respective bands, see [1]-[2]. The sensitivity provided by AMSR-E is 0.3 K at C- band and 0.6 K at X- and Ku-band, while for WindSat it is around 0.7 K. Moreover, all current radiometers can generally accurately measure only up to 100 km to the coast line, due to the signal contamination given by the antenna side-lobes illuminating the land, which is significantly warmer than the sea.

The oceanographic community is thus interested in more accurate measurements, and has formulated for this purpose a list of requirements for future radiometers measuring sea surface temperature (SST) and ocean vector wind (OVW), according to TABLE I.

TABLE I REQUIREMENTS FOR FUTURE SST/OVW RADIOMETERS.

Frequency [GHz]	Band width [MHz]	Polarization	Sensitivity [K]	Accuracy [K]	Resolution [km]	Dist.to coast [km]
6.9	300	V, H	0.30	0.25	20	5-15
10.65	100	V, H	0.22	0.25	20	5-15
		S_3, S_4	0.22	0.25	20	5-15
18.7	200	V, H	0.25	0.25	10	5-15
		S_3, S_4	0.25	0.25	10	5-15

From TABLE I it is seen that the distance to coast shall be reduced to 5-15 km and the spatial resolution and sensitivity shall be lowered by around a factor two relative to the values provided by AMSR-E and WindSat. The required 20 km resolution at C-band of TABLE I leads to an antenna aperture of around 5 m in diameter. This is considerably larger than the antennas of AMSR-E and WindSat which are in the 2 m class. The MICROWAT mission concept study, completed a couple of years ago and whose main results are reported in [3], used requirements similar to the ones of TABLE I, see [4]. Its outcome was a classic real aperture conical scanning radiometer. The antenna was a 7 m by 5 m solid parabolic offset reflector illuminated by an array of horns in C- and Ku-band. A spatial resolution of around 15 km allowed a small distance to coast, which was however larger than the desired 5-15 km. The sensitivity, less demanding than the values contained in TABLE I, was achieved. The solid reflector was realized by three foldable panels and rotated at 6 RPM. The radiometer could fit into a Soyuz launcher.

Even though the MICROWAT conical scanning radiometer could achieve the desired sensitivity and showed a spatial resolution in line with the requirements, the feed array and the scanning mechanism were based on a traditional scheme, which made the reflector quite heavy (147 kg), requiring a momentum compensation during the rotation that was critical. On the basis of these results, ESA expressed the interest of studying alternatives to the design proposed by MICROWAT, awarding in 2013 a contract to the team consisting of TICRA, DTU-Space, HPS and Chalmers University. Three topics were of particular interest for the study. First, an alternative to the conical scanning scheme, namely the push broom scenario, should be studied. Such a system was studied in the Eighties providing high sensitivity and a successful prototype at 37 GHz [5]. The conical scanning antenna rotates around a vertical axis, and the swath on the Earth is obtained by rotating the antenna and integrating the receivers' response. For the push-broom system there are no moving parts but the antenna radiates as many beams as required to cover the swath. The push-broom system achieves very high sensitivity since all across track footprints are measured simultaneously. The antenna has the clear advantage of being stationary, but the number of beams and receivers is very high, and this is why the concept was on hold for many years, due to the prohibitive number of receivers and relative power consumption needed for a realistic application. Second, the use of large deployable light-weight reflector antennas should be considered in order to lower the reflector mass and simplify the momentum compensation. Foldable light weight reflector antennas have been studied and manufactured in the US for the SMAP radiometer, ready to be launched in 2015. The SMAP antenna is a 6 m reflector rotating at 14.6 RPM working in L band [6]-[7]. The same technology has been studied in Europe as well, see for example [8], but is not fully available in the market yet. Finally, since most flying radiometers use parabolic reflectors with a cluster of feed horns, the possibility of using a dense array of feeds [9], such as introduced in the radio astronomy community for the Square Kilometer Array, should be investigated in order to increase the radiometric sensitivity.

In [10] it was shown that a radiometer with an antenna aperture of around 5 m provides the ground resolution required by TABLE I, but cannot achieve the desired sensitivity in a traditional single radiometer channel/beam concept. The sensitivity of TABLE I can only be met by considering several simultaneous beams in the along- and across-track, in either a push-broom system, or in a multi-beam scanning system. The trade-off between a conical and a push-broom scanning system relative to reflector optics and feed array design was described in [10], and indicated the push-broom antenna as the most promising candidate.

