Millimetre Wave & Sub-mm Wave Frequency Extenders for Planck Telescope Antenna Validation

D. R. Vizard

Farran Technology Ltd , Ballincollig, Co. Cork, Ireland.

Tel: +353 21 4872814 Fax: +353 21 4873892 email: drvizard@farran.com

Abstract – **Millimetre wave and sub-mm wave frequency extenders are described which interface with a state of the art microwave antenna range facility to provide high resolution characterisation of the Planck Telescope Antenna. Novel architectures and state of the art components allows an all solid state approach with greater than 100 dB amplitude discrimination from 70-320 GHz. Such resolution is critical to the scientific objectives of the Planck cosmic background measurement mission by providing pre-launch antenna beam validation.**

I. INTRODUCTION

Planck is one of ESA's cornerstone scientific missions, and belongs to the Horizon 2000 program. Planck will map the temperature anisotropies of the Cosmic Microwave Background (CMB) over the whole sky with a sensitivity of $\Delta T/T = 2.10^{-6}$ and an angular resolution of 10 arc-minutes, in the range 30 to 900 GHz. It will complete and refine the missions of COBE (1990), and MAP (2001) to measure 12 cosmological parameters. This will be achieved thanks to a wide wavelength range telescope delivering signals to a cryogenic Payload Receiver Module. The Planck satellite will be launched in 2007 on a single ARIANE V launcher. This paper describes the design and realization of high resolution mm and sub-mm testing equipment for the antenna validation process.

II. SCIENTIFIC BACKGROUND

Cosmology, the science that aims at explaining how the Universe formed and evolves, has become a rich field of experimental research. Key discoveries made during the last eight decades show that in the past the Universe was very small, dense and hot, and that it started to cool and expand – a process that is still going on today – about 15 000 million years ago. This version of events, known as the Big Bang theory, is currently considered a firm scenario. But the picture is still far from complete. Questions such as what triggered the birth of the Universe, or how it will evolve in the future, remain unanswered.

In 1964 Penzias and Wilson, two researchers at Bell Labs detected by chance a radiation coming from everywhere in the sky, a 'glow' filling the whole Universe with the same intensity. This radiation has best be interpreted as a 'fossil' of the 'Big Bang' itself. The Cosmic Microwave Background radiation comes from every direction in the sky with almost the same brightness. However, by measuring the apparent 'temperature' of the CMB all over the sky, it was discovered that very small, in fact tiny, differences do exist from place to place. These differences can be as small as one part in a million.

In fact, all of the valuable information that the Cosmic Microwave Background can provide lies in the precise shape and intensity of these temperature variations, often called 'anisotropies'. In 1992, NASA's satellite COBE obtained the first maps of the anisotropies in the CMB. The objective of Planck is to map these features as fully and accurately as possible. **Figure 1** shows a view of the complete instrument with data taken from the above mentioned COBE mission.

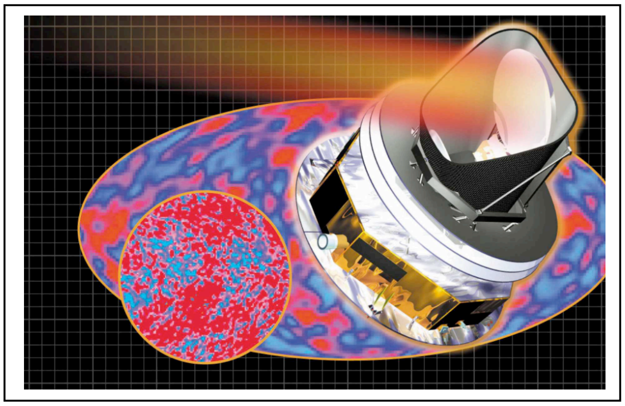


Figure 1 Planck Telescope with Recent Cosmic Background Anisotropy Measurements [Inlay]

III. PLANCK TELESCOPE

The general architecture of the spacecraft is shown in Figure 1-1. It is mainly composed of a service module (SVM) and a Receiver Payload Module as mentioned above. The receiver module consists of two elements, the Low Frequency Instrument [LFI] and the High Frequency Instrument [HFI]. The SVM provides the interfaces to the launcher. It contains the active cooling systems of the LFI and HFI and satellite control equipment. The LFI and HFI modules operate in nine frequency channels ranging from 30 GHz to 857 GHz.

