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Next Generation Sub-millimetre Wave Focal Plane Array Coupling Concepts – An ESA TRP project to develop multichroic focal plane pixels for future CMB polarisation experiments.

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ABSTRACT

The main objective of this activity is to develop new focal plane coupling array concepts and technologies that optimise the coupling from reflector optics to the large number of detectors for next generation sub millimetre wave telescopes particularly targeting measurement of the polarization of the cosmic microwave background (CMB). In this 18 month TRP programme the consortium are tasked with developing, manufacturing and experimentally verifying a prototype multichroic pixel which would be suitable for the large focal plane arrays which will be demanded to reach the required sensitivity of future CMB polarization missions. One major development was to have multichroic operation to potentially reduce the required focal plane size of a CMB mission. After research in the optimum telescope design and definition of requirements based on a stringent science case review, a number of compact focal plane architecture concepts were investigated before a pixel demonstrator consisting of a planar mesh lens feeding a backend Resonant Cold Electron Bolometer RCEB for filtering and detection of the dual frequency signal was planned for manufacture and test. In this demonstrator the frequencies of the channels was chosen to be 75 and 105 GHz in the w band close to the peak CMB signal. In the next year the prototype breadboards will be developed to test the beams produced by the manufactured flat lenses fed by a variety of antenna configurations and the spectral response of the RCEBs will also be verified.

1. BACKGROUND

This paper summarises the current status of a European Space Agency Technical Research Programme (TRP) investigating alternative architectures for focal plane configurations suitable for future space missions to detect the B-mode component of the Cosmic Microwave Background (CMB) anisotropy. The requirements of such future missions will require much enhancement of sensitivity and systematic control required of previous missions such as the Planck Surveyor. In this 18 month programme we are trying to development relevant technology to replace the traditional corrugated horn antennas used on many missions. Corrugated horns have many desirable characteristics such as good beam control over symmetry, low cross polar and low sidelobe levels with good beam taper on the telescope. They also have many negative characteristics in that they are heavy and difficult to cool especially in configurations where up to 3000 horns may be required to reach the levels of sensitivity required over a very wide frequency range (e.g. circa 60 to 800 GHz). In this programme we assume a reflective telescope configuration and large focal plane as a baseline mission with many pixels (circa 3000 individual) for increased sensitivity over current generation of mission with the additional strict requirements on optical performance required including high polarisation sensitivity, low optical aberrations, and excellent beam symmetry with high levels of optical characterisation at a system level. We outline a focal plane pixel concept based on a planar mesh lens design feeding a planar antenna coupled to a RCEB detector as a prototype pixel capable of dual polarisation multi-frequency operation. This configuration is adaptable to other detector types (e.g. KIDs or TES detectors) also and although we prototype this configuration due to the

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expertise of the consortium we show the arrangement is flexible to different antenna types (planar antennas such as sinuous, slot or log periodic which have wide bandwidths inherent in their design). This work is relevant to development of technology for proposed missions such as COrE+, a current ESA M5 candidate mission. In this TRP programme we examine the driving background science, the current state of the art in each component of the Mission (telescope designs, antenna types, filter types, detector types, beam forming techniques, polarisation separation techniques etc) and then propose a solution to a planar pixel capable of dual frequency operation in the W band (75 to 110 GHz). We propose a technology with dual frequency operation but in principle the pixel should operate over more potential channels. Introducing multichroic or multi-frequency operation means that the focal plane pixel number can be reduced by combining the traditional single frequency pixel into a multichroic pixel.

In recent decades the CMB has been observed by means of a number of ground based, balloon-borne or space-borne microwave and mm-wave telescopes. Together with complementary observations (the imprint of baryonic oscillations in large surveys of galaxies; the Lyman-α absorption in distant quasar spectra; the luminosity distance of type Ia supernovae…) CMB observations with Planck and WMAP have driven spectacular advances in our modelling of the cosmological model. Future missions are planned in Europe and the US to build on this strong heritage. Measurements from missions like Planck have pinned down the parameters of the standard model very accurately and support the fundamental paradigm of inflation, in which the Universe underwent exponential expansion within its first fraction of a second.