The purpose of the present paper is to focus on the detailed design of the push-broom antenna radiometer.

The paper is organized as follows: in Section II the antenna requirements are summarized, in Section III the geometry of the push-broom antenna and its focal plane array are described. The principles behind the optimization of the focal plane array are given in Section IV, while the detailed RF performances of the antenna are given in Section V. Finally, Section VI describes the mechanical realization of the push-broom reflector and Section VII summarizes important results on the feeding network and the necessary power. Conclusions are finally drawn in Section VIII.

II. ANTENNA REQUIREMENTS

The requirements for the radiometer antenna can be derived from the radiometric requirements of TABLE I.

One requirement concerns the cross-polarisation of the antenna. The radiometer shall measure brightness temperatures in two linear polarisations, vertical and horizontal, and with an accuracy of 0.25 K. This is fulfilled when the cross-polar power received from the Earth does not exceed 0.33% of the total power coming from the Earth for that polarization state [10].

The instrument must be able to measure as close as 5-15 km from the coast. Assuming a brightness temperature of the sea between 75 and 150 K, and of the land of 250 K, the required accuracy of 0.25 K is obtained if the coast line is located outside a cone, around the main beam and with angle θ_c, containing 99.72% of the total power on the Earth. In order to obtain a small distance to coast, this cone must be as narrow as possible, see Fig. 1.

The satellite height above the Earth and the incidence angle are assumed equal to 817 km and 53°, respectively. The required swath width was initially set to 1500 km. It was however realized very early in the study that for the push-broom system this will lead to a very large antenna. The swath was thus reduced to 600 km. Even with this reduction the radiometer will represent a major advancement in the study of the oceans.

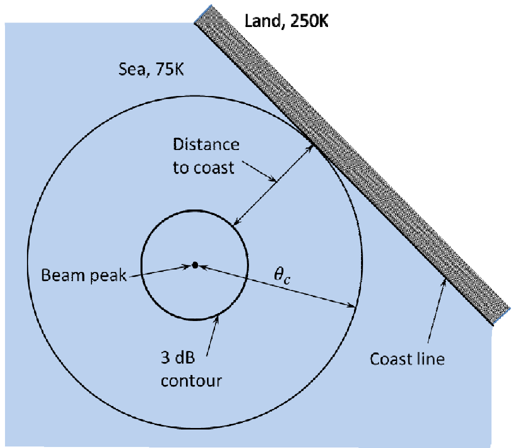

Fig. 1 Schematic drawing of the distance to coast concept.

III. THE PUSH-BROOM ANTENNA

A. Antenna geometry

The push-broom antenna consists of a torus reflector obtained by rotating a section of a parabolic arc around a rotation axis. The projected aperture *D* of the parabolic generator is 5 m and its focal length is selected equal to 5 m. The feed axis is chosen parallel to the rotation axis, implying that all feed element axes are parallel and orthogonal to the focal plane. The feed array becomes therefore planar, simplifying the mechanical and electrical design. The reflector rim is found by intersecting the torus surface by the feed cone up to the outmost scan positions. The antenna shall be able to provide a scan of ±20° corresponding to a swath width of 600 km. The final design is shown in Fig. 2, where the projected reflector aperture is 5 m by 7.5 m.

B. Feed array

The sensitivity provided by the torus push-broom is always one degree of magnitude better than the one provided by the conical scanner. This is at the expenses of a very large number of beams, and correspondingly large number of receivers. For a swath of 600 km we need:

- 58 beams across track at 6.9 GHz
- 89 beams across track at 10.65 GHz
- 156 beams across track at 18.7 GHz.

The array elements are arranged in a ρφ-grid around the rotation axis. The distance between the elements is approximately the same in the ρ-direction and in the φ-direction, and set equal to 0.75 wavelength. This distance was proven to be the optimal distance [12]. For analysis purposes the array elements are assumed to be half-wave dipoles located a quarter of a wavelength above an infinite ground plane. Each element consists of both an *x*- and a *y*-directed dipole with separate ports. They only radiate in the upper half space above the ground plane.

