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Future High-Performance Spaceborne Microwave Radiometer Systems

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***Abstract*—In a traditional spaceborne microwave radiometer system with a scanning antenna there is often a conflict between spatial and radiometric resolution. Integration over many beams per frequency might be necessary to improve radiometric resolution. Many beams may be generated using many classical feed horns or by a Focal Plane Array (FPA) system. At C-band horns are bulky and replacing several such horns with a FPA is an interesting option. The FPA concept uses many small antenna elements, many receivers, and powerful on-line digital processing. A focal plane array system that can replace 4 horns is evaluated, especially concerning power consumption.**

***Index Terms*—focal plane array, microwave, radiometer, receiver**

I. Introduction

New and challenging spaceborne microwave radiometer systems, encompassing the classical frequencies from C-band through Ka-band, are presently being considered by the space agencies. Compared to present systems, requirements to spatial resolution and radiometric resolution are significantly tougher, and beam quality (polarization purity, land-sea-contamination) is also an important issue.

To fulfill spatial resolution requirements, antenna apertures in the 6 - 10 m range are considered. Tough requirements to both spatial and radiometric resolution leads to a conflicting situation due to a small dwell time per footprint, and the only remedy is to integrate over many antenna beams per frequency. Thus we need several classical feed horns with associated classical receivers, or we can go for a focal plane array (FPA) system. In this system – well known and used operationally in radio astronomy - many small feed elements (could be 30) illuminate the antenna reflector and by properly adding the output of each element in amplitude and phase, a number of almost perfect antenna beams can be generated [1], [2].

Classical horns and associated receivers are well-known technology, meaning low development risk – an important issue in all space projects. The FPA system is a new concept for space, that have never flown but only studied theoretically, and antenna breadboards have been evaluated. An obvious challenge is that the system may employ 30 receivers, 30 fast analog to digital converters (the full RF bandwidth must be digitized), as well as significant and fast digital processing hardware – all on-board and real time. This means development risk and possible power consumption issues.

The new system may combine the two options: C and X bands could use FPA, while the higher frequencies rely on classical horns. This seems an interesting combination since there will be technology challenges for the FPA system at high frequencies, while the FPA can replace big horns at low frequencies. Such a system has been considered where 4 relatively big C-band horns are replaced by an A4 sized (21 x 30 cm) FPA system producing again 4 beams. In the following we will discuss a first order design of such a system especially focusing on power resource issues for the FPA system.

II. System Assumptions and Relations

Users of multi-frequency radiometer data have for years been served by the AMSR type of data, having a spatial resolution of ≈ 50 km at C-band and ≈ 20 km at Ku band. Now more ambitious systems are being studied, opting for: ≈ 15 km at C-band and ≈ 5 km at Ku band. At the same time improved radiometric resolution is highly desired. So, we are talking about a 4 times bigger antenna: from the 1.6 – 1.8 m range to the 7 - 8 m range, and more sensitive receivers or in practice integration over several antenna beams.

As an example we will in the following study a system with conically scanning by a rotating antenna, see Fig. 1.

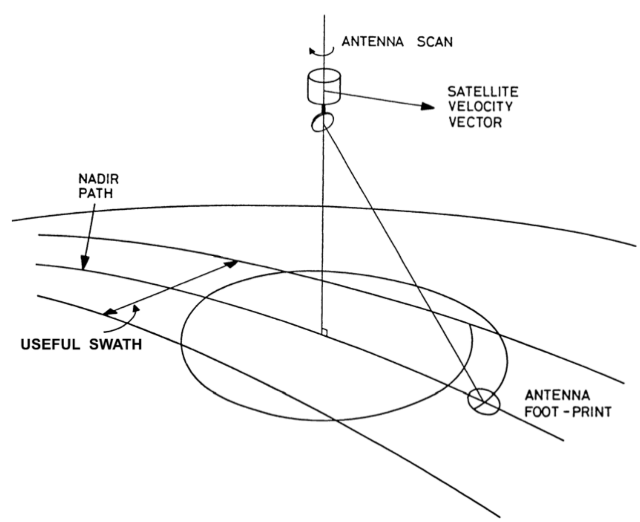

Fig. 1. Typical scanner situation

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The satellite altitude is a typical 817 km and the incidence angle a typical 55°. The antenna temperature is assumed to be 150 K (between sea and land signatures). The footprint (FP) is the intersection between a plane Earth surface and the antenna beam at -3 dB level. The single value for FP is the mean of the footprint along track (FPL) and across track (FPS). 20% FP overlap is assumed both across track and along track to avoid aliasing in the sampling process.