In addition to the precisely measured anisotropies, the CMB is expected to be slightly polarised and measuring this polarized signal is the goal of many future missions. Primordial polarisation arises at the surface of last scattering, through the polarisation dependence of the Thomson cross-section. The tiny level of the anisotropies results in an expected polarisation level that is low, and hence difficult to measure perhaps a factor of 100 or more less than the temperature measurements making the sensitivity requirement of future missions very stringent. The polarisation field can be expanded into an even parity component (E-modes) and an odd parity component (B-modes). Scalar perturbations produce only primordial E-mode polarisation. Most models of inflation, however, generically predict also a background of gravitational waves (tensor perturbations), which produces both E-modes and B-modes, at a faint level that depends on the energy scale of inflation. There is hence a strong interest in measuring CMB polarisation, and in particular the B-modes, as the unambiguous detection of primordial B-modes from tensor perturbations in the early Universe would represent the final confirmation of the inflation hypothesis, constrain the possible inflation scenarios, and constrain the energy-scale of inflation. The need to observe foregrounds to fully constrain the B mode component is also very important and this places the requirement to include many frequency channels from 60 GHz through to 1 THz id possible to observe foregrounds carefully. This means many focal plane pixels over many channels which is technically challenging.

The search for B-modes is an extremely challenging task, considering the fact that whilst the temperature fluctuations in the CMB are around $\Delta T \sim 160\mu K$, the E-mode signal is detected at an amplitude of the order of $\Delta T \sim 8\ \mu K$, and the best upper limits on B-modes are of the order $\Delta T \sim 0.1\ \mu K$. The next-generation experiments will be required to reach the exquisite sensitivity required to detect B-modes at an even lower level. It is therefore an objective of this work to define a roadmap of instrumental developments that are necessary to detect, or place a cosmologically significant upper limit, on B-modes. Any experiment designed to detect the B-mode component of the CMB signal will also need good control of systematic effects. The requirements for a B-mode polarisation satellite are thus especially stringent. Ideally it requires an all-sky survey with angular resolution sufficient to remove lensing signatures and with $5\mu K$.arcmin pixel noise on the final maps. It should be noted that modern detector technologies will be limited not by inherent noise but from the photon noise arising in the CMB 2.725K blackbody emission itself in each pixel. Thus to achieve the low level detection required it is necessary to populate the focal plane with as many pixels as possible. Further, to remove foregrounds it will be necessary to observe at several bands (and preferably many bands) to enable spectral removal of synchrotron, and dusty source foregrounds, and check that the colour of the remaining polarisation fluctuations is compatible with the expected emission law of CMB polarisation anisotropies.

These scientific requirements then translate to extremely constrained instrument requirements and this is challenging. The large number of focal plane pixels dictates an inherently large focal plane area which in turn demands good optical performance for a large telescope. To minimise stray light also each focal plane pixel should inherently have the requirement to maintain beam control and polarisation purity (or knowledge) over this extended area. The polarisation needs to be measured to below ~ 170nK within each beam footprint, and to within about 1nK for the quadrupole. This background science translates to a technically challenging mission – aspects of which we analyse here.

2. PROGRAMME OVERVIEW

This TRP programme is divided into a number of work packages. The initial months of work review the field scientifically and technically before proposing a potential solution prototype pixel design to meet the stringent optical criteria and detector noise requirement and also have the potential to be multi-frequency in operation and so reduce the focal plane area required which would be typical of the current single band detectors used traditionally with horns/corrugated feed horns. This 18 month programme is divided into a 2 month review followed by 4 months to define and carry out detailed RF analysis of a prototype pixel design. A flow chart of the overall plan of the TRP programme is illustrated in figure 1 below. After the initial review two potential technologies are selected. One will be the prototype design and the second technology will be a backup design.

