Novel Multi-Beam Radiometers for Accurate Ocean Surveillance

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***Abstract*— Novel antenna architectures for real aperture multi-beam radiometers providing high resolution and high sensitivity for accurate sea surface temperature (SST) and ocean vector wind (OVW) measurements are investigated. On the basis of the radiometer requirements set for future SST/OVW missions, conical scanners and push-broom antennas are compared. The comparison will cover reflector optics and focal plane array configuration.**

I. INTRODUCTION

The assessment of ocean parameters like salinity, sea surface temperature and ocean vector wind based on spaceborne microwave radiometer measurements is an important and challenging task, not only concerning geophysical algorithms but also concerning technical aspects.

A thorough and very recent review of ocean sensing was carried out by ESTEC and leading oceanography expert groups worldwide, producing the instrument requirements that future radiometers shall aim at, according to Table 1. The satellite height above the Earth and the incidence angle are assumed equal to 817 km and 53 deg, respectively.

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

Table 1. Radiometer characteristics for the conical scan antenna at C-, X- and Ku-band.

It is seen that SST and OVW are measured from C to Ku band, with a desired ground resolution of around 20 km at C and X band, and 10 km at Ku band. The desired sensitivity is around 0.22 K. It is easily derived, see the procedure described in [1], that a radiometer with antenna aperture of around 5 m provides the required ground resolution but cannot achieve the desired sensitivity in a traditional single radiometer channel/beam concept, even with the state-of-the-art noise performance of receivers available in the market. The required sensitivity 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, as depicted in Fig. 1.

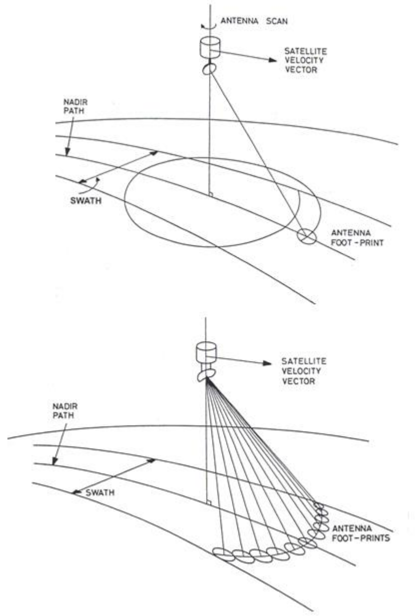

Fig. 1. Conical scan (on top) and push-broom (bottom) scenario.

The push-broom system achieves very high sensitivity since all across track footprints are measured simultaneously by their own receivers [2]. The antenna has the clear advantage of being stationary, but the number of beams and receivers is very high. An advanced feed design and reflector are necessary, and its light-weight mechanical realization is challenging. The multi-beam scanning system achieves high sensitivity by measuring each footprint several times followed by integration. The antenna is mechanically smaller than an equivalent torus, but presents numerous challenges in order to achieve a well-balanced rotation at satellite level [3]. Again, an advanced feed design is necessary.

In February 2013 the ESA contract 4000107369-12-NL-MH was awarded the team consisting of TICRA, DTU-Space, HPS and Chalmers University. The purpose of the activity is to identify the antenna requirements for a conical scanning and a push-broom radiometer for accurate SST and OVW measurements, and to make a trade-off of such two antennas, with respect to reflector optics, focal plane array configuration, ultra-light mesh reflector technology, mechanical stability, and calibration and RFI mitigation techniques. The purpose of the present paper is to describe the reflector optics and feed array design used for the trade-off, for a conical scanning and a push-broom radiometer antenna satisfying the requirements of Table 1. The paper is organized as follows: In Section II the optical design is described, while in Section III the antenna requirements derived from the radiometer requirements are highlighted. The feed array design is finally given in Section IV.

II. Optical design

Following the procedure described in [1] it was found that a reflector antenna with projected aperture of around 5 m provides the required ground resolution. A conical scanning and a torus-push-broom antenna implementation were then considered. They are described in more detail in the following subsections.

A. Conical scanning radiometer antenna

The conical scanning antenna is an offset paraboloid with projected aperture D of 5 m. The clearance is set to 1 meter in order to provide space for the feed cluster and the focal length f is set to 3 m in order to make the design more compact. For a swath of 1500 km, the sensitivity of Table 1 can be achieved by:

- 2 beams along track at 6.9 GHz
- 3 beams along track and 7 beams across track at 10.65 GHz
- 5 beams along track and 6 beams across track at 18.7 GHz.

