ULTRA-HIGH PERFORMANCE C & L-BAND RADIOMETER SYSTEM FOR FUTURE SPACEBORNE OCEAN MISSIONS

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***Abstract*— A next generation spaceborne radiometer system for hi-quality ocean measurements is discussed. Instead of a classical horn, a focal plane array is used as antenna feed. The antenna beam is created by adding the outputs from many small antenna elements, thus providing an antenna beam of un-surpassed quality. This solves the classical polarization purity and land / sea contamination issues. The concept requires many microwave receivers and fast analog-to-digital converters as well as fast digital signal processing on-board the satellite. This is discussed, and resource budgets, especially concerning power, are provided.**

Keywords—microwave; radiometer; focal plane array; receiver

I. INTRODUCTION

Future generations of space borne microwave radiometer missions, measuring sea surface temperature and the wind vector, will require a very good radiometric sensitivity around 0.25 K for the full Stokes vector, and at the same time good spatial resolution approaching 20 km at C and X bands and 10 km at Ku band [1] and [2].

For a typical 800 km orbit and 53 deg incidence angle, the footprint requirement calls for antennas with 5 m electrical aperture.

These performance requirements represent a significant improvement compared with existing spaceborne radiometer systems, such as AMSR-E and WindSat. They feature spatial resolutions around 55 km, 35 km, and 20 km at C, X, and Ku bands respectively, and the radiometric 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.

An important requirement concerns the cross-polarization of the antenna. The radiometer shall measure brightness temperatures in two linear polarizations, vertical and horizontal, and with an accuracy of 0.25K. This requires that the cross-polar power received from the Earth does not exceed 0.34% of the total power coming from the Earth for that polarization state. This represents a severe antenna requirement, and it is difficult to design a reflector antenna with a traditional feed horn that fulfils this challenge. A focal plane array (FPA) used as feed can do the job.

Another very challenging requirement is that the instrument must be able to measure ocean parameters correctly 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 99.7% 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 5-15 km requirement represents a major improvement as current systems feature about 100 km distance to coast capability (the so-called land / sea contamination issue). Again, a severe antenna requirement, and it is practically impossible to achieve such a performance with a reflector and a traditional feed horn. A FPA as feed can do the job.

