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EQM front-end receivers at 183 and 229 GHz for the Microwave Sounder on MetOp-SG

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Abstract

RAL Space has delivered four engineering qualification model (EQM) front-end receivers (FERXs) for the Microwave Sounder (MWS) and Microwave Imager (MWI) on-board the MetOp Second Generation (MetOp-SG) satellites. This mission will provide the European and wider global communities with weather forecasting services from 2022 to 2043. The two EQM FERXs developed by RAL for the MWS operate in the 183 and 229 GHz frequency ranges, featuring average double sideband (DSB) noise figures (NFs) of 5.3 and 6.2 dB, respectively. This paper presents the design and main characterisation results of these two state-of-the-art FERXs for the MWS and compares their performance with other in-orbit microwave sounding instruments, including those on-board MetOp.

1 Introduction

The first generation of the European Polar Orbiting System operated by EUMETSAT, consisting of the MetOp series of satellites, has provided operational meteorological observations from polar orbit since 2006 and its mission will be continued and enhanced by the MetOp Second Generation (MetOp-SG) series of satellites [1]. MetOp was a single satellite programme with three series of satellites. The space segment of MetOp-SG will consist of two satellites, Sat-A and Sat-B, with three series of satellites launched periodically every 7 years from Kourou, French Guiana. Sat-A will launch 1 year before Sat-B, with the first launch expected to take place in Q4 2022. The MetOp-SG satellites will fly in the same orbit as the current MetOp, at an altitude of 817 km, and will provide a continuity of meteorological observations from polar orbit from 2022 until the end of life of the mission in 2043.

The Millimetre-wave Technology Group at RAL Space, in collaboration with its project partner Radiometer Physics GmbH (RPG), is contracted by Airbus Defence and Space to provide front-end receivers (FERXs) operating from 165 to 325 GHz for three instruments of the mission: the Microwave Sounder (MWS), the Microwave Imager (MWI) and the Ice Cloud Imager (ICI) [2, 3]. In addition, RAL Space is supporting RPG on the supply of FERXs at 448 and 664 GHz for the ICI.

A major milestone in the MetOp-SG FERX development programme has recently been accomplished by RAL Space. Four Engineering Qualification Model (EQM) FERXs have been delivered to MWS and MWI customers: two FERXs for the MWS operating at 183 and 229 GHz and two FERXs for the MWI operating at 166 and 183 GHz. RAL is also responsible for developing a 166 GHz FERX for the MWS, for which it has not been necessary to build an EQM.

This paper presents the design and main radiometric characterisation results of the 183 and 229 GHz EQM FERXs for the MWS instrument.

The MWS on MetOp-SG is a cross-track scanning total power microwave radiometer. It is equipped with a single rotating antenna followed by a quasi-optical network and six FERXs operating in the 23.8 - 230 GHz range. The main observational goal of the MWS is to measure atmospheric temperature and humidity profiles in clear and cloudy air, to support numerical weather prediction [2]. The MWS on MetOp-SG can be considered an evolution of the previous meteorological microwave sounders on board MetOp: the Advanced Microwave Sounding Unit A (AMSU-A) and the Microwave Humidity Sounder (MHS). Other meteorological sounders flown include the Advanced Microwave Sounding Unit B (AMSU-B) on the National Oceanic and Atmospheric Administration Polar Operational Environmental Satellites and the Advanced Technology Microwave Sounder (ATMS) on the Suomi National Polar-orbiting Partnership (SNPP) satellite. The MWS will allow for a finer detection of noise-equivalent changes in temperature (NEΔT) and will add new observational channels.

2 Front-end receiver design

The schematics of the 183 and 229 GHz FERXs are shown, respectively, in Fig. 1 and Fig. 2. Both FERXs are double sideband (DSB) heterodyne down-converters.