The number of beams in the along track direction is selected such that they cover the same strip width on the Earth. The antenna rotates at 11.5 RPM and the radiometer has a for-and-aft look.

B. Torus push-brom radiometer antenna

The push-broom antenna is a torus reflector with projected aperture D of 5 m. The torus is obtained by rotating a section of a parabolic arc around a rotation axis. The focal length of the parabolic generator is also 5 m. A possible way of obtaining the torus is shown in Fig. 2: the feed axis is selected 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 the illuminated rotated aperture up to the outmost scan positions, see Fig. 3.

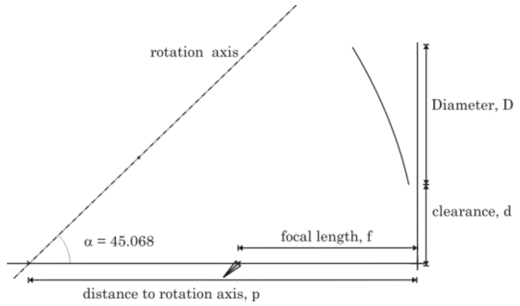

Fig. 2. Torus design.

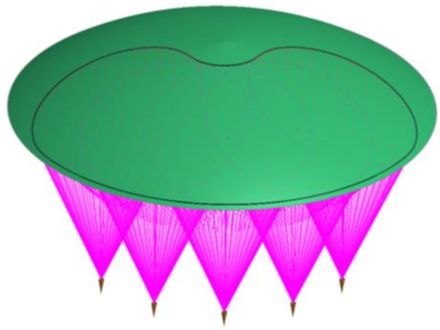

Fig. 3. Rim trace for toroidal push-broom antenna design.

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. 4, where the projected reflector aperture is 5 m by 7.5 m. It is recalled that the swath of the torus push-broom was reduced from 1500 km to 600 km in order to decrease the horizontal size of the reflector from 11 m to 7.5 m. This also reduces the feed array size and simplifies the electrical and mechanical realization.

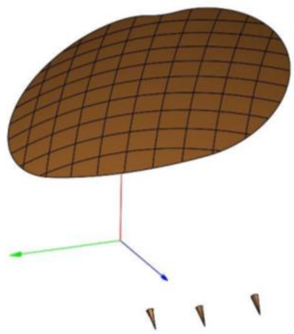

Fig. 4. Torus push-broom antenna with projected aperture D of 5 m, three feeds located at 0° and ±20°, f/D=1, and swath of 600 km.

It is noted that the sensitivity provided by the torus push-broom is always one degree of magnitude higher 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 antenna is stationary in contrast to the conical scan antenna.

III. ANTENNA REQUIREMENTS

A. Acceptable cross-polarization

The requirement for the cross polarisation is not given directly in Table 1. We know, however, that the radiometer shall operate with two linear polarisations, vertical and horizontal, and that the accuracy indicated in the column "Bias" in Table 1 shall be achieved. It can be shown that the required $\Delta T \leq$ 0.25K implies that the cross-polar power must not exceed 0.33% of the total power on the Earth.

B. Acceptable side lobes and distance to coast

Table 1 states that the radiometer shall operate satisfactorily within 5-15 km from the coast. It is assumed that this distance D_c is measured from the 3 dB footprint of the beam. The reason behind the requirement is that the brightness temperature of land areas is much higher than the brightness temperature of the sea, which is what we want to measure. Assume that the coast is located at the angle θ_c from boresight. It turns out, with $\Delta T \leq$ 0.25K, that the power from boresight up to θ_c shall contain 99.71% of the total power on the Earth. The value of θ_c is determined by integration of the power pattern.