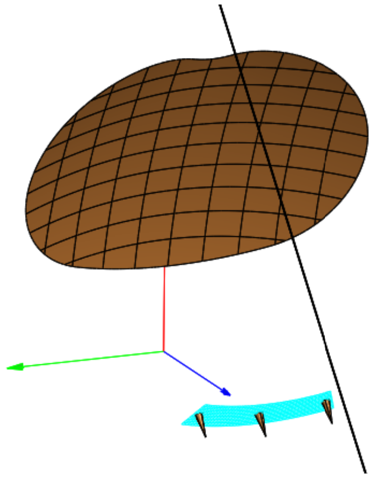

Fig. 2 Torus push-broom antenna with projected aperture *D* and focal length *f* of 5 m. The three feed positions represent scan directions of 0° and ±20°. The feed array is shown in light blue.

IV. FEED ARRAY DESIGN PRIINCIPLES

It was realised early in the project that a traditional one beam-per-feed arrangement was not possible and a dense focal plane array was needed. This means that many array elements take part in the formation of one beam and the same array element takes part in the formation of many beams. The composite feed array must be excited by a multi-mode beam-forming network.

The feed array design was investigated almost independently by both TICRA and Chalmers. Initially, TICRA used the Conjugate Field Matching (CFM) method to determine the feed element excitations. It turned out that this approach was too restrictive and gave rise to a number of feed elements larger than the one obtained by Chalmers [10] with a dedicated optimisation procedure.

Since behind each array element sit two receivers for the respective orthogonal polarization, it is of high importance to reduce the number of array elements to the minimum necessary, in order to minimize the power consumption and the complexity of the feed array. TICRA developed therefore an alternative algorithm, in which the array excitations are obtained by directly minimising the distance to coast, i.e. minimizing the half angle $\square_c$ of the circular cone in which 99.72% of the total power is contained. The optimisation can be formulated as an eigenvalue problem, where the eigenvalue represents the maximum radiated power inside a given cone and the eigenvector holds the excitations to generate this field. The number of elements along the ρ and φ direction must be given as input to the algorithm. Such a number of elements is smaller than the number of elements found by CFM.

The optimisation method developed by TICRA is similar to the one developed by Chalmers [11]. The difference lies in the way the cost function is defined: it is the ratio of the power inside and outside the angular cone for TICRA, while it is the ratio of the power inside a specified small region to the noise power outside this region for Chalmers. The radiometric performances obtained by the two algorithms are very similar and will be described in the following.

V. RF PERFORMANCE RESULTS

A. Central beam at Ku band

The reflector surface is not a paraboloid and the performances are therefore expected to be most critical at the highest frequency. In this section the central beam at Ku-band, 18.7 GHz, is thus presented.

The feed array has 8 elements in the ρ-direction and 21 elements in the φ-direction. The total number of array elements to generate the central beam is therefore 168. The element excitations are determined by TICRA's optimisation approach described earlier. The synthesized excitation coefficients in amplitude are shown in Fig. 3. The far-field pattern of the antenna is depicted in Fig. 4. It is evident that this pattern is not rotationally symmetric and one could therefore get the impression that the actual orientation of the coast line would be very important for the instrument performance quality. However, one can find that the -30 dB contour is nearly a circle with radius of 0.5°. This circle contains 99.72% of the power and the coast line can therefore be located anywhere outside this circle and its orientation is not important.

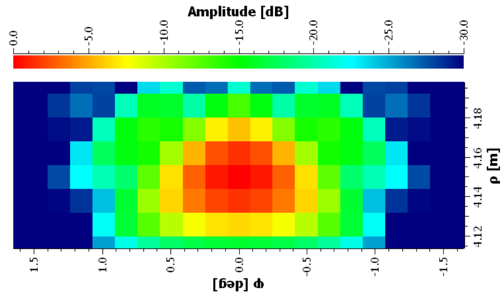

Fig. 3 Excitation coefficients for the centre beam for minimum distance to coast.

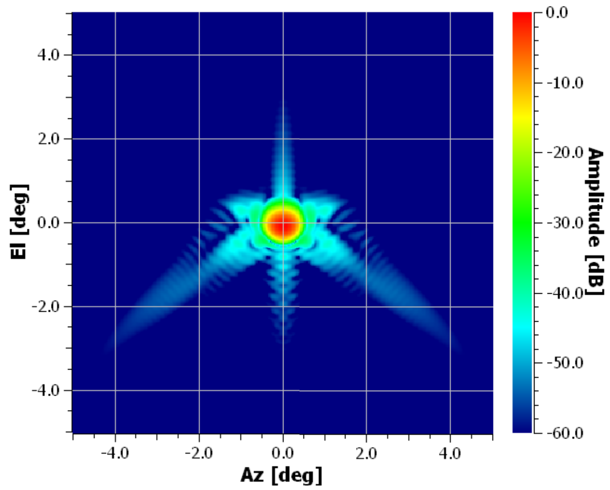

Fig. 4 Image plot of the co-polar far field of the centre beam for the push-broom antenna optimised for low distance to coast.

