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SUB-MILLIMETRE-WAVE AND FAR INFRARED ESA MISSIONS WITH A FOCUS ON ANTENNA TECHNOLOGIES

Peter de Maagt⁽¹⁾, Arturo Martín Polegre⁽²⁾, Gerry Crone⁽³⁾

*European Space Agency, ESTEC,
PO BOX 299,
Noordwijk,
The Netherlands,*

(1) Peter.de.Maagt@esa.int

(2) Arturo.Martin.Polegre@esa.int

(3) Gerald.Crone@esa.int

ABSTRACT

The area of (sub)millimetre wave and far-infrared antenna technology is a very dynamic sector in electromagnetics. Several future ESA missions have been planned and their requirements are pushing the limits of existing technologies.

Feasibility studies have provided baseline concepts, which have helped to grasp the main features of these instruments and to identify their critical aspects. A number of scientific and technical activities have then followed, dedicated to specific topics. The paper discusses (sub)millimetre wave and far-infrared Earth observation and astronomical instruments.

Furthermore, generic technology work carried out in the frame of ESA contracts, applicable to this frequency range, is reported on.

1- INTRODUCTION

Several Earth observation instruments (MASTER, SOPRANO, PIRAMHYD) and astronomical missions (FIRST, PLANCK) that use (sub)millimetre and far-infrared wavebands are being planned and developed by ESA. These instruments have many commonalities in their design and construction techniques.

One of the issues that the above missions have in common is that they require state-of-the-art technology to achieve their ambitious goals; the highest resolution, the highest sensitivity, the highest frequency of operation. Although technology is advancing at a rapid pace in this frequency range, the requirements for these instruments go well beyond those of related (sub)millimetre-wave and far-infrared instruments developed outside ESA. This has resulted in the need for new antenna configurations and in the refinement of existing configurations and technologies for top performance.

Antenna performance is a critical aspect in (sub)millimetre wave and far-infrared limb sounding, since it determines the resolution and accuracy with which the concentration profiles of atmospheric species can be retrieved. Antenna performance is also a critical aspect of (sub)millimetre-wave and far-infrared astronomical missions. For pointed observatories, which seek to map point-like or not very extended objects, the emphasis is placed on beam efficiency and the control of main beam shapes. For survey missions, the level of far side lobes also becomes very important and, in some cases (such as PLANCK), this exerts a critical influence on the success of the mission.

This paper describes the reflector antenna configurations of PLANCK/FIRST and MASTER, and their feed-assemblies. The ADMIRALS project, whose main objectives are the definition,

development, manufacturing and testing of a two-metre-class submillimetre wave antenna, will also be presented.

The generic technological work done, in the frame of ESA contracts, in the field of integrated lens antennas (KASIMIR, SISIRT, IAD), micromachined front-ends (MRFE) and photonic bandgap antennas is also be reported on.

2-MOTIVATION FOR (SUB)MILLIMETRE AND FAR-INFRARED WAVE TECHNOLOGY

There are several very important processes taking place in the atmosphere that deserve our attention, like the greenhouse effect and ozone layer depletion. There is an ever-growing awareness on the possible detrimental effects of man's activities on climate. Sub-millimetre wave frequencies can be used to obtain data for studies on ozone depletion mechanisms, while millimetre wave frequencies can focus on exchanges between troposphere and stratosphere, bringing complementary information that is useful for studies on global changes. Far-infrared frequencies can be used to get information about hydrogen, a key component in many chemical reactions.

One of the most challenging problems in cosmology is the identification of primordial density perturbations that grew to form the structures that we see in the universe today. Such perturbations left imprints as small temperature anisotropies in the cosmic microwave background. The combination of millimetre and sub-millimetre wave frequencies allows contamination from galactic emission and extragalactic sources to be removed from the cosmological temperature anisotropies. This will enable to strongly constrain basic astronomical parameters. Also space based astronomy observations at submillimetre and far-infrared wavelengths will open up a virtually unexplored part of the spectrum which cannot be observed well from the ground. This could answer some of the big questions of how galaxies formed in the early universe, and how stars form, and have been forming, throughout the history of the universe. It will also find many new sources, considerably increasing our knowledge.

3- (SUB)MILLIMETRE WAVE AND FAR-INFRARED LIMBSOUNDING

In order to make best use of the capabilities of limbsounding for atmospheric studies, the scientific

Fig. 1 Dual shaped MASTER antenna with Quasi-optical feedbox.