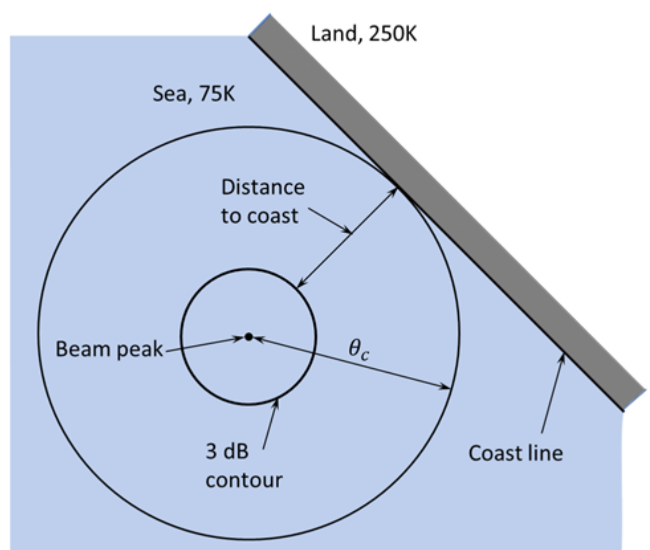

Fig. 1. Schematic of the distance to coast issue

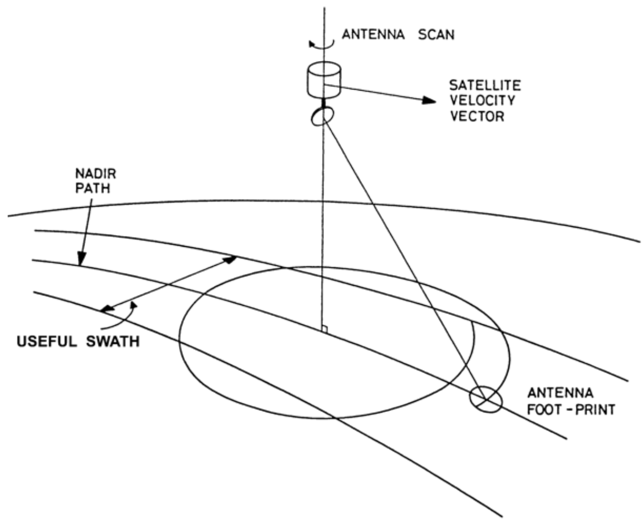

Fig. 2. Scanner

For all three frequency bands, the bandwidths are limited to a few hundreds of MHz, and hence even the most optimistic receiver noise properties cannot ensure the required radiometric sensitivity when considering a single-beam scanning system. For a scanner, as shown in Fig. 2, the only solution is to employ several independent antenna beams per frequency, and improve sensitivity by integration of several footprints. This calls for a host of feeds/beams and associated receivers – could be up to 30 beams at Ku band. The scanner will cover a swath of ≈1500 km.

II. From Traditional Feed Horn to FPA

Many beams make it impractical to consider traditional feed horns due to congestion in the feed area. The cross polarization purity requirement, and the distance-to-coast requirement translate into the need for a very fine antenna beam with low side-lobes and high beam efficiency – not practically possible to achieve with a traditional feed horn. Instead, a dense array of a large number of smaller antenna elements can be used, and by summing the outputs from clusters of those, adjusted properly in phase and amplitude, the individual beams having very good performance can be generated. Fig. 3 illustrates the concept: to the left is shown a traditional set-up where one antenna horn is connected to a radiometer receiver. When several beams are needed, individual horns may be connected to as many receivers, as shown top right, but this may lead to congestion in the horn area. Bottom right shows the system in which x beams are created by many small elements (*) and connected to x receivers. Also, it shows how the signal from one element contributes to more than one beam.

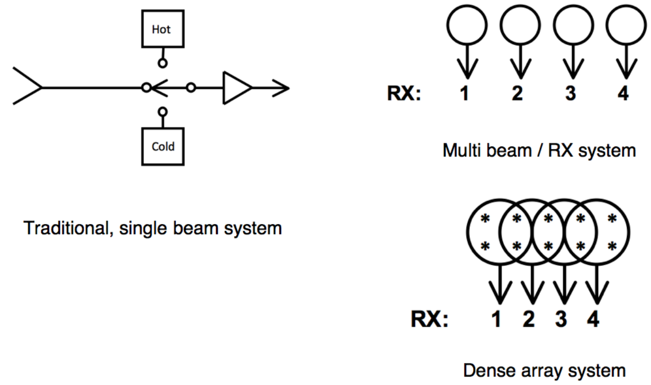

Fig. 3. From traditional horn to dense array system

Generally, many elements are needed – could be 30 H polarized and 30 V polarized elements – to build one beam. As already stated the outputs of the elements are summed, properly adjusted in amplitude and phase, to make a beam. The V pol. beam primarily consists of contributions from the V pol. elements, but small contributions from the H pol elements are added to obtain a final beam with very low cross polarization. Also, this method of creating the beam by contributions from many small elements enables an almost perfect beam with very low sidelobes. This enables correct ocean measurements very close to coast lines (and sea ice). Finally it is noticeable that it is possible to make more than 1 beam using the same elements. Two beams are thus readily possible. Many beams require more elements, but the number of elements does not increase proportionally with the number of beams. More about these issues can be found in [4] and [5].

III. A New C & L band System with FPA Feed

The issues discussed above, as well as the consequences for receiver design and resource demands, will be evaluated by means of an example based on the TWIST instrument originally proposed as a candidate for the Earth Explorer 9. The baseline requirements for the instrument are measurements of brightness temperatures at frequencies near 7 GHz (6.9 GHz and 7.3 GHz) with a radiometric resolution around 0.2 K and with a spatial resolution on ground around 20 km. In addition, measurements using the same antenna aperture at 1.4 GHz with a radiometric resolution around 0.15 K are required. A summary of the specifications for TWIST is shown in Table 1.