The radiometer characteristics obtained by TICRA for the center beam at Ku band shows that the cross-polar power is 0.14 %, the footprint is 10.32 km and the distance to coast is 7.08 km. Equivalent results were obtained by Chalmers.

B. Reduction of feed array rows along ϕ

It was seen in the previous section that a feed array with 8 rows along φ gives a distance to coast of 7 km which is actually better than the required 15 km. It was thus investigated if it was possible to reduce the number of feed array rows to 7 or 6 still maintaining acceptable performances.

The excitations are again determined such that 99.72% of the power is contained in the smallest possible cone around the beam peak. Using a smaller number of rows generates a more elliptical illumination on the reflector and a more elliptical far-field beam. It was found that with 6 rows the footprint becomes 10.86 km, and the distance to coast reaches 9.19 km. These are acceptable values and thus the number of rows is reduced from 8 to 6.

C. Total feed arrays for C-, X- and Ku-band

The centre beams in C- and X-band are realized again with a feed array having 6 elements in the ρ-direction and 21 elements in the φ-direction, as it was done in Ku band. The element excitations are again determined by optimizing the distance to coast and the calculated results are summarized in TABLE II. It is seen that at X and Ku band the performances fully meet the requirements of TABLE I, while at C-band the footprint size and the distance to coast slightly exceed the necessary values. Increasing the number of rows from 6 to 7 or 8 will solve the problems at C band.

TABLE II Radiometer characteristics for the centre beam at C-, X- and Ku-band.

Frequency	Cx-power %	Foot-print [Km]	Distance to coast [km]
C-band	0.20	23.26	16.41
X-band	0.14	16.53	12.28
Ku-band	0.08	10.86	9.19

Having determined the feed array for the centre beam the complete feed array can be designed. The Ku-band feeds are located close to the focal circle of the push-broom torus, while the feed arrays for C- and X-band are located on either side of the Ku-band array. The three feed arrays are shown in Fig. 5. The total number of array elements for the two polarizations is 1284, 1956 and 3156 for C-, X- and Ku-band, respectively. This means a total of 6396 array elements, and thus 6396 receivers.

D. Additional performance checks

The push-broom antenna was analysed more in detail. The results can be summarized as follows:

Scan performance. The antenna is able to scan up to 20° to both sides without any severe scan degradations. The excitations are practically identical for all the beams, but shifted in the φ-direction according to the actual scan direction.

Bandwidth investigations. The required bandwidth is 300, 100 and 200 MHz at C-, X- and Ku-band, respectively. The radiometer performances are almost constant over the bands.

Sensitivity to excitation inaccuracies. The feed element excitations can only be realized to certain accuracy, therefore two types of excitation errors were investigated. Excitation errors up to 10% for each separate element and up to 3% of the largest excitation are acceptable. This is very well in line with the observation that it is acceptable to discard all elements with an amplitude lower than 30 dB below the strongest excited element.

Redundancy aspects. It was finally demonstrated that it is possible to re-optimize the excitation coefficients in case of a receiver failure and in this way remedy the consequences of the failure.

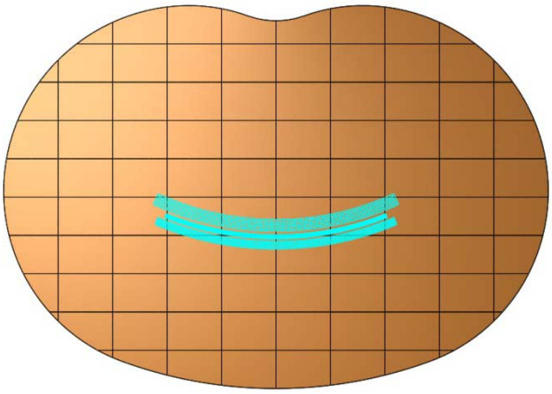

Fig. 5 Feed arrays for C-, X- and Ku-band.

VI. Mechanical design of the push-broom torus antenna

The mechanical realization of the torus reflector proposed by HPS consists of a double layer pantograph and two triangular wire-band nets, one in the front and one in the back, fitting a VEGA launcher. The corners of the triangles of the two nets are connected by adjustment wires, as shown in Fig. 6. The front net forms the support of the reflector.