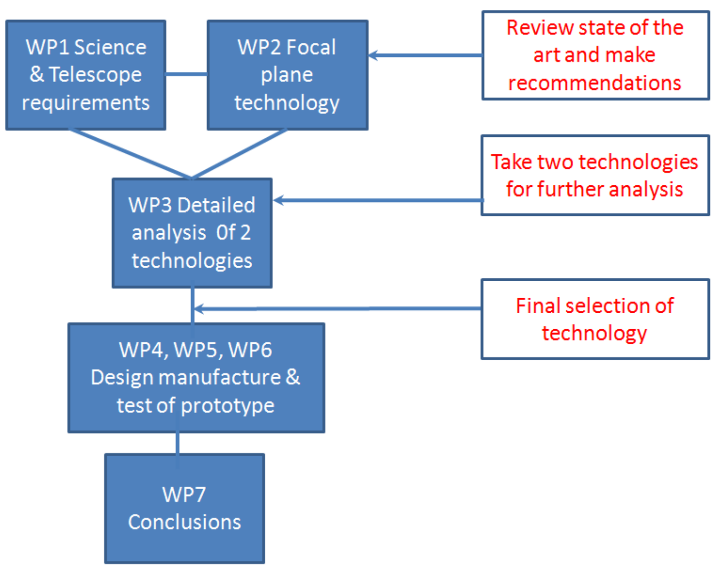

Figure 1 A flowchart of the planned structure of the TRP programme

In the first work package, (WP1) a comprehensive review of the astronomy requirements was undertaken and the technical requirement for the number of pixels for a future B mode mission was defined. The objective of this WP1.1 was to review the science and mission requirements of a future CMB satellite, derive the implication in terms of required frequency coverage, number of bands, angular resolution, overall sensitivity, number of detectors, acceptable level of instrumental systematic etc. These requirements were then fed into a second work package (WP1.2) exploring the telescope design needed based on the scientific requirements of WP1.1. After an extensive literature review of the optical performance of different telescope designs for potential CMB polarisation missions, the crossed Dragonian design and the off-axis Gregorian layout were selected as candidate telescope designs based on their optical performance over a large focal plane area. Due to the large number of channels and the large number of pixels in each channel to achieve high sensitivity the focal plane becomes very large (circa 500mm). To achieve good optical performance over this large area becomes difficult and a certain optical performance even for the marginal pixels is required. A Strehl ratio of 0.8 is required as a minimum over this area which is a real challenge for telescope designs. IN our analysis programme as well as an initial ray tracing analysis we carried out a full physical optics analysis of the telescope propagating beams from different parts of the focal plane to the sky and examining g beam characteristics to ensure stringent criteria were met.

Pixel displaced by +400mm in x direction (linear y polarisation at pixel)

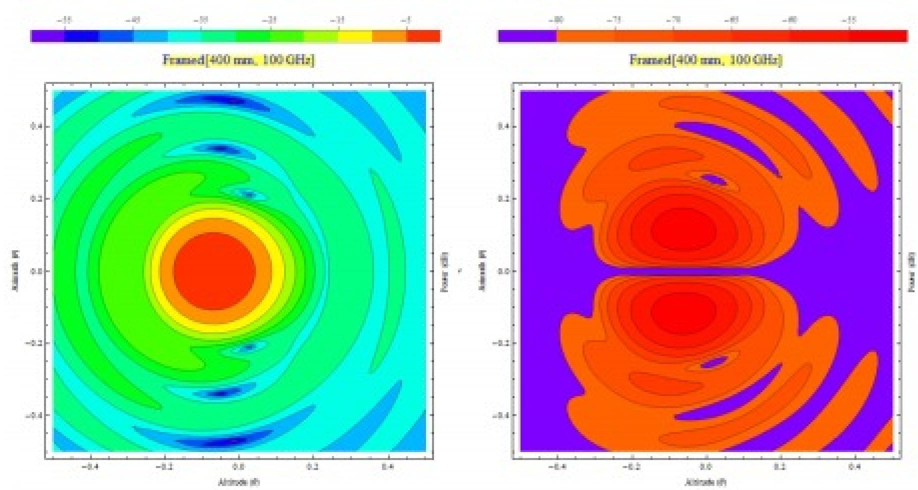

Figure 2: The co-polar and cross-polar beam contour maps for a pixel displaced by +400 mm in the focal plane in the defined x direction. The beam on the sky is plotted in elevation and azimuth over a 1°×1° area. The copular beam is still quite symmetric and the cross polar level is low at -40dB. The beam ellipticity is calculated and the degree of ellipticity fed into models to ensure that B mode detection is still achievable.

At the end of this study phase, a 1.2 m crossed Dragonian design was selected as a good telescopecandidate to include in future analysis of the focal plane pixels under investigation. The main focus of this programme was the technical description of the focal plane planar pixel capable of good optical performance and multi-frequency operation. Traditional focal planes included the use of single moded often corrugated horns which give excellent beam characteristics; in this TRP programme the aim is to develop a compact planar alternative focal plane pixel design that can also receive more than a single frequency bandwidth of the order of 20%.