TABLE I. TWIST specifications

Altitude	Inc. angle	Antenna	Rotation Rate	Swath
817 km	53°	5 m	12 RPM	1524 km

Frequency	Polarization	ΔT	No of beams	Acc.	FP	Distance to coast/ice
6.9 GHz	H & V	0.18 K	2	0.25 K	20 km	15-20 km
	Stokes 3 & 4	0.25 K				
7.3 GHz	H & V	0.2 K	2	0.25 K	19 km	15-20 km
	Stokes 3 & 4	0.28 K				
1.4 GHz	H & V	0.10 K	2	0.25 K	99 km	50-100 km
	Stokes 3 & 4	0.14K				

A. Radiometric Resolution

A conically scanning system is evaluated concerning antenna size, spatial resolution, radiometric resolution, coverage, and antenna rotation rate.

For this, the method as described in [3] is used. A circular antenna electrical aperture and classical, circular feed horns are assumed. During the Advanced Radiometer Study [2] careful modeling confirmed that spatial resolution found this way is very realistic also when focal plane arrays in the end are used. The altitude is assumed to be 817 km. The incidence angle on ground is 53°. The scanning antenna is rotating around a vertical axis, and the boresight direction, where the footprint centers will be located, traces out a circle on the ground. The maximum useful swath can be reasonably defined by using ± 60° of the potentially ± 90° scan angle. Beyond 60° the increase in effective swath is limited. Only forward looking is assumed. This does not preclude utilizing both fore-and-aft looking at later stages if the spacecraft layout permits this. Calibration is assumed to take place while the scanner looks away from the useful ± 60° swath. If both fore-and-aft looking is utilized, the ± 60° definition leaves enough time available - or space available for external targets.

In [3], assumptions about receiver bandwidth and noise figures are made in order to carry out a general discussion. Here, actual bandwidths and current estimates of state-of-the-art noise performance are used. The bandwidth at C-band is 200 MHz and the noise figure is 1.4 dB corresponding to TN = 110 K. The parameters at L-band are 19 MHz and 76 K.

Low loss antenna feed elements are assumed, with the very small (MMIC) receivers mounted directly on the feed element ports. State-of-the-art total power receivers are assumed for such a scanner.

The antenna is assumed to look at a calm sea surface at V polarization. Hence the brightness temperatures can be calculated using Klein & Swift, resulting in TA = 155 K at C-band, and 145 K at L-band. Thus the system noise is TSYS = TA + TN = 265 K at C-band and 221 K at L-band.

The result for a TWIST-like instrument is that a 5 m aperture leads to elongated footprints (15 by 25 km) with an average value equal to the required 20 km. A 5 m aperture leads to a 100 km footprint at L band.

The C-band channels will have a ΔT around 0.26 / 0.28 K (lower / upper band) and the antenna will rotate with 24 RPM. Neither the radiometric sensitivity nor the rotation rate for such a large reflector are acceptable. We can implement several beams along track in order to lower antenna rotation rate. Lower rotation rate leads to longer integration time, hence better sensitivity. 2 beams along track and 2 associated receiver systems will result in $\Delta T = 0.18$ / 0.20 K and 12 RPM rotation. For comparison, SMAP with its 6 m mesh antenna rotates with 15 RPM.

The L-band channel will have a footprint of 100 km, which is acceptable, and a $\Delta T = 0.14$ K. Some will say that 0.14 K is good enough, others not. As already explained, we can implement several beams along track and achieve better sensitivity. We can also implement several beams across track such that a point on ground is measured several times with short time interval. Integrating over these independent measurements results in better sensitivity. 2 simultaneous beams, along track or across track, and associated receiver systems yield $\Delta T = 0.10$ K.

It should be noted that the above discussion assumes that the instrument only have one look towards the ground: fore or aft. However, an accommodation scheme, having both fore-and-aft un-obstructed view of the ground, is sometimes possible. This results in more integration (noting that the relatively small time lag between the 2 views is unimportant), hence better radiometric resolution. This way an L-band instrument having only 1 beam can achieve 0.1 K. Beware: even though radiometric resolution is improved, we cannot avoid 2 along track beams at C-band due to antenna rotation speed issues. Henceforth we shall stick to the classical situation without both fore and aft view, but note that radiometric resolution improvements are a possibility if satellite geometry permits.

It must also be noted that more along track beams might be a favorable option even if not required due to radiometric resolution: it leads to lower antenna rotation rate which can be a very important issue for the mechanical system design.