IV. FEED ARRAY DESIGN

A. Conical scanning radiometer antenna

To design a feed array for the conical scanning radiometer antenna of Section II(A), and at the same time compensate for the cross-polar component generated by the small *f/D,* a single-feed-per-beam approach is not possible. A feed array with many closely spaced elements is a good candidate. A "feed" is here understood as the collection of the elements used to generate a particular beam.
In the following, we will assume that:

- The feed array element is a half-wave dipole above an infinite ground plane
- The feed array elements are arranged in a square grid with a spacing of 0.75 wavelengths
- Each feed can be represented by a sub-array of 5 by 5 elements

We wish to design the feed arrays for the three frequencies and to calculate the properties of the least scanned and the most scanned beams. This will require the following steps:

1. Determine the necessary feed array size for each of the bands C, X and Ku.
2. Position the feed arrays in the focal plane

The conical scan antenna is a focusing system and the half-power beam-width is inversely proportional to the frequency. With this in mind, and the previously mentioned required number of beams, it is a simple task to determine the size of the feed arrays for the three frequencies. The result is shown in Fig. 5. The layout is selected such that the scan, measured in beam-widths, for the most scanned beam has been minimized. It is noted that the required number of beams is obtained by assuming that the beams overlap at the -3 dB cross-over points.

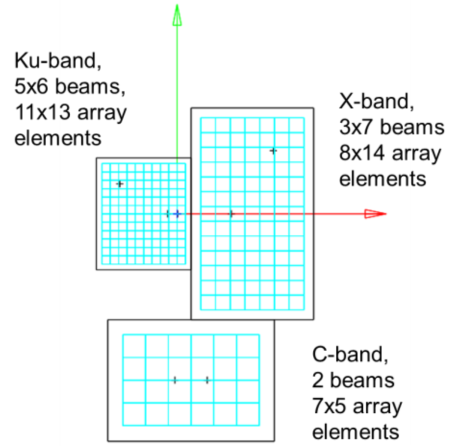

Fig. 5. Feed arrays located in the focal plane.

To calculate the performance of the conical scan antenna we select the least scanned and the most scanned beam for each frequency. The feed positions corresponding to these beams are indicated by small black crosses in Fig. 5. In order to find the feed array excitations necessary to generate these beams, the following procedure is used:

1. Illuminate the reflector with a Gaussian beam with correct direction and orientation
2. Calculate the focal plane field
3. Determine the top 30 dB co- and cross-polar element excitations

The direction of the Gaussian beam in step 1 is given directly by the selected beam. The orientation of the beam is especially important for the scanned beams: it must be such that the beam on the Earth is vertically and horizontally polarized. The Gaussian beam incident on the reflector has a taper of 20 dB. The focal plane field is calculated in step 2. This field is used to calculate the excitation of the array elements in step 3 applying the Conjugate Field Matching (CFM) method. Only the elements with excitations from the maximum value and down to 30 dB below the maximum value are included, in order to account for realistic receivers.

The radiometer characteristics for the six beams of the conical scan antenna are summarized in Table 2. It is seen that the X- and Ku-band beams satisfy the requirements of Table 1, relative to distance to coast, footprint and cross-polar power. The performances for the C-band beams are not acceptable with respect to cross polarization, while the distance to coast is around 20 km, slightly more than the required 15 km. The design and performances of the above feed array was obtained both by TICRA and Chalmers, following the same procedure.

Beam	Number of active elements		cr-polar power	Peak directivity	Foot-print	Distance to coast
	x-dir.	y-dir.	%	dBi	km	km
C_1	52	23	0.72	48.13	21.34	20.7
C_2	52	23	0.74	48.15	21.29	19.14
X_1	26	10	0.18	52.08	13.79	10.03
X_2	40	16	0.30	51.98	13.76	15.45
Ku_1	21	12	0.11	56.96	7.87	5.73
Ku_2	31	16	0.24	56.57	7.93	13.28

Table 2. Radiometer characteristics for the conical scan antenna at C-, X- and Ku-band.

B. *Torus push-brom radiometer antenna*

To design the feed array for the torus push-broom antenna, a slightly different procedure than the one described in Section IV(A) is necessary. This is due to the fact that the push-broom reflector is not a paraboloid and the antenna is not a focusing system for which results obtained at one frequency can easily be scaled to another frequency.

As a starting point, the influence of the taper of the Gaussian beam incident on the reflector is investigated at 10 GHz. The center beam is considered. The taper is varied from 20 dB to 60 dB in steps of 10 dB. The associated focal plane fields are shown to the left in Fig. 6 for the 20 and the 60 dB cases. It is seen that the extent of the field decreases as the taper of the incident beam increases. This means that if we can use a higher taper of the incident Gaussian beam we can apparently reduce the size of the feed array.