In the second major task of this programme a review of all possible focal plane architectures and associated technologies (filters, polarisers, detector types etc) was undertaken and the consortium investigated possible focal plane arrangements that would reduce the size (area and mass) of a focal plane coupling array by considering novel array architectures including potential horn arrays and planar antennas. A large study was undertaken reviewing the technologies being used or proposed for future missions with all the advantages and disadvantages being discussed from each of the focal plane concepts included in the study. In this review the focal plane requirements of beam forming, polarisation separation, spectral filtering and coupling to detector types was undertaken.

3. TECHNOLGIES PROPOSED

Then based on this comprehensive review and the expertise of the consortium, two promising technologies were selected for further investigation in work package 3. In this phase of the programme these two focal plane technologies were analysed in detail and traded off for the technology that would be manufactured and tested as a prototype array in the programme. Starting from the telescope concept described in task 1, the match to the optics required each pixel in the focal plane to have a beam width (FHWM) of about 20-30° and an equivalent F number of 2. In this task we studied various pixel concepts in order to achieve this beam width value using a particular technology. After much consideration of the technologies and the constraints of the programme's budgets and timeframe two alternative focal plane concepts were chosen for further analysis in this third phase of work.

As the primary technology to take forward, it was proposed to investigate a flat planar mesh lens feeding a planar antenna developed by [Pisano et al 2013]. A flat lens based on subwavelength periodic metal meshes was developed using photolithographic techniques and was adapted in order to achieve wide bandwidth and symmetric beam properties. These mesh grids are stacked at specific distances and embedded in polypropylene in successive layers to achieve the desired beam parameters. An analysis code was developed to optimize more than 1000 transmission line circuits required to vary the device phase shift across the lens flat surface, mimicking the behaviour of a classical lens based on a polypropylene substrate. A schematic of the mesh lens is illustrated below in figure 3.

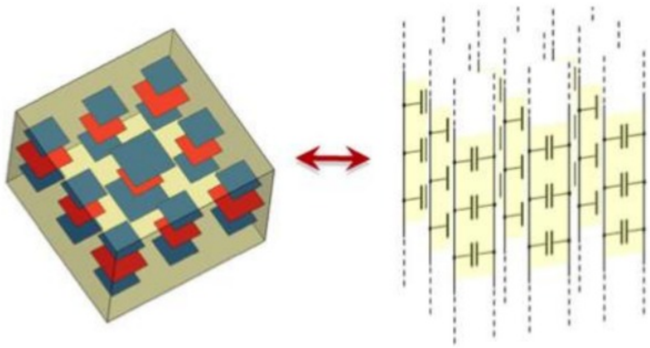

Figure 3: Inhomogeneous metal mesh devices can be modelled with a two-dimensional array of different Transmission lines [Pisano et al, 2013].

This novel technology could be adapted in many different configurations and a number of alternative setups were investigated (e.g. a large mesh lens covering many antennas with detectors or a number of small mesh lenses individual to each antenna etc). The planar antenna to be used at the focal plane of the mesh lens also required investigation and needed to operate with good performance over a wide bandwidth to achieve dual frequency operation. The log periodic sinuous antenna and an arrangement of slot antennas operating together in a configuration refereed to a 'seashell antenna' were investigated in parallel as alternative antenna designs. A final choice of antenna will be made after a number of different designs will be manufactured and tested in the current phase of the programme.

The second, backup technology was based on a phased array of planar slot antennas targeting initially dual frequency operation in W band (75 and 105 GHz) using Resonant Cold Electron Bolometers (RCEBs) as the detector for a prototype array. Based on the requirement to deliver an experimentally tested prototype array in a limited time, it was decided to take the planar mesh lens pixel concept forward for manufacture and take the phased array as the backup option in the final stages of the programme which includes array design, manufacture and test. The concept of phased array is quite attractive for multichroic systems because it can yield good beam characteristics and quasioptical coupling without any external elements such as horns or lenses. The antenna system of orthogonal slots is easily produced and gives good optical characteristics. However, the microstip line (MSL) network to feed each antenna for each polarisation is complex and has many challenges in both design and fabrication to realise especially in the timeframe of this TRP programme. The mesh lens deign is very promising allowing multi-frequency operation with a small geometric area and good optical beam properties to satisfy the strict requirements of a future CMB polarisation mission.

4. DESIGN, MANUFACTURE & TEST

In the final phases of the programme a prototype focal plane array is to be finalised, manufactured and tested experimentally to verify its operation. Proposed is a flat lens based pixel array (7 element array is illustrated below in figure 4).