Fig. 2 Breadboarded quasi-optical demultiplexer

community concluded that one should look in the submillimetre-wave range (to focus on chlorine chemistry in the stratosphere, providing data for studies on ozone depletion mechanisms), in the millimetre-wave range (to focus on exchanges between troposphere and stratosphere, bringing complementary information that is useful for studies on global changes) and at far-infrared frequencies.

Some pre-phase-A instrument studies were started like MASTER (Millimetre-wave Acquisitions for Stratosphere/Troposphere Exchanges Research), SOPRANO (Sub-millimetric Observation of PRocesses in the Atmosphere Notheworthy for Ozone), and PIRAMHYD (Passive Infra-Red Atmospheric Measurements of HYDroxyl) with the goals of establishing instrument feasibility, making a preliminary design of one instrument concept, and drafting a development plan for the complete instrument.

MASTER targets mainly the detection of water vapour, carbon monoxide and ozone in the upper troposphere and lower stratosphere. High resolution maps of these species are needed for appropriate modelling of atmospheric effects related to global changes, such as radiative forcing, exchanges between the stratosphere and the troposphere, and upper tropospheric chemistry. Although relying on the use of frequencies at the upper end of the millimetre-wave range, the high vertical resolution required for the retrieval of species in the upper troposphere translates into an antenna with a diameter of 2m.

Stratospheric depletion of ozone layer is the main topic addressed by SOPRANO measurements. Ozone, chlorine monoxide, hydrogen chloride and nitric oxide are the main target species. The submillimetre-wave frequencies and more relaxed vertical resolution requirements allow for a much smaller antenna, with a vertical diameter of only 1 m. The instrument is still big, weighing about 150 kg, and consuming about 300W.

ESA investigations have been relatively modest on the subject of hydroxyl detection. This radical is a main player in many chemical reactions, and considerable insight into atmospheric processes would be gained by providing measurements of hydroxyl in the upper troposphere and lower stratosphere. Three quite different instrument principles can be considered for PIRAMHYD. One could attempt to detect hydroxyl either using a Fabry-Perot interferometer, a microwave receiver, or a Fourier transform spectrometer. Each technique has, as always, its advantages and its disadvantages. In the case of the microwave receiver, heterodyne detection offers good performance even at 300 K operating temperature, with high spectral resolution and relatively good spectral coverage. However, the local oscillator is quite complex.

The priority has been given to MASTER and SOPRANO in the last years. The microwave version of the PIRAMHYD instrument has not yet been the subject of comprehensive ESA activities with the space industry.

In preparation for an atmospheric limb sounder operating in that frequency range, the Agency has been undertaking technological activities on antennas which were pursued up to breadboard level. The selected instrument was MASTER+, which is basically MASTER complemented with a submillimetre-wave frequency channel of SOPRANO.

The activities performed in the frame of these contracts include the design and prediction aspects for the complete antenna, and realisation and testing of the breadboard of the five frequency bands quasi-optical demultiplexer located nearby the antenna focal plane [1].

The present electrical requirements lead to an instrument operating in 5 frequency bands, with very low insertion loss (<0.75 dB) and very high beam efficiency (98% in a certain horizontal slab region) [1,2]. These requirements lead to a dual shaped elliptical Cassegrain antenna with high directivity (within the 60-70 dBi range) with a diameter of 2.2x0.8m and equivalent focal length of 1.4m.

An elliptical antenna with an axial ratio of 2.75 (see figure 1) was selected because there is only a strict beam width constraint in the elevation plane. To avoid high side lobes, it is necessary to provide an elliptical illumination of the main reflector so that the rim illumination is constant. This was achieved by shaping the hyperbolic subreflector, while a planar phase front of the field radiated was maintained by shaping the main reflector. The shaping, based on geometrical optics (GO), was done by the program DORELA. GO makes the shaping insensitive to frequency, which is necessary as a wide frequency band is required.

The quasi-optical feedbox has to fulfil two functions: separation of the different frequency bands with routing towards the input feed horns, and generation of primary radiation patterns needed for high beam efficiency of the overall antenna system. Such a quasi-optical feedbox has to comply with: low insertion loss for pass-band signals, high rejection of out-of-band (including image) signals, low mass and volume, and additional constraints (e.g. thermal aspects, assembly, integration and test).