A large feed array covering the same part of the focal plane as Fig. 6 is now generated. The element spacing is 0.75 wavelengths = 22.5 mm and the number of elements is 73 in both directions. The total number of elements is actually 2x73x73 = 10,658 because there are two orthogonal dipoles at each element location.

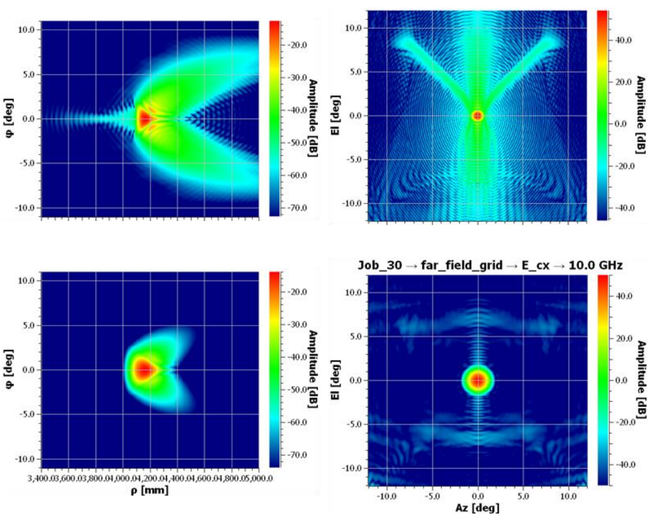

Fig. 6. Focal plane field (left) and far field (right) for incident beam tapers of -20 dB (top) and -60 dB (bottom). The center beam is considered.

The focal plane fields in Fig. 6 are used to determine, again with the Conjugate Field Matching (CFM) method, the excitations of all the 10,658 dipole elements, which then are used to generate the radiated center beam. The co-polar component of the calculated far fields is shown to the right in Fig. 6 and it is seen, as expected, that the beam becomes broader as the taper increases, and, at the same time, the side lobes become smaller.

The radiometer characteristics for the center beams of Fig. 6 are shown in Table 3. We see that the cross polarisation requirement is always perfectly met. The footprint and the distance to coast increase as the taper increases. The results here are for 10 GHz which is close to the X-band frequency, where the requirement to footprint and distance to coast is 20 and 15 km, respectively.

Taper of incident field	Number of active elements		co-polar power	cr-polar power	Peak directivity	Foot-print	Distance to coast
dB	rho-dir.	phi-dir.	%	%	dBi	km	km
20	5329	5329	98.83	0.07	53.27	12.08	7.93
30	5329	5329	99.74	0.03	51.84	14.16	9.89
40	5329	5329	99.93	0.02	50.68	16.12	11.51
50	5329	5329	99.98	0.01	49.74	17.93	12.89
60	5329	5329	99.99	0.01	48.96	19.60	14.11

Table 3. Radiometer characteristics for the toroidal push-broom antenna at 10 GHz for varying taper of the incident beam.

The results in Table 3 include all the elements in the feed array. It is of course of interest to reduce the number of active elements. Fig. 6 shows that the extent of the field in the focal plane decreases as the incident beam taper increases so from a feed array size point of view it is better to use a high input taper. Table 3 shows that with an incident taper of 50 dB a very acceptable beam is obtained. It is therefore attempted to use this focal plane field but only use those elements in the feed array with an excitation larger than a certain value below the maximum. Table 4 shows the results obtained when this limit is set to 40, 30 and 20 dB below the maximum.

Amplitude excitation limit	Number of active elements		co-polar power	cr-polar power	Peak directivity	Foot-print	Distance to coast
dB	rho-dir.	phi-dir.	%	%	dBi	km	km
40	292	56	99.96	0.02	49.63	18.31	12.77
30	155	2	99.79	0.12	49.46	18.66	13.60
20	69	0	99.35	0.14	49.09	19.49	40.18

Table 4. Radiometer characteristics for an incident field taper of 50 dB and excitation limits of 40, 30 and 20 dB.

It is seen that with a 30 dB limit both the cross polarisation, the footprint and the distance to coast meet the requirements and the number of active elements are reduced from 10,658 to 157, i.e. 155 in the radial direction and 2 in the azimuthal direction.

