AIRBORNE TO SPACEBORNE – QUALIFYING A RADIOMETER FOR SPACEFLIGHT

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A microwave radiometer is a noise measuring instrument comprised of two RF assemblies, which consists of bespoke millimetre wave equipment at the front-end of the instrument and IF assemblies, of generally off-the-shelf components, at the back-end of the instrument, before conversion of the RF input to a DC output for further processing. In terms of a UK project, like the Met Office instrument being upgraded under the European Space Agency (ESA) Cloud and Precipitation Airborne Radiometer (CPAR) project, the instrument front-ends, being above 43GHz, would be covered by UK export controls, but the IF assemblies, although much lower in frequency, are, in some areas, subject to US EAR99 and potentially ITAR restrictions.

The European Space Agency and EUMETSAT are planning to build a series of radiometers for flight on the Second Generation Operational Polar Orbiter Mission (METOP2G) with development likely to commence in 2013. For RF spaceborne applications virtually all US RF components are covered by ITAR. So for European based Space projects European sources of radiation-hardened standard components (mixers, multipliers, oscillators, amplifiers etc) are required, thus avoiding the complexities of ITAR for each new future project.

In this paper we present a survey of the available radiation-hardened microwave technologies in Europe and where technologies need to be developed for spaceborne radiometry outside of ITAR restrictions. This represents an opportunity for European based MMIC foundries to provide RF radiation-hardened components, using industry standard build-to-print designs, into the spaceborne radiometer marketplace.

THE SPACE ENVIRONMENT

Microwave components on board spacecrafts will be subject to the effects of high energy particle radiation. The observed radiation effects may in some cases result in minor component performance degradation whereas in others can cause catastrophic failure, with the potential for complete component breakdown.

The three major radiation effects on components can be identified as:

Total Ionising Dose (TID)

TID is the measure of the energy deposited in a medium by ionising radiation per unit mass where all electronic/microwave devices are susceptible to long-term radiation effects; due mostly to the effect of electrons and protons. The main sources of these electrons and protons are solar particle events usually occurring with the advent of solar flares and the effects of the South Atlantic Anomaly, where the dip in the magnetosphere (Figure 1) causes more radiation to be trapped. TID has therefore the potential to cause damage through the cumulative long term build up of defects which can ultimately result in component failure.

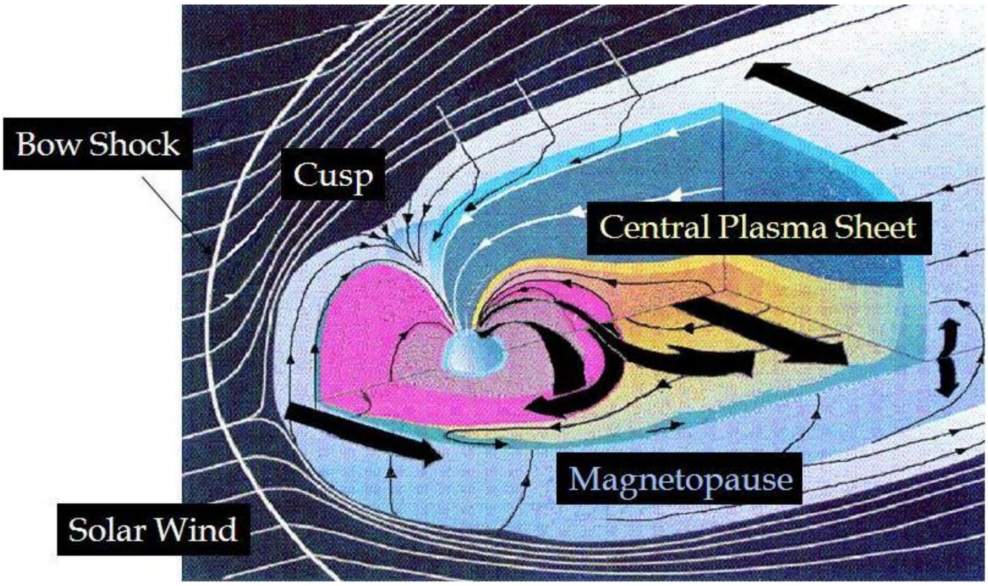

Figure 1: The Earth's Magnetosphere [from Barth J.L. & Gorsky C.D.: Variations in the Radiation Environment]

The magnetosphere is defined by the interaction of the earth's magnetic field and the solar wind, where in the solar direction the magnetosphere is compressed into ~10 earth radii and in the anti-solar direction is stretched into a long magnetotail of ~300 earth radii and open at the earth's poles.