Channel specifications and requirements are shown in Table I. BW is the bandwidth and ΔT is the radiometric resolution.

TABLE I. RADIOMETRIC SPECIFICATIONS

FREQUENCY (GHZ)	6.925	10.65	18.7	36.5
BW (MHZ)	300	90	180	300
FP (KM) GOAL	15	10	5	3
ΔT (K) REQ.	0.2	0.3	0.3	0.7

Now calculation of important parameters like antenna aperture size (D), integration time τ, antenna rotations per minute (RPM), and ΔT can be carried out as described in [3] and as illustrated in Table II. As an example Ku band is shown.

It is seen that in order to fulfill the required 5 km footprint, an antenna with a reflector close to 8 m aperture is required. This is in itself a technical challenge, but at the same time we note a far from satisfactory ΔT and a large RPM far from acceptable. Several beams per frequency are required along track in order to improve ΔT by integration and to lower the RPM (and at Ku band even extra beams across track are required to improve ΔT).

By carrying out calculations as illustrated in Table II at all frequencies we find that strict fulfillment of specifications leads to:

- 4 beams along track @ C-band, ΔT = 0.13 K
- 6 beams along track @ X-band, ΔT = 0.36 K
- 12 beams along + 2 beams across track @ Ku band, ΔT = 0.30 K
- 20 beams along track @ Ka band, ΔT = 0.48 K
- 6.5 RPM

We note that a great many beams (hence receivers) are needed especially at the higher frequencies. Typically, there will now be discussions between the instrument provider and the data users in order to ensure a reasonable complexity and cost while still providing usable data. One might relax on footprint overlap, spatial resolution, radiometric resolution at certain frequencies.

Here we assume that such discussions have lead to a viable system at all frequencies, technical solutions have been found, and concentrate on C-band requiring 4 beams. Classical C-band feed horns are large and bulky, and we will now consider a FPA solution.

TABLE II. PARAMETER RELATIONS – KU BAND

D(M)	FPS(KM)	FPL(KM)	FP(KM)	τ(MSEC)	RPM	ΔT(K)
5	5.79	10.09	7.95	1.0	49.2	0.93
6	4.82	8.41	6.61	0.7	59.0	1.12
7	4.13	7.21	5.67	0.5	68.8	1.13
7.9	3.66	6.38	5.02	0.4	77.7	1.47
8	3.62	6.30	4.96	0.4	78.7	1.49
10	2.89	5.04	3.97	0.2	98.3	1.87

III. CLASSICAL HORNS OR FPA

In a traditional system a feed horn is connected to the receiver via some kind of calibration system, see Fig. 2, left.

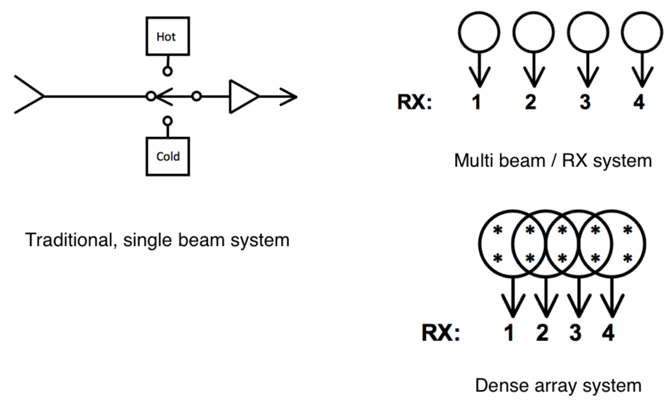

Fig. 2. Classical feed horn + RX and focal plane array system

In our C-band system we need 4 of these as illustrated in Fig. 2, right, top. In the FPA system we use many small, closely spaced antenna elements, and sum the output from a number of them to provide one antenna beam similar to that of the traditional feed horn, see Fig. 2, right, bottom. That summation is illustrated in Fig. 3, left where the small antenna elements for practical reasons are shown as a row of asterisks. Power splitters and summers in principle do the job. For signal loss reasons this will not work, and we have to go to Fig. 3 right, where it is seen that the outputs of the antenna elements are individually connected to as many receivers, the full bandwidth is A-to-D converted, and finally summed in phase and amplitude in a fast Field Programmable Gate Array (FPGA).

The C-band traditional and the FPA feed antenna layouts are shown in more detail in Fig. 4. The information is taken from [4]. The 4 traditional horns are seen in positions such that the required 20% footprint overlap results. The horns are quite large having a diameter of about 22 cm (and a significant length), while the FPA is of A4 size (and quite flat). In Fig. 4 the FPA consist of 35 antenna elements, and something like that is suited for 4 beams.