In summary, the baseline option fulfilling requirements calls for:

- 2 beams along track @ 6.9 GHz, $\Delta T = 0.18$ K
- 2 beams along track @ 7.3 GHz, $\Delta T = 0.20$ K
- 1 beam (or 2) @ 1.4 GHz, $\Delta T = 0.14$ K (0.1 K)
- 12 RPM
- fore or aft look

B. FPA / Beams / RX Issues

The receiver system configuration and resource demands – especially concerning power consumption – is discussed and evaluated in the following, using existing state-of-the-art components. These are important issues in the present context: it is of little practical interest that excellent beam performance can be achieved if the receiving system becomes impractical and very power consuming.

The antenna is based on a feed system where a dense array of a large number of small antenna elements is used, and by summing the outputs from clusters of those elements, adjusted properly in phase and amplitude, the individual beams are generated. Fig. 4 (left) illustrates in a classical way the concept, where signals from different elements (*) are added and fed into a receiver to create one beam. Each element contributes to more than one beam.

However, it is impossible to apply power splitters and combining network directly after the elements from a noise point-of-view, so each element must be connected to its own receiver, followed by A/D conversion, see Fig. 4 (right). The beam forming then takes place in an FPGA, using complex digital multipliers and adders.

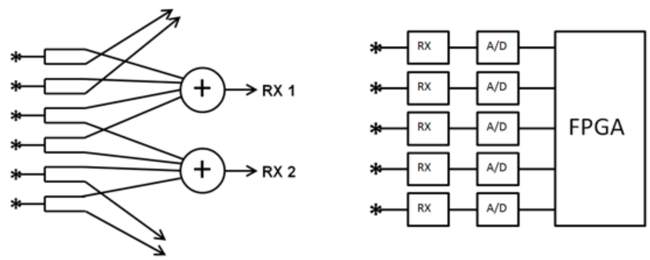

Fig. 4. Dense array receiver system

As already noted, each antenna element is assigned its own receiver and A to D converter. Hence, the total number of components in a single receiver must be multiplied with the number of antenna elements, and a major concern is the total number of components in the system, with respect to mass, size and especially to power consumption.

For the present design example a 4 x 8 + 5 x 7 = 67 element Vivaldi antenna array was chosen for C-band in order to investigate modeling of a broad-bandwidth antenna element [6], see Fig. 5. For L-bands an existing dual-polarized space-proven patch / cup antenna element was chosen. Fig. 5 also shows how the L-band elements can be fitted around the Vivaldi array.

Once the array layout is fixed, the resulting beam can be modeled using an optimization process in order to obtain the best result. In the present case the C-band performance fulfils all requirements. Fig. 6 illustrates the performance of one beam (in color code) including a lineout of the -3 dB footprint. A second along-track beam is also shown using a lineout of its -3 dB footprint. A suitable overlap in order to ensure proper sampling of the brightness temperature scenario has been assumed. The requirements state a max. 0.34% cross-pol. contamination. The modeling shows that we can achieve 0.15% corresponding to a 0.1 K error. The modeling also shows that we can achieve 99.7% of the power within a cone angle of 0.8° such that the 15 km distance to coast requirement is fulfilled [7].