Displacement Damage (DD)

DD is a non-ionising damage effect which is essentially imparted by protons. In this case the incident proton can create defects by colliding with an atom in the material and damaging the electrical/microwave characteristics of the component.

Single Event Effect (SEE)

SEE is the perturbation of the behaviour of electronic/ microwave devices, circuits and/or systems due to a single ionising particle. In the Space environment there are two principal reasons for the occurrence of the SEE, namely cosmic rays and high energy protons. Typically, a cosmic ray SEE is a result of direct heavy ion bombardment ionisation. The source of cosmic rays will either be galactic or solar.

Tests performed against the above criteria serve to determine the limit to which candidate microwave components may be used in Space applications.

Figure 2 illustrates the radiation environment in Space and Figure 3 shows the flux densities and particle energies prevalent in the Space environment, where long duration to exposure, unpredictable solar proton activity and the ambient galactic cosmic ray environment all have the potential to inflict damage.

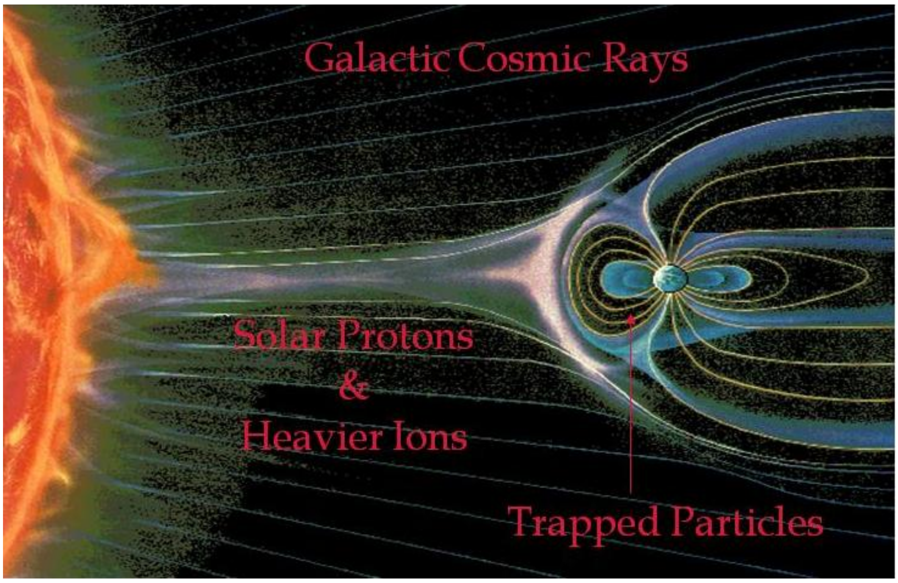

Figure 2: The Radiation Environment [from Barth J.L. & Gorsky C.D.: Variations in the Radiation Environment]

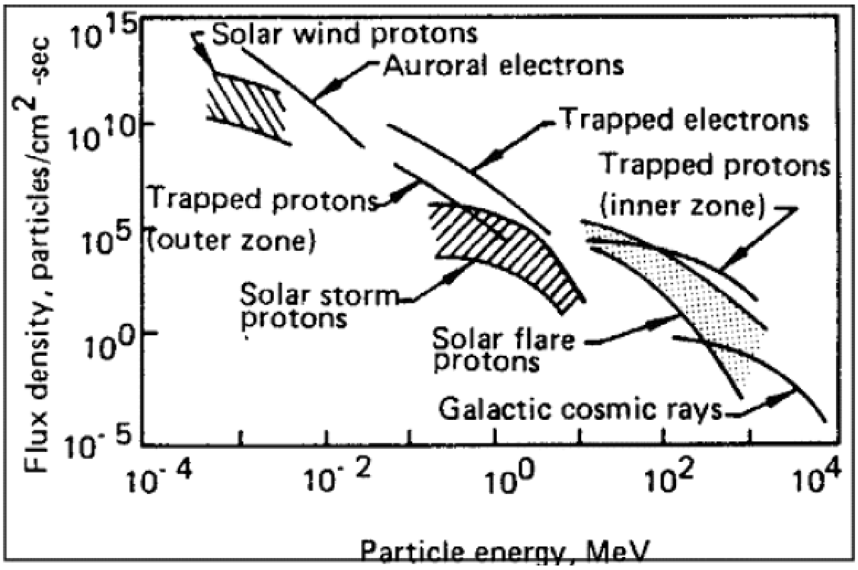

Figure 3: Subatomic Particle Density and Energy encountered by Spacecraft in the Space Environment [from Keys A.S. et al: Radiation Hardened Electronics for Space Environments (RHESE)]

Most of the galactic cosmic rays, originating from deep space, consist of subatomic particles; protons and electrons, as well as atomic nuclei.