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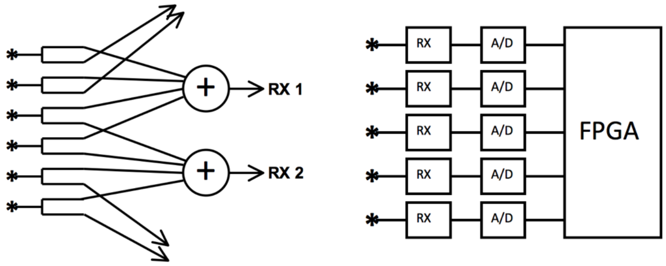

Fig. 3. Dense array receiver system

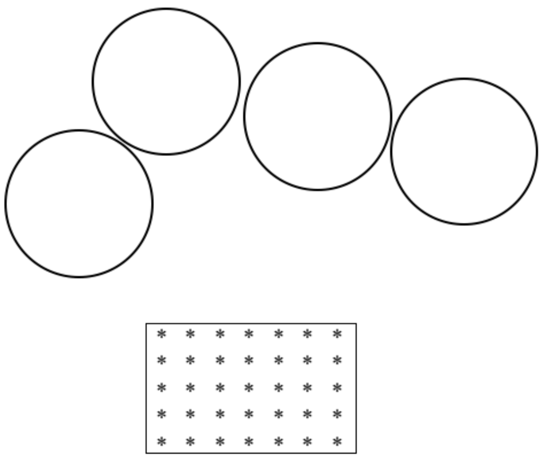

Fig. 4. C-band antennas. Horn diameter ≈ 22 cm. FPA is ≈ 20 x 27 cm

IV. FPA Receiver Design and Power Budget

The receivers are designed according to the super-heterodyne principle thus enabling a flexible IF frequency to fit the A-to-D (analog to digital) converters, see Fig. 5. The input switch can select a reference noise signal from a central noise diode in order to validate coherence between all the receivers and thus ensure correct summing of antenna element signals. The switch can also select hot or cold calibration points in the form of a matched, hot load (HL) or an active cold load (ACL). The switch is followed by suitable amplifiers and a mixer. This is fed from a central local oscillator (LO) common for all receivers. Fig. 5 does not represent a final design, but focuses on power consuming and frequency selecting components.

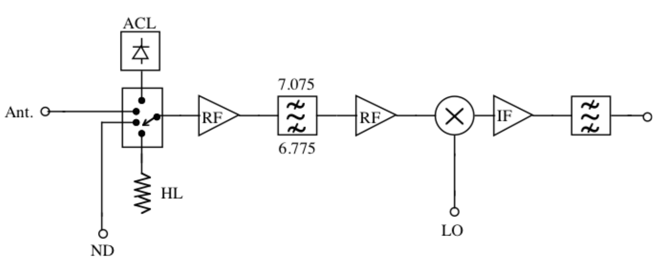

Fig. 5. C-band receiver

Several component types have been considered: switch, low-noise amplifier, mixer, local oscillator, IF amplifier, and especially A-to-D converters. No search for space qualified components or fancy, new laboratory developments has been made – just small, low noise commercially available components have been considered.

All components are of the MMIC (Monolithic Microwave Integrated Circuit) type or similar being very small and low weight. Hence, weight and bulk is no issue, and only power will be dealt with in the following.

Relevant components are:

- Input switch: MA4AGSSW4, L through X bands, 0.4 – 0.6 dB loss, very little power.
- Mixer: powered by LO circuitry.
- Oscillator: 300 mW
- A range of amplifiers, see Table III.

The table shows also X-band amplifiers since it is possible to design an FPA able to handle both C and X-bands, see Section V.

TABLE III. Commercially Available Components

Frequency	Type	NF dB	Gain dB	Power mW
IF (100 – 300 MHz)	GALI-S66		20	60
C	CGY2120	0.6	13	50
X	CGY2124	1.2	33	275
C and X	TGA2600	0.7	30	45

The CGY amplifiers are from OMMIC, the GALI from Mini-Circuits, and the TGA from TriQuint. The gains of these amplifiers are such that the C-band receiver (in addition to one pre-amp) needs 3 RF amplifiers in series and 2 IF amplifiers in series.