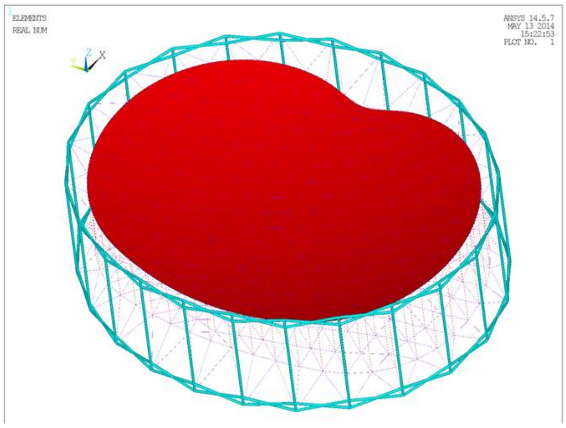

Fig. 6 Mechanical realisation of the torus push-broom reflector dish.

Initially it was assumed that the front net would be covered with a knitted metal mesh in order to provide the necessary RF reflection. It was realized, however, that the triangular facets would generate high and unacceptable grating lobes unless the triangles were made very small, i.e. 100 mm size. Consequently, it was proposed to construct the reflector as a doubly curved CFRS (Carbon Fibre Reinforced Silicon) surface. The triangular net is maintained to support the CFRS but the size of the triangles can be much larger, around 400 mm. The reflector mass is around 40 Kg.

VII. FEEDING NETWORK AND RECEIVER ISSUES

As illustrated in Fig. 7, each feed array element is connected to a direct detection circuit, one for each polarization channel, and is assigned its own receiver and A/D converter. A major concern is the total number of components in the system, with respect to mass, size and especially power consumption.

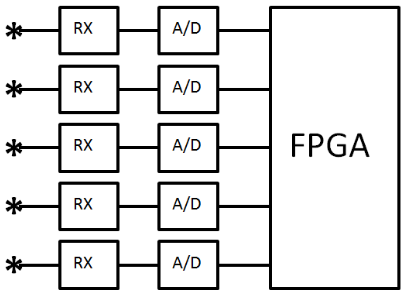

Fig. 7 Dense feed array receiver system.

The A to D converter is the most critical component, as it is traditionally the largest and by far the most power consuming. A realistic power budget based on state-of-the-art components results in a power consumption of approximately 850 mW per receiver at X-band and 1100 mW at Ku-band and C-band. The total power budget is dominated by X- and Ku-band due to the many receivers at these frequencies, and for global power budget estimates we can assume 1 W per receiver. Adding also power for the beam forming network and RFI processor we end up with 1.38 W per receiver. With 6396 receivers this gives a total power of 8.8 kW, which is not realistic now or in the near future.

Already now A/D converters able to sub-sample signals up to X-band are available in research labs and within very few years Ku-band is also served. The development concerning amplifiers is also impressive, especially when it comes to noise figure at high frequencies and power consumption. For global power budget estimates we can within a few years assume 49 mW per receiver, including beam forming network and RFI processor. This amounts to a total power consumption of 6396 x 49 mw = 313 W, which is certainly realistic in a five years time frame.

VIII. CONCLUSIONS

A novel antenna architecture for real aperture multi-beam radiometers accurately measuring in C-, X- and Ku-band and up to only 15 km from the coast line was presented. The radiometer is a push-broom system with a torus reflector of 5 m by 7.5 m. The push-broom radiometer shows very high sensitivity and has the big advantage of being fully stationary, relative to conical scanning architectures. The reflector is realized by a light-weight mesh reflector technology, folded by a double layer pantograph and with a doubly curved reflector made by CFRS material. The reflector is illuminated by a dense focal plane array, where the elements are half wave dipoles over a ground plane displaced by 0.75 wavelength.

The torus push-broom antenna designed by the team satisfies all radiometric requirements. However, further studies are necessary in order to account, with a full wave analysis, for the mutual coupling in the feed array and the finite size of the ground plane. Moreover, the team wishes to design, manufacture and measure a small but representative portion of the dense feed array system (5 by 7 elements), including receivers, A/D converters and FPGA. Finally, the mechanical realization of the torus reflector must be refined, especially with regards to a suitable CFRS material able to provide the necessary RF reflectivity.

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