We intend to demonstrate the operation of this array in W band centred on two frequencies (75 and 105 GHz). The verification will require a series of room temperature and cryogenic measurements to verify the operation of all components (mesh lens, planar antenna, spectral filtering and detection).

The consortium is proposing to have a series of different test breadboards that will allow for the retrieval of all the necessary information regarding the prototype demonstrator array concisely and all components will be tested individually and together to validate the operation. This step-by-step strategy is to develop a series of breadboards answering several questions in order to build a future overall detection chain with each component being well understood. This will also demonstrate the modularity of the design and the interchangeability of the detector or antenna.

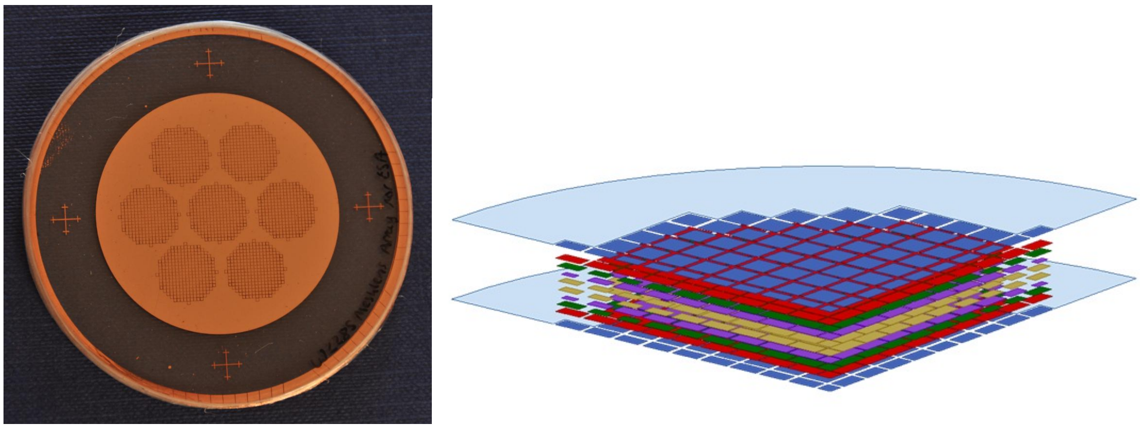

Figure 4: A plan view of the prototype mesh lens focal plane array showing the front of the seven element array The array consists of seven pixels arranged with honeycomb geometry. The mesh-lens array comprises of ten copper grids supported by polypropylene substrates (illustrated right hand side).

A number of different components are currently being tested at lower frequencies (10 GHz) and at W band frequencies to verify the manufacturability of the devices. The test plan can be summarised as

1 - Room temperature sub-system breadboards: beam forming

- Starting with 10 GHz planar antenna designs, the goal is to check the manufacture performance and compare the measurement results with the simulations, allowing for an antenna design selection.
- The selected antenna design will then be developed for W-band to be associated with the flat lens breadboard
- A W-band lens array (7 pixels) to be used in conjunction with a waveguide probe (of similar beam performance of the planar antenna) will be manufactured and tested to test the mesh lens focusing over the W band.
- The final breadboard targeting the beam forming performance will be formed by the conjunction of the lens array with a small planar antenna array.
- Beams will be measured and propagated through telescope to test telescope level performance

2 - Cryogenic sub-system breadboards: spectral selection and detection

A backend breadboard comprising of a cold detector, a spectral filter and an antenna which will operate only at cryogenic temperatures will be characterised. Various preliminary breadboards are planned to build up a full understanding of the component behaviour are planned.
The combination of these series of breadboards and their associated tests, complemented by RF, thermal and mechanical modelling will allow us to get the full picture in term of performance, not only at component level but as a complete unit.

5. CONCLUSIONS

In this paper a review of the currently ongoing TRP programme entitled "Next Generation Sub-millimetre Wave Focal Plane Array Coupling Concepts" was given and the status of the programme was summarised. The goal of the programme was to realise a focal plane pixel design that was capable of multi-frequency operation over a wide bandwidth using a planar technology that still conserved the optical characteristics of a traditional corrugated horn array. We have proposed a planar mesh lens being fed with a planar antenna coupled to a Resonant Cold Electron Bolometer (RCEB) as a potential technological solution to meet these criteria. In the current manufacture and test phases of this programme through manufacture and testing of a prototype array we hope to demonstrate this required performance through a number of dedicated experimental tests.

6. ACKNOWLEDGEMENT

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7. REFERENCES

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