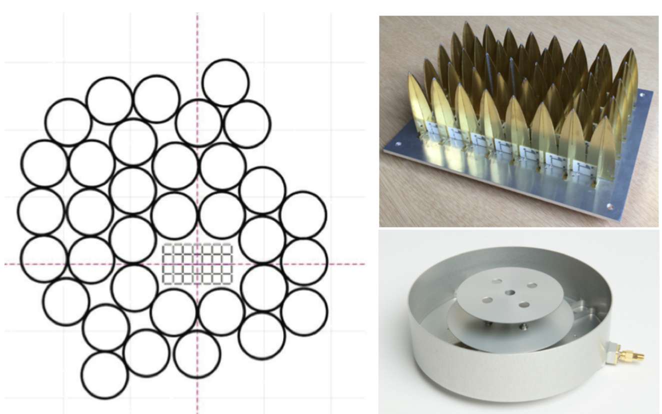

Fig. 5. Focal plane array layout and elements

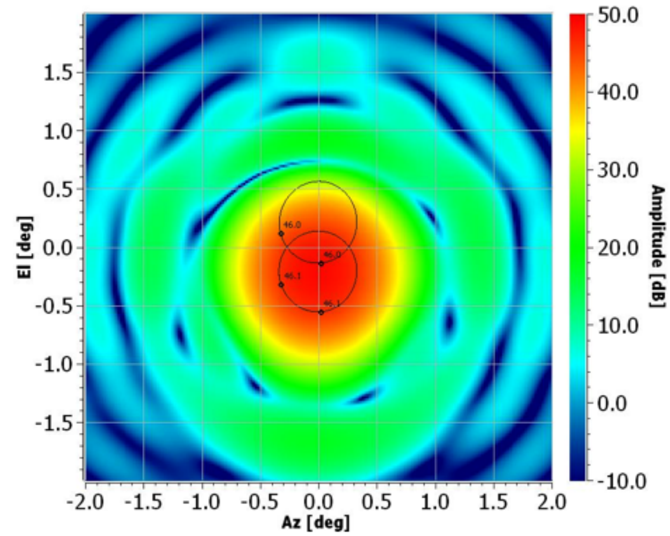

Fig. 6. C-band FPA makes 2 beams with suitable overlap

C. Receiver Design and Power Consumption

Receivers can be designed using the direct or the super-heterodyne method. The direct layout can in principle serve L and C-band using advanced but present day A to D converter technology. But fast converters require much power. The super-heterodyne layout means more analog components, especially including mixer and local oscillator, but a suitable IF frequency relaxes A to D converter demands.

Fig. 7 illustrates a straight forward implementation of a receiver system able to handle the C-band frequencies. The C-band receiver is actually a two-band receiver (C1/C2).

The input switch can select a noise signal (ND), common to all receivers. This signal is primarily to validate coherence between channels, but can also be used for calibration. Hot or cold calibration points (a matched load and an ACL – active cold load) can also be selected by the switch. The switch must be low loss. A low noise amplifier without too much gain (enough to allow subsequent split of the signals, but limited in order not to saturate due to RFI signals in the broad input band) supplies the 2 channels where filters and mixers generate the IF signals suitable for A to D conversion.

The following component types have been addressed: Switch, low-noise amplifier, mixer, local oscillator (LO), IF amplifier, and especially A to D converter. No specific search has been made for space qualified components, or fancy new laboratory developments – just small, low noise commercial components.

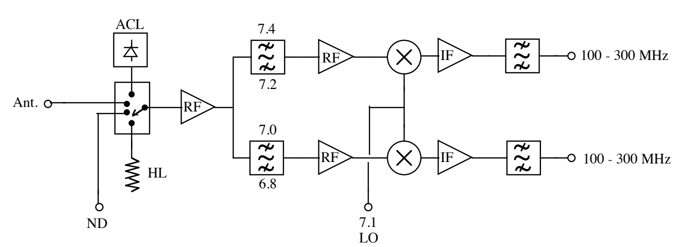

Fig. 7. Dual frequency C-band receiver

The A to D converter is a critical component, as it is the most power consuming. The Hittite HMCAD1520 is a good solution. The converter features two parallel channels, each with 12 bits, and a power consumption of 490 mW per device. For medium bandwidth (up to 320 Msamples/sec, useful for the L-band receivers), the two parallel channels may be used for the two polarizations of one antenna element. For operation up to 640 Msamples/sec (required for the C-band receivers), only one channel is available, but still with a 12-bit resolution.

Other relevant components are listed below:

- Input switch (MA4AGSW4): L through Ka bands, 0.4 – 1.0 dB loss, very little power
- Mixer: powered by LO
- Oscillator: 300 mW
- IF amplifier: GALI-S66, 20 dB gain, 60 mW power
- C-band amplifier: CGY2120, 0.6 dB NF, 13 dB gain, 50 mW power
- L-band amplifier: CGY2151, 0.4 dB NF, 17 dB gain, 225 mW power

The gains of these amplifiers are such that the C-band receiver (in addition to the pre-amp) needs 3 RF amps in series and 2 IF amps in series in each branch, and the L-band receiver need 2 IF amps in series. Otherwise a single amplifier can do the job.

A realistic power budget for one C1/C2-band receiver can now be established, and the result is 1620 mW per receiver. Our system has 35 + 32 = 67 C1/C2-band receivers, so:

- In total for the C1/C2-band receivers: 109 W

The L-band receiver, see Fig. 8, is slightly simpler than the C1/C2-band receivers discussed so far.

A realistic power budget for one L-band receiver is 1105 mW.