The quasi-optical feedbox consists of five optical paths, each with an equal number of components and using the same fundamental structure: an input corrugated horn or Potter horn illuminating a 45 deg offset paraboloid, followed by a 45 deg offset ellipsoid. Modularity by devoting only 1 function to each optical component provides some flexibility, tuning or even re-engineering capability. The demultiplexer has a modular and compact configuration (the dimension of the baseplate is 430mm x 350mm). It was breadboarded, integrated and aligned on a test holder, as shown in figure 2. After this it was tested in a dedicated facility and farfield amplitude and phase pattern cuts were recorded for each band. For all bands nearly identical amplitude patterns were achieved, but phase patterns varied slightly. Excellent match between measurement and prediction was observed [1]. The measured patterns from the feedbox were used as inputs for a overall antenna performance prediction which showed that it should be possible to meet the ambitious overall performance [1].

4- (SUB)MILLIMETRE WAVE AND FAR-INFRARED ASTRONOMICAL MISSIONS

Planck will survey the entire sky and produce maps of it at nine different frequencies. These maps will then be used to infer in very great detail (to one part in one million) the temperature of the universe at the time when it became transparent, some 300000 years after the Big Bang. Using this

Fig. 3 FIRST and Planck in the carrier configuration

data it will then be possible to estimate fundamental characteristics of the universe, such as its density, the rate at which it expands and the kind of matter that fills it.

One of the most significant issues in the design of the Planck spacecraft is to achieve adequate rejection of unwanted radiation, which include those produced by both the so-called internal (spacecraft thermal self-emission) and external sources (Solar System sources and the Milky Way). If not suppressed adequately, this unwanted radiation will result in a degradation of the sensitivity of the instruments. In order to achieve low level of sidelobes, Planck's telescope is partially surrounded by a shielding structure (see figure 3). The sidelobe rejection levels for the celestial bodies can be as high as 90 dB. However, in order to comply with the required rejection a shielding structure alone is not enough. At these frequencies, issues like particulate contamination, surface cleanliness, roughness and accuracy and micro-cracking become an issue.

Planck consists of an aplanatic antenna with a 1.5-meter projected aperture with an effective focal length of about 1.8m. The antenna configuration optimisation has been performed using the optical tool CODE V, while the performance has been validated using GRASP8. The merit function in the optimisation was the wave front error and the output of the optimisation is a complete geometrical description of the antenna system (eccentricities, distances between main and sub, angle between mirror axes, etc.).

The antenna focuses radiation onto two different kinds of detectors to measure its intensity: the Low Frequency Instrument (or LFI)- an array of tuned radio receivers, based on HEMT amplifier technology and operating around-253 degrees C, and working at 30, 44, 70,100 GHz; and the High Frequency Instrument (or HFI) - an array of bolometers covering the frequencies 100,143, 217, 353, 545, 857 GHz . The two instruments have a total number of 76 feeds in the focal plane assembly.

In the frame of the activities carried out by ESA regarding Planck, an internal study was performed to assess the impact of straylight on the sensitivity of the instruments [3]. A selected set of at 30, 100 and 353 GHz can be found in [4]. The computation of the radiation patterns was done using Physical Optics (PO) or multi-reflector GTD with the software package GRASP8.

The Far Infra-Red and Submillimetre Telescope (FIRST), is a space observatory that will undertake observations in the one of the least explored windows on the universe. FIRST is designed to observe the birth of stars and galaxies throughout the history of the universe. The detection of the far-infrared and submillimetre emission radiated by gas and dust heated by young stars it will help us understand the physics of how stars form and will enable us to detect galaxies forming in the very early universe.

FIRST will have three instruments, employing photoconductor, bolometer, and superconducting mixer detectors. In order to detect the very faint cosmic emissions, these detectors and part of their optics and electronics have to be cooled down to near absolute zero (-273 degrees C), using liquid helium cryostat technology developed for the very successful ISO mission.

The FIRST telescope will be 3.5 metres in diameter. Protected by a shield and exposed to open space it will cool itself to about -200 degrees C.

5- (SUB)MILLIMETRE WAVE AND FAR-INFRARED DESIGN AND ANALYSIS TOOLS

Despite the importance of this wavelength range, there is still considerable debate as to which of the many electro-magnetic analysis techniques should be used for systems design. To some extent this debate is hindered by the fact that the languages of the "optical" and "radio" community are very

different. Most importantly, however, there are specific problems associated with modelling complex (sub)millimetre wave and far-infrared optics. For example, at submillimetre wavelengths one is in the situation where diffraction and scattering effects are important, and yet the systems are often too complex to make it realistic to perform numerical simulations during early stages of design. To make matters worse, it is sometimes necessary to model partially coherent fields rather than the fully coherent fields common in most antenna engineering problems. To address this defiance, ESA has commissioned a study to investigate sub-millimetre and far-infrared optical design and verification techniques.