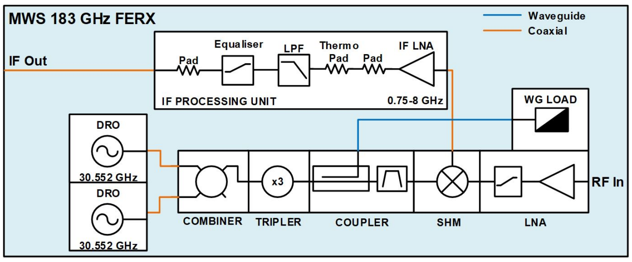

Figure 1. Functional diagram of the 183 GHz FERX.

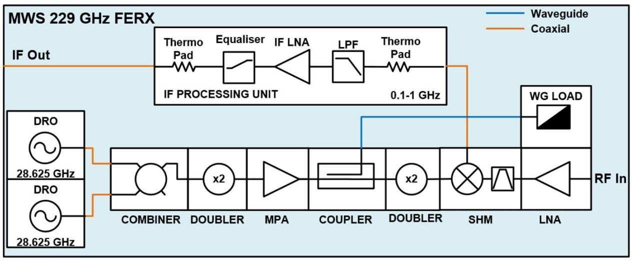

Figure 2. Functional diagram of the 229 GHz FERX.

The 183 GHz FERX is designed to measure atmospheric water vapour profiles in the 175.311 - 191.311 GHz frequency range. The 183 GHz FERX features five intermediate frequency (IF) channels within the 0.75 - 8 GHz frequency range, which allow the atmospheric water vapour profiles to be measured at different altitudes. The FERX comprises an input radio frequency (RF) low noise amplifier (LNA) followed by a double sideband (DSB) subharmonic mixer (SHM) and an IF processing unit (IPU) incorporating a drop-in IF LNA and additional circuitry for padding, filtering, passband flattening versus frequency and gain compensation versus temperature. The local oscillator (LO) chain comprises two (nominal and redundant) free-running dielectric resonator oscillators (DRO) with an integrated active doubler and power amplifier monolithic microwave integrated circuit (MMIC), operating at 30.552 GHz, a Schottky tripler and a W-band directional coupler for LO test port access.

The 229 GHz FERX is designed to measure the 228 - 230 GHz quasi-window. The 229 GHz FERX features a single 0.1 - 1 GHz IF channel. Similar to the 183 GHz FERX, the 229 GHz FERX includes a first stage of signal amplification, followed by an SHM and an IPU with a drop-in IF LNA and additional circuitry for signal conditioning. The LO chain in the 229 GHz FERX includes two free-running DROs similar to those in the 183 GHz FERX, but operating at 28.625 GHz, a passive MMIC doubler module, a medium power amplifier, a V-band directional coupler for LO test port access and a Schottky doubler.

All the RF and LO components in the 183 and 229 GHz FERXs for MWS were designed by RAL or RPG, with exception of the DROs and the IF LNAs, which were supplied by L3-Narda-Miteq. The RF LNAs use MMICs from Fraunhofer IAF [4]. The Schottky mixers and multipliers use diodes from either Teratech Components Ltd or ACST GmbH.

Fig. 3 shows a photograph of the 229 GHz EQM FERX for MWS. The 183 GHz FERX is not shown as it has the same footprint as the 229 GHz EQM FERX. The size of both FERXs is approximately 161 x 86 x 75 mm and their mass is approximately 1 kg.

Figure 3. Photograph of EQM 229 GHz FERX for MWS.

3 Front-end receiver performance

The FERXs for the MWS have to be compliant with multiple RF performance requirements. However, the focus of this paper is on presenting the radiometric performance of the 183 and 229 GHz FERXs in terms of noise figure (NF), gain flatness and sideband balance (SBB).

To enable the observational goals of the mission to be accomplished, the FERXs for the MWS must be compliant with a NF specification of 5.5 dB (183 GHz FERX) and 6.6 dB (229 GHz FERX). Additionally, the FERXs must be compliant with the specifications of the mission for gain flatness and sideband balance, i.e. the difference in amplitude between the upper and the lower sidebands of the DSB signal down-conversion. The gain flatness within each IF channel must be $\leq$0.6 dB. The SBB must be $\leq$1 dB on average within each channel.