A realistic number of L-band receivers is 68, so:

- In total for the L-band receivers: 75 W

Concerning the local oscillator system, we need 10 mW per mixer. We have 2 x 67 = 134 + 68 = 202 mixers i.e. 0.01 x 202 = 2 W. The signals for the mixers are generated in two oscillators each 300 mW, followed by amplification. Assuming an amplifier efficiency of 50 % this means that:

- In total for the local oscillator circuitry: 5 W

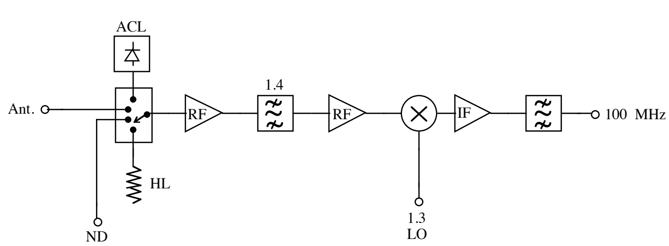

Fig. 8. L-band receiver

The noise injection calibration circuitry contributes by an insignificant amount.

The beam forming network is based on FPGAs of the Virtex 5 class. Each C-band channel requires 4 FPGAs while the L-band channel requires 2 FPGAs, in total 10 FPGAs each consuming about 9 W. Thus we find:

- Total for beam forming circuitry: 90 W

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

- **Total power consumption for the receiver system: 279 W**

This power consumption is quite acceptable.

IV. Summary

A spaceborne imaging microwave radiometer system, having hitherto unseen performance, has been designed and evaluated. It is a candidate for the next generation ocean mission. The instrument focuses on C-band, which is important for sea surface temperature (SST), wind vector measurements, and sea ice parameters. The instrument is designed to fly behind MetOpSG, and the Microwave Imager will thus provide necessary data at higher frequencies. This means that we can utilize a large mesh antenna reflector that can be folded for launch (much like the SMAP). The baseline design uses a 5 m aperture providing a 20 km -3 dB footprint on the ocean surface.

The instrument is augmented by an L-band channel thus providing sea surface salinity (SSS) and thin sea ice measurements at 100 km -3 dB footprint.

Land/sea contamination (and sea-ice/sea contamination) has been a challenge ever since the start of microwave radiometry from space! The problem is the large brightness temperature contrast when passing over the coast (or ice) line in combination with realistic antenna patterns. No matter how well you design the feed horn it is just not good enough when considering this issue. The problem can be solved by using a focal plane array (FPA) as feed: many small feed elements (around 30 per polarization) illuminate the reflector, and by properly adding the output of each element in amplitude and phase an almost perfect antenna beam can be generated. The challenge is that where a traditional system would have 1 radiometer receiver per polarization, the FPA based system will for each polarization have 30 receivers, 30 fast A/D converters (the full RF bandwidth must be digitized), as well as significant and fast digital processing hardware – all on-board and real-time. Technology has developed such that this is now totally realistic.

Radiometric sensitivity also becomes an issue in high-spatial resolution, wide swath imagers. By using 2 simultaneous beams at each frequency, and the latest technology, a ΔT = 0.2 K can be achieved at C-band, and 0.10 K at L-band.

The new instrument, having a 5 m antenna rotating with 12 RPM, will from an 817 km orbit measure a 1524 km swath at 53° incidence angle, thus providing frequent coverage of the Earth (especially in ice infested Arctic regions). Two C-band channels at 6.9 GHz and 7.3 GHz will measure all 4 Stokes parameters with $\Delta T = 0.2$ K (0.3 K for Stokes 3 and 4) and will provide meaningful measurements of the ocean as close to coast (and sea ice) as 15 – 20 km. This is just so much better than anything seen hitherto! Also cross-polarization issues are handled by the FPA concept, and the instrument will provide unsurpassed V & H-polarization purity.

Using off-the-shelf commercial low-power components, the power consumption for the basic receiver and processing units is calculated to 279 W.

The instrument will provide unique all-weather sea surface temperature globally, i.e. also in cloudy areas like near equator and far north/south, as well as wind vectors under severe weather conditions. The measurements have excellent quality even very close to coasts and sea ice edges.

Acknowledgment

The work has been supported by the European Space Agency through contracts with ESTEC.

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