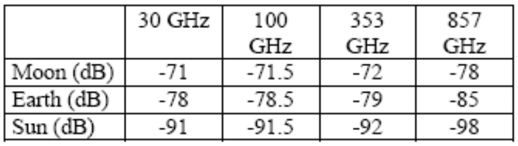
To reach the unprecedented sensitivity goals of the project, the LFI detectors comprising High Electron Mobility Transistors (HEMT) for the 30 to 100 GHz channels and the bolometers for the 100 to 857 GHz channels, are cooled to 20 K and 0.1 K respectively. The detector horns are distributed over the focal surface of an off-axis telescope operating at a temperature between 40 K and 60 K.

Figure 1-1 Planck Telescope Showing SVM, Off-axis Antenna, LFI and HFI Modules

The optics of the telescope is derived from a classical radio frequency antenna design. It is an off-axis Gregorian telescope with two reflectors, a large elliptical primary with dimensions 1.9 x 1.5 m and a smaller elliptical secondary of size 1 x 0.8 m. The wavelength spectral domain ranges from 0.350 mm (857 GHz) to 10 mm (30 GHz). The angular resolution on the sky is better than 13 arcmin for a wavelength of 3 mm (100 GHz).

IV. ANTENNA REQUIREMENTS

The aims of the Planck instruments are to obtain an image of the CMB fluctuations and subtract the primordial signal from contaminating astrophysical source of emissions. This can be achieved by excellent control of systematic errors induced by the 'straylight'. There must be excellent control and verification of the antenna to provide maximum rejection towards specific directions such as the sun, moon and the earth and the self emission of the complete spacecraft. To obtain the required level of characterization the antenna needs to be measured over a very wide dynamic range. Additionally given the large antenna diameter compared to the wavelength special facilities are needed to measure the pattern accurately, as discussed briefly below.



	30 GHz	100 GHz	353 GHz	857 GHz
Moon (dB)	-71	-71.5	-72	-78
Earth (dB)	-78	-78.5	-79	-85
Sun (dB)	-91	-91.5	-92	-98

Table 2-2 : Rejection requirements towards Sun, Moon and earth direction

V. ANTENNA TEST REQUIREMENTS

For the accurate measurement of the Planck antenna far field patterns including phase it becomes necessary to employ special techniques as the so called 'far field' is not developed until a considerable distance from the antenna. In order to accurately measure an antenna's far zone performance, the deviation of the phase of the field across its aperture must be restricted. The criterion generally used is that the phase should be constant to within π/8 radian (22.5°). Under normal operating conditions this criteria is easily achieved since there is usually a large separation between transmitting and receiving antennas. During antenna testing however, it is desirable because of various practical considerations to make antenna measurements at as short a range as possible. Generally the range parameter $R = 2D^2/\text{lambda}$ is used to define the far field distance, which is over 150 m in the case of a 1.5 metre antenna operating at 100 GHz (3 mm). See **Figure 1-2** below