THE RADIATION HARDENING PROCESS

Radiation hardening is the process of designing and testing an electronic component to make it as resistant as possible to the damage, or to malfunctioning, created by the effects of high energy particle radiation. Almost all radiation-hardened components are derived from their commercially developed counterparts with manufacturing and design variations implemented to mitigate against the susceptibility to damage, or malfunction, from the high energy particle radiation described above. This process requires a significant investment in such technology and therefore an extensive development programme, with testing, to produce a radiation-tolerant end product. Hence radiation-hardened components lag behind the COTS (Commercial Off The Shelf) equivalent product in timescale by a period of up to typically 10 years.

Well established companies, like Space Micro Inc in the US, currently offer a radiation hardened (against SEE) linear power amplifier, amplifying multiple signals in X-band, and Narda Microwave offer an extensive range of both passive and active radiation hardened devices in their Space portfolio.

Figure 4: An Illustration of Radiation Hardened Microwave Technology - a Linear X-Band Power Amplifier: image from Space Micro Inc.

It should be remembered that the approach to radiation hardening is often carried out on a case by case basis and that the method used for one environment or for one technology may be entirely different for another, where the details of the processes used are important in achieving the desired end result. The approach to taken to address radiation hardening involves such areas as:

- improving material hardness (including the use of new materials)
- adopting design techniques to improve radiation tolerance
- using re-configurable hardware techniques and
- using software modelling tools to predict and improve the radiation hardness and the tolerance of devices to radiation effects

The energy deposited by a heavy ion strike can cause such damage that to minimise such a threat a number of different strategies can be employed, where analysis of ion strikes can serve as a guide to designers to achieve radiation hardened components for Space use. By design, this could affect the layout of circuits, shielding and include the use of redundancy. For testing purposes the designs are exposed to particle fluxes like those encountered in

Space using suitable radioactive isotopes (Californium-252 and Cobalt-60) to simulate high-energy ion strikes and gamma rays.

As an example of the interest in the development of radiation hardened components in Europe, Alcatel Space, in 2004, reported that radiation-hard foundries were on the decline, due to reduced demand from military customers and too small a volume requirement, resulting in only one supplier being left in Europe (ATMEL, a manufacturer of semiconductors) at that time. The solution to this malaise, proffered by Alcatel, was to radiation harden commercial products (in this case CMOS technologies), and that this had inspired a lot of interest from the European Space community. It is on this basis that potential exists for the development of radiation hardened microwave components to satisfy the demand for such components for radiometers in future Space missions like METOP2G.

THE CURRENT STATUS OF EUROPEAN RADIATION-HARDENED COMPONENT TECHNOLOGY

According to the State of the Satellite Industry Report in June 2011, the global satellite market is currently in steady growth with annual revenues of almost $170 billion. Electronic equipment for satellite use is manufactured throughout the world, including Europe and Asia, but the vast majority of components, and in particular microwave components qualified for Space use, originate from manufacturers in the USA. Only relatively small developments and production occurs elsewhere and are often developed in conjunction with the support of ESA and in some cases with the French national Space centre at CNES (Centre National d'Etudes Spatiales).

An example of this collaboration would be STMicroelectronics new family of radiation-hardened power MOSFETs which are fully qualified to European Space Component Coordination specifications to cater for the growing worldwide demand for satellite-based communications: STMicroelectronics have also added operational amplifiers to their European radiation-hardened aerospace portfolio.

Figure 5: STMicroelectronics Clean Room: image courtesy of ESA

RF FRONT-END COMPONENTS

European activities involving Space-based RF components and systems for the front-end of a radiometer have been undertaken by Radiometer Physics GmbH (RPG) in collaboration with ESA. Figure 6 illustrates some of the products that form part of RPG's Space heritage and are qualified for Space use.