The NF and gain characterisation results at room temperature are shown in Fig. 4 with measurement spectral bandwidths that range from 10 MHz to the maximum IF frequency of each FERX. The NF and gain measurements were performed by application of the Y-factor method with a WR-5 and a WR-4 conical aperture feed horns mounted to the input of the 183 and 229 GHz FERXs, respectively, and alternatively pointed to a cold load at 77 K and a hot load at 295 K. The in-band average NFs of the 183 GHz and 229 GHz FERXs are 5.3 dB (< 5.5 dB specification) and 6.2 dB (< 6.6 dB specification), respectively, and the in-band average end-to-end gains are 44.7 dB and 48.6 dB, respectively. The SSB measurements for the EQM receivers were performed by injecting a tone over the RF input range of the FERX with a WR-5 (183 GHz FERX) or a WR-4 (229 GHz FERX) VNA head and measuring the resulting IF output with a spectrum analyser.

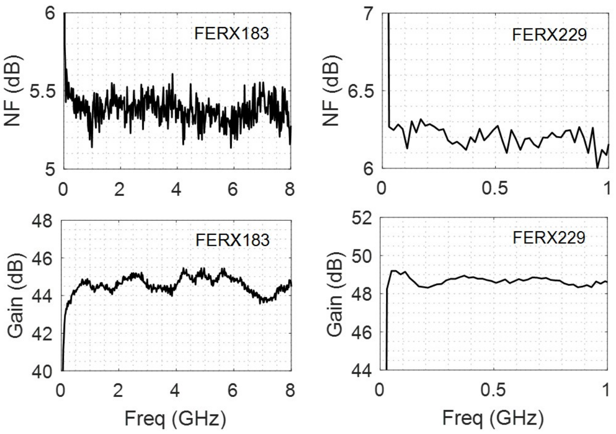

Figure 4. Measured DSB NF and end-to-end gain of the (left) 183 GHz FERX and (right) 229 GHz FERX.

In order to ensure compliance to the gain flatness and SBB specifications of the 183 GHz receiver, a dedicated optimisation of RF LNA output matching was performed in parallel with the EQM receiver qualification. The results of this optimisation, shown in Table 1, show an improvement compared to the performance presented in Fig. 4. The revised design of the RF LNA leading to improved gain flatness and SBB shall be applied to all flight receivers.

Table 1. Measured gain flatness and SBB of 183 and 229 GHz FERX for the MWS.

MWS FERX	**IF Channel (GHz)**	**SSB Average (dB)**	**Gain Flatness (dB)**
183 GHz	6-8	0.36	0.59
	3.5-5.5	0.8	0.96
	2.5-3.5	0.36	0.78
	1.3-2.3	0.31	0.64
	0.75-1.25	0.19	0.54
229 GHz	0.1-1	0.37	0.64

4 Front-end receiver qualification

The technology readiness level (TRL) of all active components developed by RAL and RPG was raised to TRL-5, as defined by the European Space Agency (ESA), prior to the delivery of the EQM FERXs. These environmental and endurance tests included the following: high humidity, high temperature (HHHT); mechanical tests incorporating vibration, shock and thermal cycling; DC and/or RF life tests. The tests were performed on RF LNA, Schottky mixer, Schottky multiplier and MPA modules. A summary of the component evaluation tests is provided in Table 2. The tests were designed to verify that the components are able to operate for more than 7.5 years in orbit after spending 20 years in storage.

Table 2. Summary of component evaluation tests to reach TRL-5.

Test	**Description**
HHHT	80-100 hours biased, 500 hours unbiased. 85°C, 70% humidity.
Mechanical	Vibration: Sinusoidal on X, Y, Z axis, 20-2000 Hz, 44.2 g_{RMS}. Shock: 20g at 100 Hz. 1000g at 1kHz. 3000g at 2kHz. 3000g at 10kHz. Thermal Cycling: 200 cycles, -50°C to +85°C.
DC Life	~1500 hours, T_{amb}=100°C, different bias conditions for each device.
RF Life	~1300 hours, T_{amb}=95°C, different bias conditions for each device.