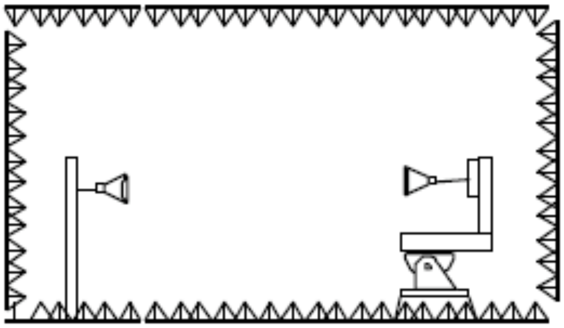


Figure 1-2 Regular Anechoic Chamber

VI. COMPACT ANTENNA TEST RANGE

A common technique to avoid the large facility that the above would entail is the use of a Compact Antenna Test Range (CATR) see **Fig 1-3.** Compact ranges are an excellent alternative to traditional far-field ranges. This method of testing allows an operator to employ an indoor anechoic test chamber at a reasonable cost and avoid problems associated with outdoor range weather and security. In a manufacturing environment, the compact range can be located near to the final testing and integration facilities. By placing a compact range in a shielded chamber, one can also eliminate interference from external sources.

The principle of operation of a compact range is based on the basic concepts of geometrical optics. Diverging spherical waves from a point source located at the focal point of a paraboloidal surface are collimated into a plane wave. This plane wave is incident on the test antenna. The resultant plane wave has a very flat phase front, however the reflector-feed combination introduces a small (but generally acceptable) amplitude taper across the test zone.

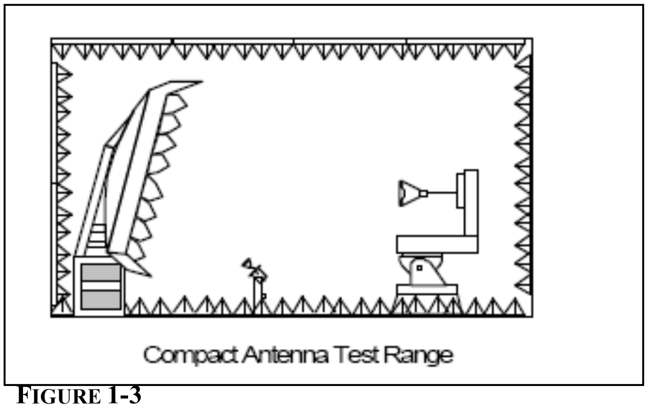


FIGURE 1-3

VII MILLIMETRE WAVE INSTRUMENTATION

To provide pre-launch antenna verification, amplitude measurements of the main beam and sidelobes with at least 100 dB of dynamic range is required at 70, 100 and 320 GHz. A high level of amplitude and phase stability is required to allow time for the complete measurement of the beam. Additionally the frequency dependence of the antenna is required to be evaluated across the > 2 GHz bandwidth of the operating channels. The transmit and receive modules must fully interface with existing ground support equipment in respect of frequency capability and control software.

These requirements have been met by adopting a fully solid state modular approach with 3 TX and 3 RX units. The 70 GHz and 100 GHz units are based on a common LO frequency conversion approach, for convenience of operation with existing equipment. The 320 GHz channel is based on a fixed frequency multiplier chain to provide the maximum possible transmit power and has a separate local oscillator for transmit and receive. **Figure 1-4** describes a generic converter arrangement.