The experience gained at 10 GHz is used to design the feed array in the three bands, following pretty much the same procedure. It is recalled that it is necessary to tilt the direction of the incident beams such that the focal plane fields for the different frequencies are located side by side, leading to the feed array parameters shown in Table 5. Again, it is assumed that beams overlap at the -3 dB cross-over points. The feed arrays are shown in Fig. 7 and the radiometer characteristics for the center beam are presented in Table 6. It is seen that the performance meet the requirements except for the distance to coast at C-band.

Freq.	Wave-length	Distance between elements	Element max, rho	Element min, rho	N_rho	N_phi	Total element number
GHz	mm	mm	mm	mm			
6.90	43.48	32.61	4078	3732	11	93	1023
10.65	28.17	21.13	4566	4314	12	163	1956
18.70	16.04	12.03	4292	4108	16	271	4336

Table 5. Table used to determine the necessary size of the feed arrays for the push-broom torus reflector antenna.

Freq.	Input taper	Exci-tation limit	Number of active elements		co-polar power	cr-polar power	Peak direc-tivity	Foot-print	Distance to coast
GHz	dB	dB	x-dir.	y-dir.	%	%	dBi	km	km
6.90	30	30	133	4	99.56	0.20	48.13	21.82	27.59
10.65	50	30	161	2	99.68	0.10	49.96	17.61	13.29
18.70	40	30	351	0	99.73	0.17	55.56	9.28	13.00

Table 6. Radiometer characteristics for the three frequency bands.

The feed array designed by Chalmers for the torus push-broom antenna is described in detail in [4]. The feed array element is a Vivaldi antenna and the element spacing is 0.7 wavelength. The number of active elements and their weight coefficients is found with a customized beam former that aims to realize the best trade-off between the maximum beam efficiency and the minimum sidelobe and cross-polarization power. To include constraints on the dynamic range of the beamformer in the course of optimization, the customized beamforming algorithm proposed in [4] has been further extended through the use of an iterative procedure. This procedure modifies the reference weights, as determined for the beamformer without constraints, while aiming to maintain the radiometer characteristics as close as possible to the references ones for a specified value of the dynamic range. The performances obtained by Chalmers coincided with Table 6, except for the distance to land at C-band which was 16.9 Km, and thus met the requirements. The total number of elements of the complete feed array for one polarization was 888, 1224 and 2184, for the C- X- and Ku-band respectively, thus smaller than the number of elements obtained by TICRA and reported in the last column of Table 5.

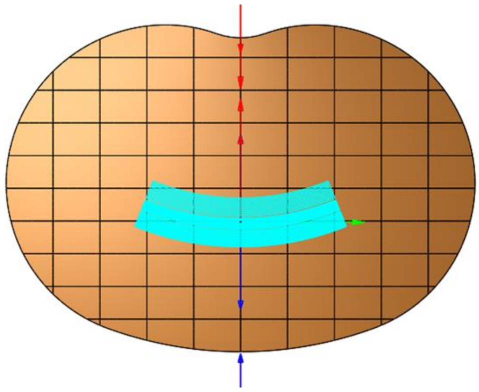

Fig. 7. The three feed arrays for the push-broom torus reflector antenna.

V. CONCLUSIONS

The reflector optics and feed array designs of a conical scanning and push-broom radiometer antenna for future SST/OVW missions were described. The conical scanning is a traditional offset paraboloid with reduced *f*/*D* rotating at 11.5 RPM, while the push-broom is a stationary torus reflector, with projected aperture of 5 m by 7.5 m. The feed array of the conical scan antenna was obtained by considering half-wave dipoles above an infinite ground plane, with a spacing of 0.75 wavelengths. The array excitations were obtained by CFM, considering a Gaussian beam with taper of 20 dB impinging on the reflector. The performances of the least and most scanned beams met all the requirements at X- and Ku-band. The performances for the C-band beams were not acceptable with respect to cross polarization, and the distance to coast was slightly more than the required 15 km. The feed array of the torus push-broom antenna was derived by TICRA in a way similar to the one used for the conical scan, while Chalmers developed a customized beam former to optimize the maximum beam efficiency and the minimum sidelobe and cross-polarization power, including constraints on the dynamic range of the beamformer. The performances of the center beam obtained by Chalmers met all the requirements at all three frequency bands, while TICRA obtained a slightly larger distance to coast at C band and used more antenna elements. The present results must be considered preliminary.

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