The EQM FERXs for the MWS successfully passed the qualification tests of the MetOp-SG mission. These included vibration, shock, thermal cycling in vacuum (TVAC), electromagnetic compatibility (EMC) and electrostatic discharge (ESD), as summarised in Table 3.

5 Comparison with state-of-the-art

To evaluate the performance of the radiometers for the MWS described in this paper, Table 4 shows a comparison with other relevant in-orbit microwave sounding instruments. More specifically, the 183 GHz FERX for the MWS is compared with the 183 GHz FERXs on the Microwave Humidity Sounder (MHS), the Advanced Technology Microwave Sounder (ATMS) and the Advanced Microwave Sounding Unit (AMSU-B). Table 4 shows that the 183 GHz FERX for the MWS features a NF that outperforms the NF of these previous 183 GHz FERX atmospheric microwave sounders for weather forecasting. To the best of the authors' knowledge, the 229 GHz FERX for the MWS does not currently have any in-orbit counterparts, and features a performance that is superior to that of other non-flight FERXs from the literature in the same frequency range [8, 9].

6 Conclusions

This paper has presented the design, main performance parameters and qualification of the 183 and 229 GHz EQM FERXs developed by RAL for the MWS instrument. These FERXs feature average NFs of 5.3 dB and 6.2 dB, respectively. A comparison with other flight radiometers, such as those on MetOp, has demonstrated that the FERXs for the MWS push the existing state-of-the-art forward and will

Table 3. Summary of receiver qualification tests.

Test	Description
Vibration	Sinusoidal: X, Y, Z axis, 5-100 Hz, $\leq$24g. Random: 2-2000 Hz, $\leq$ 29.9g^2/Hz. Micro vibration: 5-500 Hz, 0.3g.
Shock	20g at 100 Hz. 2000g at 2000 Hz. 2000g at 10 kHz.
TVAC	10 cycles from -15 to 45°C. Pressure, max: 1.2e^{-5} mbar.
EMC	Conducted emissions: Inrush currents: dI/dt < 2 Aμs. Power bundles: differential and common mode, 20 Hz - 50 MHz. Radiated emissions: Wideband: 10 kHz - 18 GHz, $<$50 dBuV/m. Narrowband notches: 1.1-2.1 GHz, $<$0 dBμV/m. Conducted susceptibility: Diff. mode: $\leq$20mVrms, 30 Hz - 50 MHz. Common mode: $\leq$20mVrms, 0.01-50 MHz. Radiated susceptibility (E-plane): 0.03-27 GHz, field strengths to 18 V/m. Radiated susceptibility (H-plane): DC - 10 Hz, field strength 1 mT.
ESD	Radiated discharges: 10kV, 10mJ, $>$3 min, rep. rate 10 arcs/min at 30 cm. Conducted discharges: 6kV, 30A at 30ns, pulse rate 1 Hz with $>$15 positive and $>$15 negative pulse directions.

Table 4. Comparison of state-of-the-art 183 and 229 GHz flight FERXs for microwave sounding.

Mission	Instrum.	RF Freq. (GHz)	Noise Fig. DSB (dB)	Ref.
MetOp-SG	MWS	175-191	5.2-5.5	This work
MetOp	MHS	182-189	6.3-7.0	[5]
SNPP	ATMS	176-190	8.7-10.8[1]	[6]
NOAA-15/16/17	AMSU-B	176-190	10.1-10.9[1]	[7]
MetOp-SG	MWS	228-229	6-6.3	This work

[1] NF derived from Treceiver=Tsys-Tscene equation, where Tsys=NEΔT*SQRT(Bτ). Integration time (τ) is assumed to be 18ms and Tscene=300K.

enable a retrieval of the atmospheric water vapour profiles with improved radiometric resolution and accuracy.

7 Acknowledgements

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