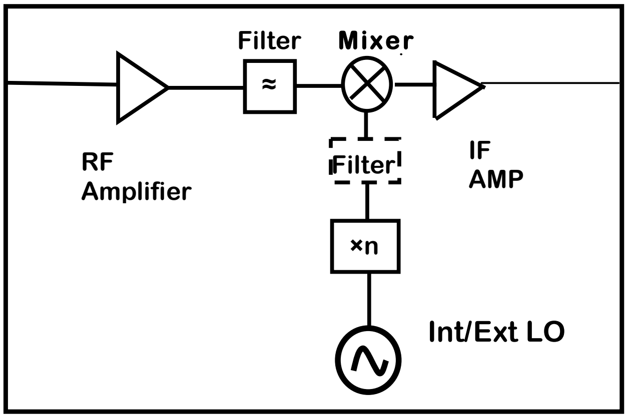


Figure 1-4 : Downconverter Architecture

VII –(A) 70 AND 100 GHZ TX MODULES

The 70 GHz and 100 GHz frequency extenders use a subharmonic mixer based upconversion technique to generate the transmitted test signal. **See Figure 1-5.** The input drive signal is set to be 3.5 +/- 1 GHz and is provided by the existing microwave equipment. A common TX and RX microwave local oscillator signal is frequency multiplied to provide the final mm-wave mixer LO. A final mm-wave power amplifier provides output power in the range 20-50 mW depending on frequency. A sample of the transmitted power is downconverted in a separate mixing process to provide amplitude compensation for variations caused by frequency or temperature. The advantages of this general approach can be summarised :

- Common LO allows use with current GSE equipment and frequency plan
- Easy coverage and control of full RF frequency band
- Subharmonic mixer approach reduces LO multiplication cost and complexity
- Solid state approach has no lifetime or high voltage safety issues
- Compact, lightweight and has low power consumption

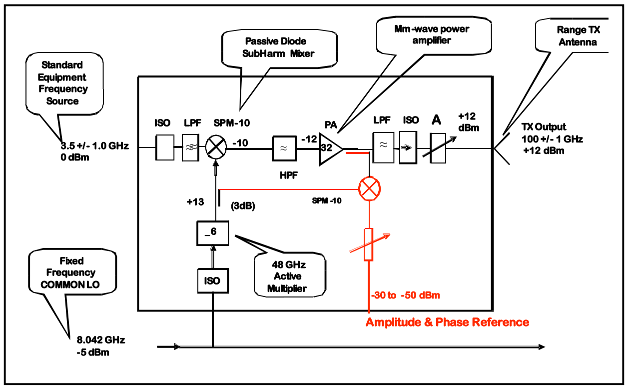


Figure 1-5 100 GHz TX Module Schematic

VII –(B) 70 AND 100 GHZ RX MODULES

The 70 GHz and 100 GHz receiver extenders use a similar subharmonic mixer based downconverter. The output IF signal is now 3.5 +/- 1 GHz and the receiver local oscillator signal provided by multiplication as before. The input noise figure is determined by a low noise MMIC HEMT mm-wave amplifier of typically < 5 dB noise figure. The same general attributes of the TX module apply to the receiver unit. The RX unit is mounted at the antenna under test and is specially packaged to meet the physical constraints imposed at the Planck instrument. 3D models are used to ensure compatibility. **Figure 1-6** shows an electrical schematic and **Fig 1-7** shows the 100 GHz module mechanical arrangement.