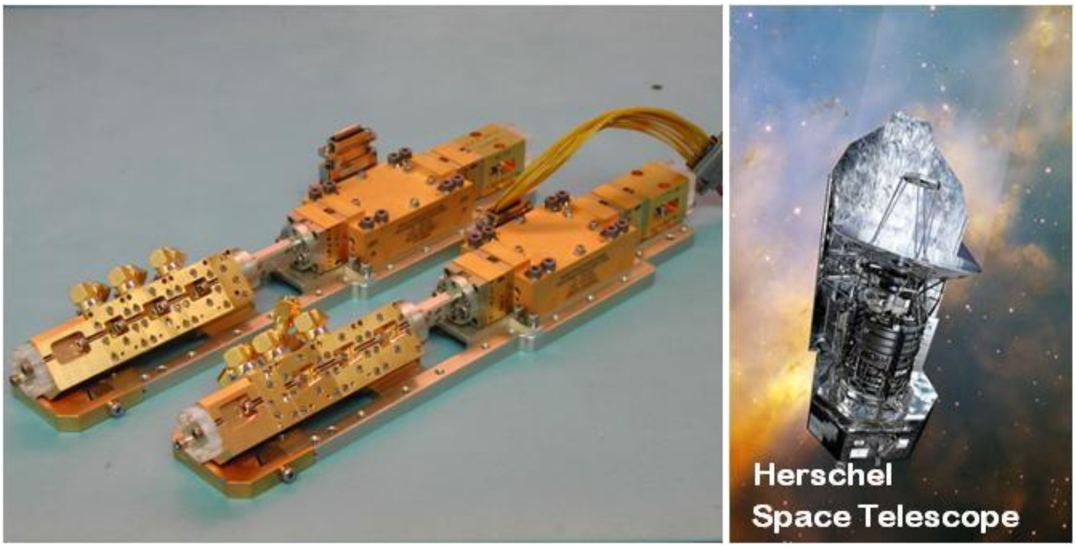

Figure 6: Local Oscillators for HIFI/Herschel (ESA) Space Telescope: image from RPG.

Figure 6 shows eight space qualified local oscillator chains from 480GHz to 1100GHz (right hand side picture of hardware) with JPL GaAs Schottky diodes. A successful operation of HIFI was conducted in radiation-hard L2 Sun orbit (at 1.5 million km) where the diode technology was compatible with the radiation-hard environment.

Figure 7 illustrates the latest European only RPG local oscillator, multiplier, mixer and complete front-end design for space applications. RPG has developed new diode designs which are fabricated in Europe by Teratec (RAL, UK) and ACST (Darmstadt) and which allows them to build fully European local oscillator, multiplier and mixer chains up to 900GHz, and above. The achieved mixer noise figures (of 1400K @ 664GHz) and local oscillator output power levels are fully competitive with US designs. A RPG diode reliability assessment for Space applications is currently in the bidding stage with ESA. Also, there are very promising ongoing activities at European MMIC development centres and MMIC foundries which would allow for the replacement of the driver amplifiers (40GHz to 90GHz, >20dBm, typically) using such European designs.

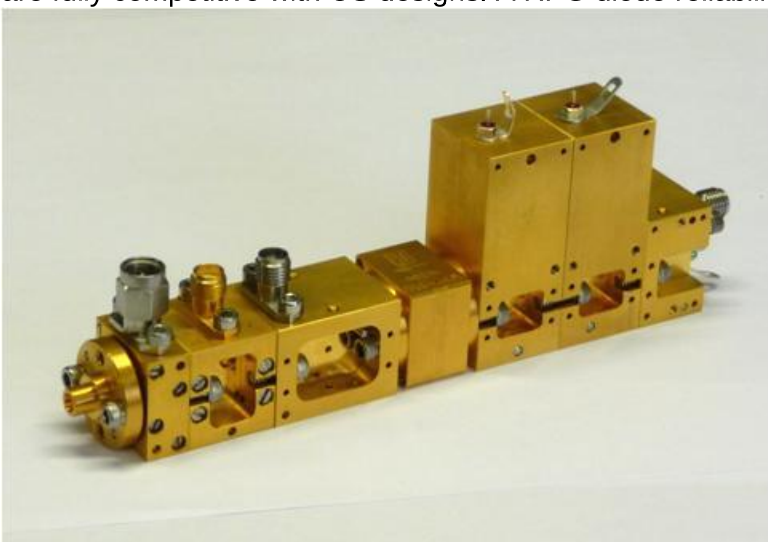

Figure 7: RPG FE (BM) for Airborne Demonstrator: image from RPG.