A realistic power budget for one C-band receiver can now be established as follows:

- 1 RF C-band pre-amp 50 mW
- 3 x RF C-band amps each 50 mW 150 mW
- 2 x IF amps each 60 mW 120 mW
- 1 ACL (low-noise pre-amp) 50 mW
- In total per receiver 370 mW

Previously, it has been stated that an FPA able to create 4 beams typically will have some 30 elements. In Fig. 4 35 elements are shown. There is no specific number of elements to be used. There is an optimization process, an in the present design we have considered 32 elements in order to fit the chosen FPGA which is attractive with its 16 input channels (see a little later). Since we typically consider dual polarization systems, this means 64 receivers.

- **In total for the C-band receivers 24 W**

Concerning the local oscillator system, we need 10 mW per mixer. We have 64 mixers i.e. 0.01 x 64 = 0.6 W. The signals for the mixers are generated in an oscillators using 300 mW,

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followed by amplification. Assuming an amplifier efficiency of 50 % this means that:

- **In total for the local oscillator circuitry 2 W**

The noise reference calibration circuitry contributes by an insignificant amount.

The beam-forming network processing is based on the powerful Zynq UltraScale+ RFSoC FPGA that includes 16 2 GSPS 12-bit A-to-D converters. Analog bandwidth is 4 GHz, and the estimated power consumption is ≈ 20 W. The 64 each C-band receivers thus require 4 FPGAs each consuming about 20 W. Thus we find:

- Initial total for A-to-D conversion and beam forming 80 W

Thus, the first estimate for the receivers, local oscillator circuitry, calibration, and beam forming is:

- Initial total for the C-band system 106 W

However, this is far from using the full potential of the FPGA and especially the potential of it's A-to-D converters. The receiver bandwidth is only 300 MHz while the A-to-D converters can operate with 2 GSPS. One antenna element requires 2 receivers (for H and V polarization). The local oscillator frequency for the H channel is set to 6.675 GHz and the LO for V is set to 6.275 GHz. The 2 IF outputs are added and fed into one A-to-D converter. Frequencies are: 100 – 400 MHz and 500 – 800 MHz. Later in the system the two channels are separated again digitally. A sampling frequency of 1.7 GHz is assumed. Thus the C-band system requires only 2 FPGAs each consuming about 20 W. Thus we find:

- **Total for ADC and beam forming 40 W**

It should be noted, however, that a slightly more complicated LO system is now required since we need two separate LO frequencies (6.675 GHz and 6.275 GHz). This does not affect power consumption significantly, and we can still stay within the 2W allocated in the budget. But it should be noted that bulk and complexity are enhanced by having two independent LO distribution networks.

Thus, the first estimate for the receivers, local oscillators, calibration, beam-forming, is:

- **Power consumption for the C-band system 66 W**

(It should be noted here that the resources in the FPGA are so large that probably there is actually room for an RFI (radio frequency interference) processor, which otherwise consumes an appreciable amount of power. This is, however, not established yet, and requires further studies).

V. C AND X-BAND COMBINED DESIGN

In the previous section we discussed how 4 bulky C-band horns can be replaced by a modest sized FPA antenna. But there are actually also other possibilities for bulk savings.

In Section II we saw that in order to strictly fulfill all user requirements we need 4 C-band antenna beams and 6 X-band beams. Lets assume that during the discussions between instrument provider and users about cost and feasibility we arrive at the following compromise: a slight under-illumination of the reflector at X-band yields slightly larger footprints equal to the C-band footprints hence we can do with 4 beams at X-band. The X-band channel is often regarded as an important support for the crucial C-band channel and this requirement is thus fully acknowledged.

It is feasible to design antenna elements covering both C and X-band. The breadboard array shown in [4] and [2] is based on Vivaldi antenna elements that are very broadband, and it is thus of interest to design one receiver handling both frequency bands.

Some moderate changes will have to be done to the FPA layout. Basically, the distance between antenna elements must be below 1 wavelength, ideally 0.7 wavelength, see [1], [4], in order to achieve low side lobe levels. Following proper compromises the 32 element array discussed before can be designed to work satisfactorily and both frequencies.

The signal from the antenna element as usual goes to the input switch where selection of calibration source and coherence check takes place, see Fig. 6. The components are wide-band so no problem with combining C and X-band.