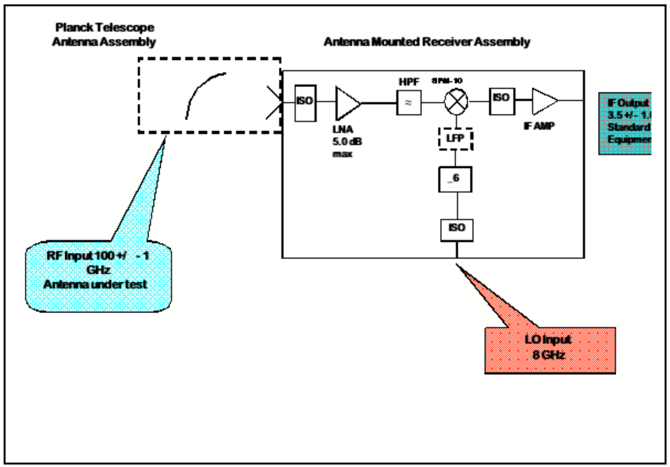


Figure 1-5 100 GHz RX Module Schematic

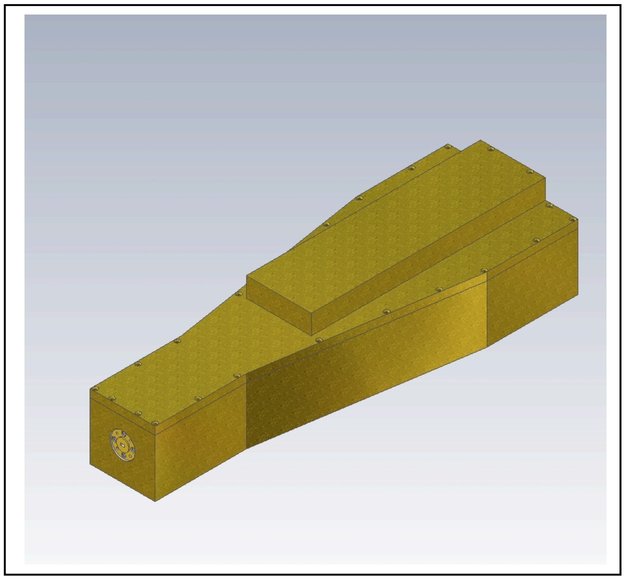


Figure 1-6 100 GHz Module Mechanical Outline

VI. SUBMILLIMETRE WAVE INSTRUMENTATION

At 320 GHz the use of an upconverter approach for the transmitter was ruled out due to the restricted output power from a mixer upconverter and the lack of power amplifiers for this frequency range. Likewise low noise amplifiers are not available and therefore a direct input mixer receiver was required. The TX module is based on an active frequency multiplier chain starting at 10 GHz with an overall multiplication factor X32, providing an output power of approx 0 dBm. The subharmonically pumped mixer based receiver uses a similar LO chain and has an overall 10 dB noise figure. In order to provide the correct frequency plan independent TX and RX local oscillators are required. The lack of amplifiers for both transmit and receive result in a lower dynamic range, and additionally the antenna is characterised at a fixed frequency only. This is an acceptable trade-off in the application, which can be offset by increasing the integration time used.

VIII DEVELOPMENT STATUS

The frequency extenders described here for the 70-320 GHz frequency range are in the process of manufacture for use in initial antenna testing trials starting May 2005. Development will be complete by Aug 2005 and the first full validation of the Planck antenna at mm and sub-mm wavelengths is expected in late 2005. Examples of previously manufactured custom modules for antenna testing are shown below, in this case for the extension of the ESA CATR facility to provide coverage over 170-260 GHz using similar techniques. **Figure 2 details the arrangement.**

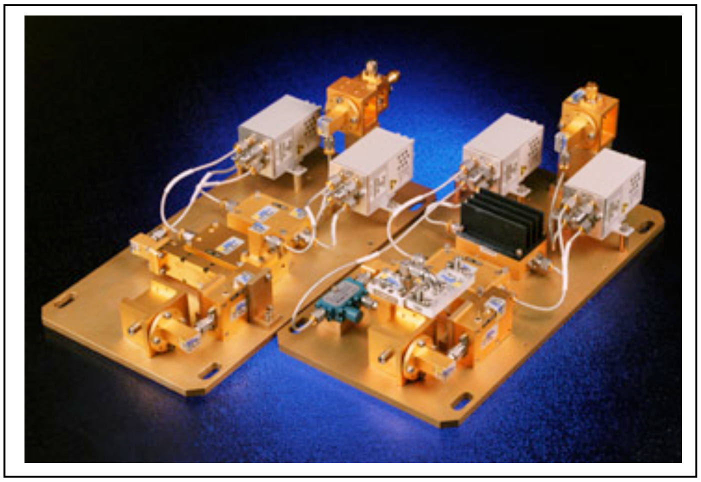


FIGURE 2 170-260 GHZ FREQUENCY EXTENDER MODULES

CONCLUSIONS

Custom designed mm-wave and sub-mm wave modules for the frequency extension of existing microwave Ground Support Equipment operating within a Compact Antenna Test Range have been described. The modules utilize state of the art mm-wave components including mixers, multipliers, low noise and power amplifiers, and provide an all solid state, compact and reliable solution to the needs of high performance antenna testing through to the sub-mm spectral region.

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