6- ADMIRALS

As mentioned in the introduction, Earth observation and astronomical instruments have many commonalities at instrument and technology level requiring the development of:

- 1) (sub)millimetre wave and far-infrared antenna technology, which results in the need for new refined antenna configurations and technologies with exceptionally high performance.
- 2) Suitable measurement techniques. Existing measurement techniques have not been validated at frequencies above a few hundred GHz, and highly accurate antenna characterisation techniques are needed due to the very stringent requirements placed on the antenna.
- 3) Antenna structures with very high dimensional stability and surface accuracy of the order of a few microns. This means that an innovative approach towards material selection and manufacturing is required.
- 4) Verification of existing design tools at frequencies between microwave and optical wavelength ranges.

ESA has recently initiated a study to address these technological challenges.

The main objectives of the present study are the definition, development, manufacturing and testing of a complete 2 metre-class millimetre/submillimetre wave antenna, bringing the technology to representative flight standard and demonstrating the integrated electromagnetic and optomechanical design and material performance in a representative configuration. The study shall focus on achieving the electromagnetic and optomechanical requirements of current millimetre/submillimetre wave antenna concepts being considered for future ESA scientific and Earth observation payloads. Suitable test methods for these types of antennas shall be defined, evaluated, demonstrated, and applied to the developed antenna.

7-ALTERNATIVE (SUB)MILLIMETRE WAVE AND FAR-INFRARED TECHNOLOGIES

Most of the above mentioned instruments have receivers that work with waveguide horn antennas as receiving elements. They have traditionally been the most common microwave antenna feed types and although the attenuation of fundamental-mode waveguides at (sub)millimetre wave and

far-infrared frequencies is high and both the effect of metal tolerances and misalignments becomes more severe, horns and waveguides have been produced for these wavelengths [5]. However, the small size can be turned into an advantage when the dimensions and tolerances required become compatible to those achieved by lithography or micromachining. In recent years the advancement of photo-lithographic and micro-machining techniques has resulted in a very reliable and repeatable process to create structures on dielectric substrates and the fabrication of

Fig. 4 Integrated Antenna with peripheral circuitry

Fig. 5 Micromachined Horn; on the left half of the horn, while on the right the assembled horn can be seen.

very complex electronic structures with a high yield is now possible. This means that a viable alternative for waveguide-based front ends has emerged.

An important advantage of the integrated planar technology is that the antenna, mixer, local oscillator and all peripheral circuitry can be realised on a single substrate, thereby eliminating the transmission lines between the separate devices.

However, there might be some problems related to planar antennas because of efficiency problems associated with the dielectric substrates on which these antennas are fabricated. If the dielectric is thick in terms of wavelength, substrate and surface wave modes can be excited. Two basic approaches have been used to increase the efficiency; dielectric lenses and photonic bandgap crystals (PBG).

The photonic bandgap antenna is still a relatively new concept and regarding the antenna performance the PBG technology is still in an experimental stage. On the contrary, research on integrated lens antennas has already shown that the radiation characteristics are very promising and the integrated lens designs have already reached some level of maturity. Several activities on the above technologies have been initiated (KASIMIR, SISIRT, IAD, etc.) with very good results (see figure 4, [6]).

While this approach has offered competing performance, micromachining in a general sense is not restricted to planar structures. It is also possible to manufacture more traditional "waveguide like" structures (see figure 5). The advantages of these come from the fact that it is possible to form a

waveguide section in which the active semiconductor can be integrated directly into, which allows more better known design approaches to be applied.

8- CONCLUSIONS

Successful execution of the planned instruments and missions will require continuous development of the technologies applicable to (sub)millimetre wave and far-infrared antennas and testing beyond today's capabilities. Several key areas are identified like:

- Development in (sub)millimetre wave and far-infrared antenna technology, leading to new refined antenna configurations and technologies with exceptionally high performance
- Computer tools for antenna analysis and design, using dedicated and existing tools at the higher frequencies. Examples include physical optics, integral equation methods, mode-matching techniques and quasi-optical techniques in a well-balanced manner to enhance accuracy.
- The use of very accurate manufacturing and integration techniques, compatible with demanding requirements of materials and dimensional accuracy. This is applicable at all levels from the feeding system, through the optics to the complete assembled antenna.
- Dedicated, accurate and precise electromagnetic measurement capability for characterisation of the feed system, as well as the complete integrated antenna at (sub)millimetre and far-infrared wavelengths.

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