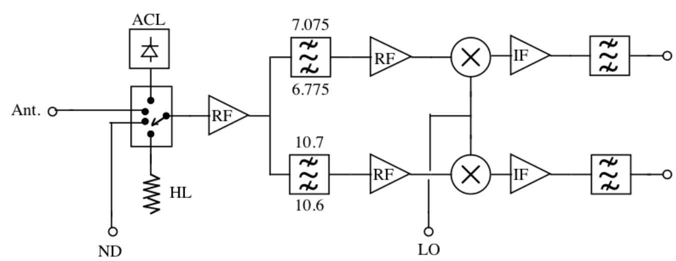

Fig. 6. Combined C and X-band receiver layout

For the low-noise pre-amplifier, the TGA amplifier already shown in Table III, is very well suited for this combined frequency receiver: the C-band noise figure is almost as for the dedicated CGY2120, and the performance at X-band is good.

A realistic power budget for one C and X-band receiver can now be established as follows.

- 1 RF C and X-band amp as pre-amp 45 mW
- 1 RF C-band amp each 45 mW 45 mW
- 1 RF X-band amp each 45 mW 45 mW
- 4 x IF amp each 60 mW 240 mw
- 1 ACL (LNA) 45 mW
- In total per receiver 420 mW

There are 64 C and X-band receivers, so:

- **In total for the combined receivers 27 W**

One possible frequency plan for this combined receiver can be worked out as follows:

Let the LO frequency be 8.650 GHz. Thus the output corresponding to the C-band channel becomes 1.575 – 1.875 GHz, and the output corresponding to the X-band channel is 1.950 – 2.050 GHz. Combining these two signals results in a signal having a bandwidth of 475 MHz requiring a sampling frequency larger than 950 MHz. If we select FS = 1.475 GHz the resulting spectrum becomes: 100 – 400 MHz and 475 – 575 MHz easily filtered by digital means.

We need one FPGA per 16 receivers, in total 4 FPGAs each consuming 20 W such that:

- **Total for ADC and beam forming circuitry 80 W**

Again we assume 2 W for the local oscillator circuitry.

Thus, the first estimate for the receivers, local oscillators, calibration, beam-forming, is:

- **Power consumption for the 32 element C and X-band receiver system is 109 W**

It should be noted again that the resources in the FPGA are so large that it may be possible to include the RFI processor. This requires further study beyond what is possible at this stage since the FPGAs are already burdened by the fact that they now must handle two independent beam forming networks (at C and at X-band).

One might argue that since the signal bandwidth is 475 MHz one might squeeze the signals from two elements into one ADC by proper frequency offsets like what was done for the basic C-band system. This would save 40 W so it is surely significant. However, it requires study beyond what is possible now to find out if the FPGA resources are adequate for this and if a proper frequency plan and filtering process can be established.

VI. Calibration and RFI Issues

Proposing to substitute a well-proved design and system by new, quite different designs, we have to briefly consider if important issues like system calibration and RFI can be handled properly.

Concerning system calibration, the scanning system as discussed here is not different from existing systems: the rotating antenna feed (being it traditional horns or an FPA) passes under the external hot target and the sky calibration mirror as described in for example [3]. But there is a difference anyway: we assume that we know the antenna pattern and that it stays unchanged in space. This is quite true for a classical feed horn. Can we be sure about this for the FPA? In Section IV it is described how internal calibration signals track phase and amplitude to ensure correct summing of antenna element signals. Fundamental problems are thus not expected, but this has to be studied in detail.

Concerning RFI detection and mitigation there is no reason to expect any new problems when going from a traditional horn to an FPA feed. The antenna beam will pick up power from RFI sources in its field of view, and this unwanted power must be detected and possibly mitigated as in traditional systems. It does not matter whether the antenna beam is created using a traditional horn or by an FPA. Actually, the FPA based system might have a slight advantage compared with at horn based system: strong RFI might enter through side-lobes creating special mitigation problems. In general, one of the advantages of the FPA system is very good beam fidelity with very low side-lobes [1] thus minimizing this problem.

VII. Summary

The focal plane array antenna feed system may offer an interesting alternative to the classical feed horn. One array can generate several antenna beams thus substituting several horns. This is interesting at the higher microwave frequencies where a large number of beams may be needed (see the references), but it is also of interest at the lower microwave frequencies like C-band, where large and bulky horns may be replaced by a relatively small focal plane array system.

There is also a possibility for combining the C and X-band systems making use a single FPA antenna.

The price to pay is: no flight heritage and increased power consumption. The present paper has discussed a C-band system in which 4 classical horns are replaced by a focal plane array having 32 antenna elements and 64 receivers (dual polarization operation). Also, a combined C and X-band system in which 4 + 4 classical horns are replaced by one focal plane array having 32 antenna elements and 64 dual frequency receivers. The power consumption is estimated to 66 W (109 W for the dual frequency system), which is more than a classical radiometer solution requires, but very far from critical in modern satellite systems.

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