RPG has been, and is currently, conducting several activities with regard to applications in the Space arena, which can be summarised as follows:

- "Integrated Schottky Structures" (664GHz FE, ICI) (with ESA - now complete)
- "Sub-Millimetre Wave Receiver Front-end" (664 GHz FE, ICI) (with ESA - now complete)
- "Millimeter-Wave Integrated Diode & Amplifier sources" (100 GHz) (EU/FP7 funded)
- Metop Second Generation (for ESA/EUMETSAT):
  - "RPG Sat-B CPI coordination and interface definition support" (with OHB)
  - MWI/ICI Receiver Performance & Test Requirements definition (with TAS-I)
- "Cloud and Precipitation Airborne Radiometer" (118 & 664 GHz FE) (with ESA)
- HALO-Airplane Microwave Package (HAMP) (with MPI-Hamburg)
- "RELIABILITY ASSESSMENT OF MIXERS AND MULTIPLIERS FOR MICROWAVE IMAGING RADIOMETERS" (proposal to ESA)
- "Dual redundant low-noise amplifier for Q/V band applications" (for ESA - under negotiation)
- 875 GHz receiver for the airborne Demonstrator (EUFAR) (an EU FP7 call)

A number of these activities will, in all likelihood, lead to the development of radiation-hardened structures where RPG is well placed to fulfil the European requirement for Space qualified components.

At the component level, UMS (United Monolithic Semiconductors, a European semiconductor manufacturer) has recently announced that use of the BES MMIC Schottky diode process has been successful in obtaining approval from ESA for the production of such components for Space applications. Due to the cut off frequency being >3THz the BES process is preferred for the design of MMIC's mixers, multipliers and switches at very high frequencies, where a 380GHz sub-harmonic mixer was produced using a BES MMIC, designed and tested by LERMA (Laboratoire d'Etude du Rayonnement et de la Matière en Astrophysique) and RAL (Rutherford Appleton Laboratory). The BES process has also been used by Farran Technology to develop a 366GHz mixer.

Figure 8: ESA METOP Second Generation Satellite: image courtesy of ESA

The MIDAS project (Millimetre-wave Integrated Diodes and Amplifier Sources) has been instigated by RAL Space to promote European technology to make Europe independent of US technology in the sub-millimetre region of the electro-magnetic spectrum with a foundry service provided in the UK by Teratech Components Ltd as a recent spin-out from RAL.

RF BACK-END COMPONENTS

To increase the quantity of European-made electronic components in Europe's Space industry the Technology Research Programme and the European Component Initiative have been implemented as an open partnership between ESA, industry and national space agencies. However, for the RF back-end components of a radiometer there are very few European manufacturers or foundries providing active or passive components for the European Space market. The companies currently offering such services are Cobham Sensor Systems in the UK (who provide Space qualified services to ESA approved standards), United Monolithic Semiconductors (UMS: formed as a joint venture MMIC foundry service between EADS and Thales, with facilities in Germany and France, manufacturing to ESA approved standards) and OMMIC (a supplier of MMIC foundry services, based near Paris, providing services approved to ESA standards).

Cobham Sensor Systems

Cobham offer ICs, components and subsystems and have participated in Space programmes to develop a variety of RF components qualified for Space use, including ESA qualified silicon and GaAs semiconductors in the form of tuning varactors, PIN diodes, Schottky diodes, step recovery diodes, NIP diodes and multi-functional integrated assemblies. More importantly, their range of European Space qualified products include advanced integrated assemblies optimising size, weight, cost including IF processing assemblies.

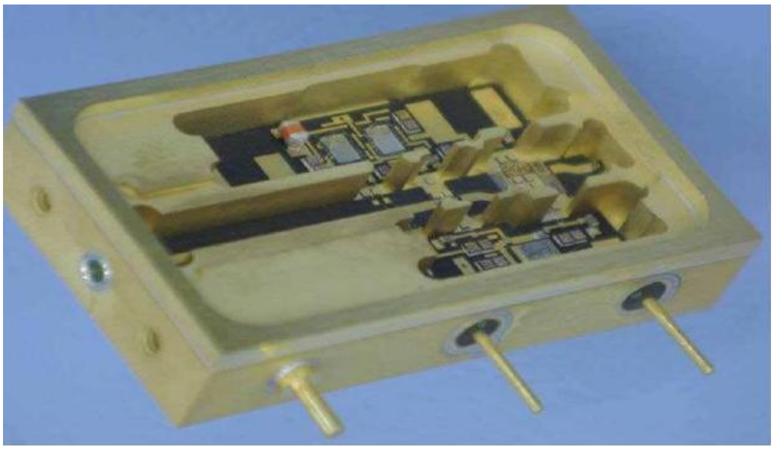

Figure 9: Integrated Microwave Assembly: image from Cobham Sensor Systems

From their portfolio of products the components that would be suitable in the IF assemblies of a radiometer include:

