Microwave and RF measurements in astrophysics and cosmology - an overview of applications and its technology drivers

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Many astrophysical phenomena and foremost the Cosmic Microwave Background radiation have been object of increasingly detailed measurements from the ground and in space for the past 5 decades. The astronomy instrumentation community has been developing microwave and RF receivers of increased complexity to achieve greater precision and accuracy in their measurements in order to advance the knowledge of this field. In this talk I will attempt to give an overview of the astrophysical and cosmological signals to be measured and the drive in technology development which they triggered.

INTRODUCTION

While radio-astronomy has been active for a long time, the use of RF technology for a wider range of observation in astrophysics and cosmology has begun to attract the attention of the RF and microwave community as some of the detailed requirements of the hardware components have increased the R&D volume (especially from academia) with potential increase in applications and novel ideas which can be applied in other sectors. In this short review, an overview of the scientific reasons for the usage of RF and microwave frequencies in astrophysics is performed with particular attention at the requirements of the technology employed in some cases and the directions it lays out for technology improvements.

Astrophysical Sources

There are a large variety of detailed astrophysical object that can produce signals in the microwave and RF spanning many scales and varying across most cosmological distances. However, most of the emissions in question can be grouped in a few physical processes and then in two global categories. These are coherent and incoherent emission. Of the latter, few have generated as much interest as the Cosmic Microwave Background (a homogeneous and pervasive background radiation with an almost perfect Planck spectrum corresponding to a T~2.73K blackbody). This incoherent background which can be observed in all directions in the microwave sky represents the limits of the electromagnetic observable Universe in as much that as radiation coming from further distance is also coming from earlier times, these are the oldest photons which we are observing (emitted at a time when the universe was a dense plasma). The observation of this background has so far produced two Nobel prizes (one for its discovery [1] and one for the measurement of its homogeneity, and a first measurement of the level to which it was anisotropic [2]).

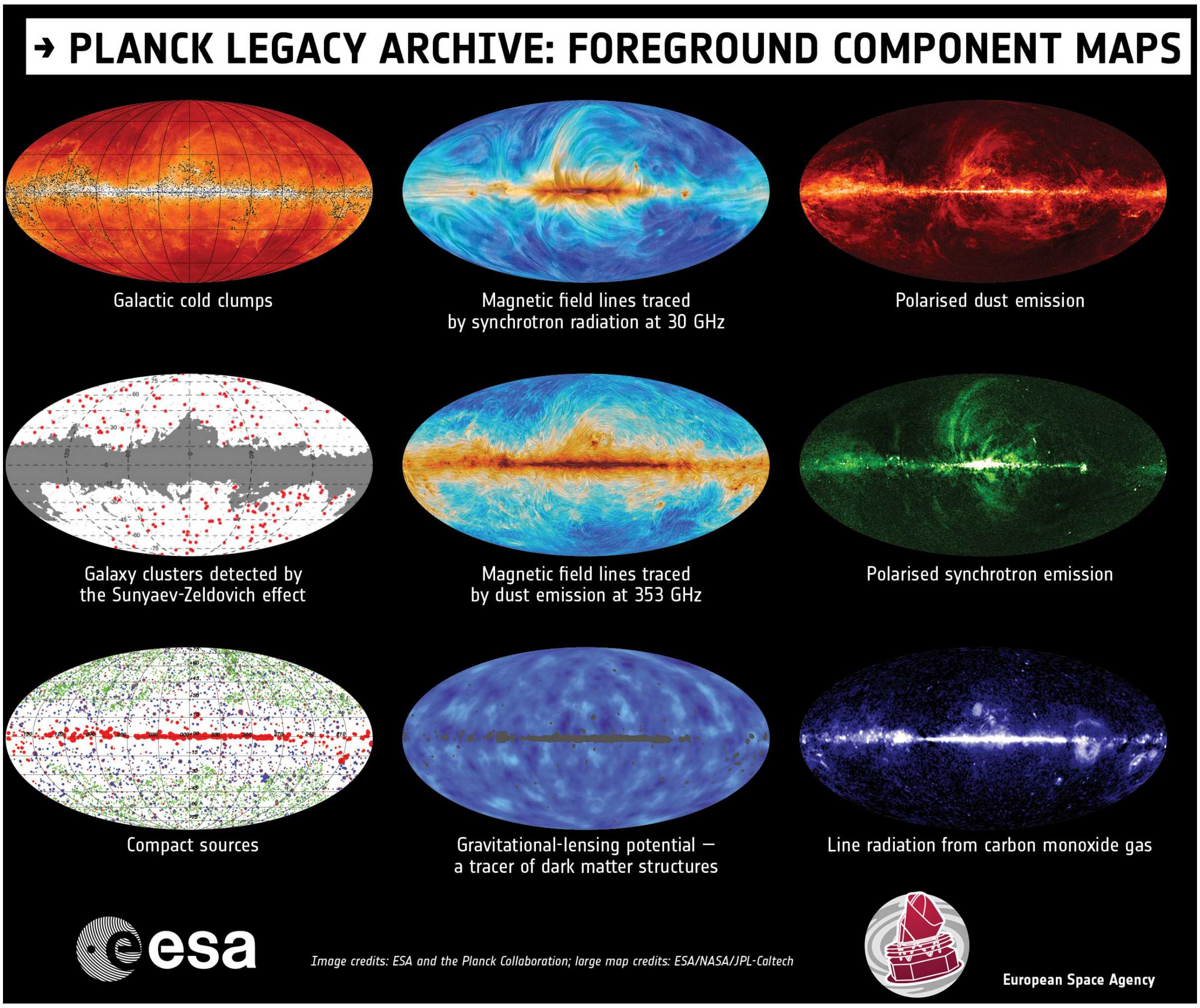

Fig 1. Schematic representation of the foregrounds present in the typical all-sky coverage observation of the CMB. (Credits: ESA)

In order to perform measurements with a precision required to extract information which is useful to cosmologists to infer the state of the Universe in its primordial stages, intensity and polarization measurements of the order of 1 part in 10^9 are required. This has posed gargantuan challenges to the instrumental community and the data-analysis teams.

Following the journey of the photons, the first of such challenges to overcome is the number of astrophysical foreground sources which lie between the CMB and the observer. These can be both incoherent (such as the thermal emission of dust particles in a given temperature equilibrium) which are not trivial to remove given a spectral index dependent on the properties and size distribution of such dust grains, as well as coherent mostly originating from synchrotron emission caused by the acceleration of charged particles in our galactic magnetic field. While the CMB spectrum has a blackbody spectral distribution with a temperature of 2.73K peaking close to 1mm in wavelength, the foregrounds which have complex spatial distribution have different spectral behaviour, with synchrotron dominating at lower frequencies and thermal dust emission by comparison with the CMB dominating at higher frequencies. This implies the first pair of requirements for a CMB mission which is the usage of as many spectral channels as possible. This translates to covering all atmospheric transparency bands from the ground and a wide enough spectral range from space which allows similar technologies to be employed.

As the overall signals are small, our first requirement has to also account for attempting to collect as many photons as possible which leads to the design of broad-band receivers (~20-30% bandwidth) which already imposes a requirement of broad-band nature of a number of components including the horn-antenna and the receiver components.

A second important factor in measurements which leads to a substantial RF requirement is the spatial structure definition and the contamination of point sources. Given that the antenna (telescope mirror) sizes have to be "modestly" contained to the order of a meter (with the exception of a few ground based facilities targeting high-resolution astrophysical phenomena, contamination from point sources is critical. Assuming that we are either on the ground (and hence measuring a limited portion of the sky) or in space (performing all-sky scans). In both cases there is a strong driver to reduce to a minimum far side-lobes and to have the best defined beam with very low near side-lobes (-30dB in both E and H cuts).

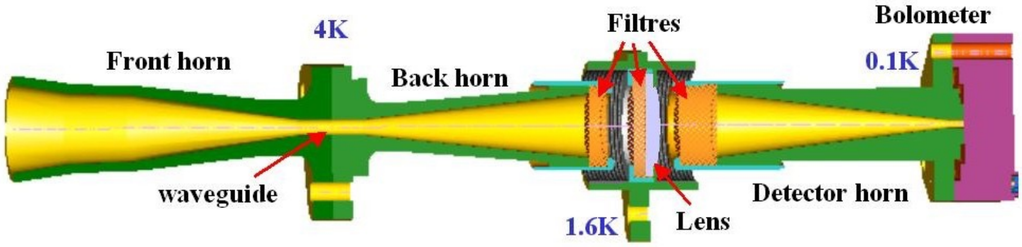

Fig 2. Planck HFI pixel architecture.(from [3])

In Planck this was addressed through a combination of single- and multi-mode horns with an architecture for the Low Frequency Instrumet (<90 GHz) which made use of cryogenic radiometers[4] and for the High Frequency instrument (>90GHz) which relied on flared profile corrugated front horns to shape the beam while maintaining a broad-band nature, and a double horn coupling section where the wavefront is coupled efficiently to the third horn leading to the detector cavity for incoherent absorption on the detector substrate. The latter was achieved on polarisation sensitive bolometers (PSBs)[5] for the single mode horns and on "spider-web" bolometers[6] for the multi-mode ones. Both of these detector types (for a total of 52 detectors in 36 optical pixels were cooled to a temperature of 0.1K in order to maximise responsivity while reducing noise.

CONCLUSION

In the post-Planck Era instrumentation has been pushing both techniques (heterodyne and bolometric) forward. Many ground based CMB experiments are now making use of large format planar arrays of detectors (in most cases with a quasi-optical stage to couple the light to the single devices, this allows detectors in the thousands to be used resulting in complex electronics architectures and massive amounts of data. On other experiments which are not photon-starved and where spectroscopy is of interest, high frequency (supra-THz) heterodyne receivers are being pursued [7].

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