- Low noise amplifiers
- Power amplifiers
- Attenuators

UMS Foundry Services

The UMS foundry offers basic services and automated on-wafer testing for full circuit characterisation of RF devices from 1GHz to 100GHz covering S-parameter, noise, power and dc testing. The range of services include:

- Delivery of a design kit compliant with the customer's simulation tools
- Layout verification, with a Foundry Design Review
- Mask manufacture
- Wafer manufacture (2 wafers for a prototype run)
- Visual inspection for wafer acceptance
- RF and dc measurements

UMS has developed GaAs based processes for high performance low noise and high power MMICs suited to the Space marketplace and are in the process of introducing GaN based parts into its service portfolio.

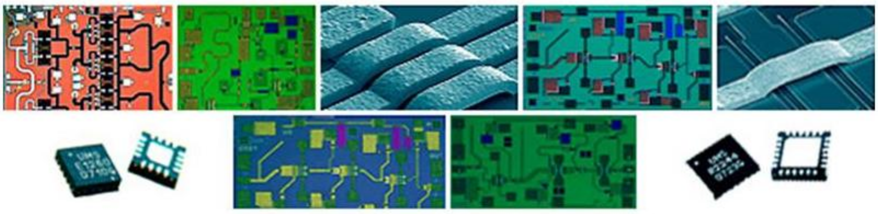

Figure 10: Example of UMS products: image from UMS

OMMIC Foundry Services

OMMIC is a supplier of MMIC circuits, a foundry service providing epitaxial wafers based GaAs, GaN and InP materials. The technologies available include E/D-Mode PHEMT, Power PHEMT, General Purpose MHEMT, Low Noise MHEMT, E-Mode MHEMT and InP DHBT. Their range of standard products include:

- Low noise amplifiers from 0.5GHz
- RF power amplifiers

In addition, OMMIC provide control components for radar, telecommunications and instrumentation applications.

DIGITAL BACK-END COMPONENTS

For the digital back-end components of a radiometer there are again only a few European manufacturers providing active or passive components for the European Space market. The companies currently offering such components are STMicroelectronics (who operate out of

Grasbrunn in Germany and provide Space qualified services to ESA approved standards) and Temex Ceramics (who provide components according to ESA specifications from their plant in Bordeaux in France).

STMicroelectronics

STMicroelectronics are the worlds fifth largest semiconductor manufacturer and offer radiation-hardened operational amplifiers for frequencies up to 1GHz and claim to be the first supplier to offer radiation hardness assurance qualified products with enhanced low dose rate sensitivity ICs. The devices offered currently are four very low power 5V operational amplifiers up to a maximum operational frequency of 1GHz and are recorded in the ESA Qualified Manufactures List (QML V qualification), thereby radiation-hardened and qualified for space-level applications. The company has established its standard hardness to ionising radiation (TID) at 300krad in Si, including low dose-rate irradiation and also claims to provide the highest hardness to the damage caused by heavy ions.

Temex Ceramics

Temex Ceramics products are mostly passive components that are used for such functions as coupling, bypassing, filtering, tuning, timing etc. The use of these components is determined by their ability to fit frequency, temperature, voltage and stability criteria for the required application. The selection criteria is based on the behaviour of their characteristics within a given frequency range. Hence, some components can be common to several applications.

A wide range of these products (trimmers, HiQ porcelain capacitors, ceramic and ferrite materials) are available according to ESA specifications. This makes them candidates for the radiation-hardened passive components required in the processing hardware in the back-end of a radiometer, after the instrument's required noise content has been detected and converted to dc voltages in each radiometer channel.

Summary and Conclusion

This paper has surveyed the available radiation-hardened microwave technologies in Europe that could be used in spaceborne radiometry and identifies the areas where such technologies need to be developed. Consideration has been given to the processes involved in radiation hardening and the current status of radiation hardening technology, together with descriptions of radiometer millimetre wave and microwave components that have been radiation hardened or have reached levels of acceptability to be appropriately listed by the European Space Agency. The paper identifies the low take up of this technology within European companies and organisations, the need for the development of radiation hardened components for the Space market and briefly identifies the challenges ahead.

The survey shows that the most economical way forward is based on radiation hardening designs developed for the commercial market. The interest in the development of such technologies in the Space community has been identified but the emphasis must now be on generating interest from companies willing to take part in this new inchoate area of development.