# Optical Design and Testing of the Planck Satellite

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## 1. INTRODUCTION

Planck ( http://www.rssd.esa.int/Planck) is a space observatory designed to image the temperature anisotropies of the Cosmic Microwave Background (CMB) over the whole sky, with unprecedented sensitivity ($\Delta T/T \sim 2 \times 10^{-6}$) and angular resolution (~5 arcminutes). Planck will provide a major source of information relevant to several cosmological and astrophysical issues, such as testing theories of the early universe and the origin of cosmic structure.

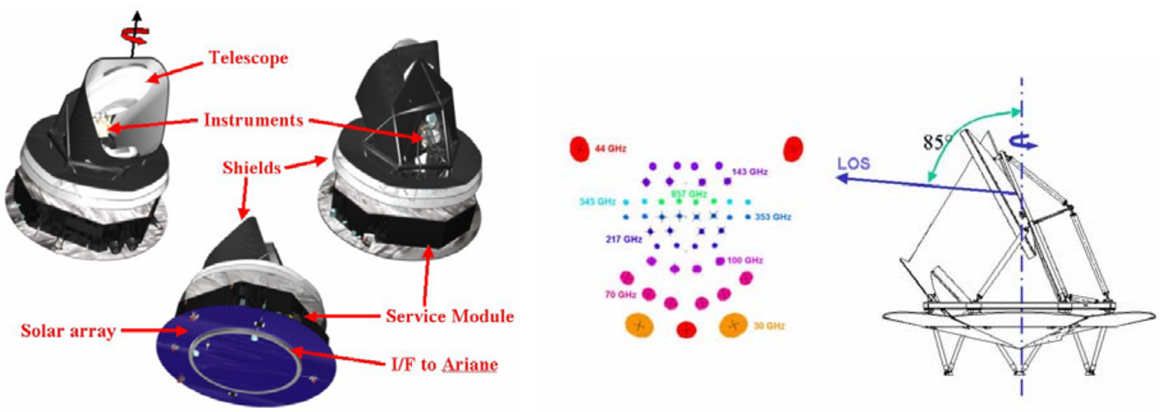


**Fig. 1**: [left] A conceptual view of the arrangement of the main elements of the Planck payload. The instrument focal plane unit contains both low and high frequency detectors. The function of the large shield surrounding the telescope is to control the far sidelobe level of the radiation pattern as seen from the detectors. Specular cones ("V-grooves") thermally decouple the Service Module (located below the payload) from the Payload Module, and allow the payload environment to reach its nominal temperature of ~50 K. The satellite's spin axis is indicated; the Sun is always kept in the anti-spin direction (perpendicular to the solar array). The satellite views are courtesy of Alcatel Space (Cannes). [right] Outline of the Planck optical system, including the telescope baffle and V-groove, which provides straylight control in addition to thermal isolation. The telescope field-of-view is offset from the spin axis of the satellite by an angle of 85°. The footprint of the field-of-view on the sky is seen in the middle; it covers about 8° on the sky at its widest. Each spot corresponds to the 20 dB contour of the radiation pattern; the ellipticities shown are also representative of the shape of the beam at full-width-half-maximum. The black crosses indicate the orientation of the pairs of linearly polarised detectors within each horn. The field-of-view sweeps the sky in the horizontal direction in this diagram.

## 2. PAYLOAD DESIGN

The scientific prescription which will allow Planck to meet its ambitious objectives calls for:

- an offset telescope with an effective physical aperture of size ~1.5 m. to achieve the required angular resolution
- state-of-the-art broadband detectors covering the range ~25 to ~1000 GHz, to achieve the required sensitivity and the ability to remove foreground sources of emission
- a survey with all-sky coverage carried out from a far-Earth orbit
- extreme attention to rejection of unwanted systematic effects.

To achieve this prescription a payload was conceived for Planck consisting of three basic components: (1) a telescope and baffling system, providing the angular resolution and rejection of straylight; (2) a Low Frequency Instrument (or LFI) -- an array of tuned radio receivers, based on HEMT amplifiers, covering the frequency range 27 -- 77 GHz, and operated at a temperature of 20 K; and (3) a High Frequency Instrument (or HFI), consisting of an array of bolometers operated at 0.1 K and covering the frequency range 85 -- 1000 GHz. The major elements of the Planck payload and their disposition on the spacecraft can be seen in Fig. 1.

## 3. OPTICAL DESIGN

In early 2000, ESA and the Danish National Space Centre (DNSC) signed an Agreement for the provision of the two reflectors that constitute the Planck telescope. DNSC and ESA have subcontracted the development of the Planck reflectors to Astrium GmbH (Friedrichshafen, Germany), who have manufactured the reflectors using state-of-the-art carbon fibre technology. The telescope structure was built by Contraves Space AG (Zürich, Switzerland), also using carbon fibre technology. Overall responsibility for assembly and testing of the telescope has been delegated to the satellite's main contractor, Alcatel Space (Cannes, France).

The telescope collects radiation from deep space and feeds it to a focal plane which is shared by the two instruments (LFI and HFI; see Fig. 1). In both instruments, the detectors are fed by corrugated horns, single-moded except for the two highest frequency channels, which support multiple modes. The single-moded horns illuminate the telescope with a Gaussian-shaped pattern, which is heavily tapered (to ~-30dB at the edge of the reflectors); whereas the illumination pattern of the multi-moded horns has a shape closer to a top-hat than a Gaussian. The detectors are very broad-band, accepting a range of frequencies ~30% wide around each channel's centre frequency.

The telescope was originally designed as an off-axis Gregorian, which obeyed the so-called Dragone-Mizuguchi criterion, making its polarization purity very high on the optical axis. However, the required field of view (FOV) was very large and the level of aberrations was unacceptably high near the edge of the FOV. Therefore the design was further optimized [1], taking into account the tapered nature of the detector illumination. The main tool used to predict the angular response on the sky is GRASP, a Physical Optics package designed and commercially sold by TICRA (Denmark). However, this tool is unsuitable for optimization due to the heavy computing time needed for each prediction run. Therefore two optical softwares were used, CodeV (Optical Research Associates, California) and ASAP (Breault Research Organisation, Arizona) which allow better flexibility. GRASP was only used on the last iterations to confirm the design. The optimization allowed to vary the conical constants of the reflectors, the inclination and taper of the feedhorns, and the location of the focal plane with respect to the telescope; and the design was optimized against aberration level across the focal plane, and straylight response. The final design consists of an aplanatic telescope with two ellipsoidal reflectors, and provides good optical quality across the focal plane.

## 4. OPTICAL PERFORMANCE

The performance of the optical system is driven by two main elements:

- the optical quality of each detector's response, which should not be degraded from the "theoretical" one. This performance is expressed in three main parameters: (a) the allowed degradation in Wavefront Error from the level calculated for an ideal telescope; (b) the equivalent degradation in peak gain; (c) an allowed degradation in the theoretical ellipticity of the main beam. The theoretical performances are based on an ideal telescope and Gaussian beam feedhorns.
- the response to straylight, which must be kept at very low levels. External straylight for Planck is defined as the detector signal generated by radiation entering the system through the sidelobes (i.e. from outside the main beam). Internal straylight is due to self-emission from the satellite itself. The main external straylight sources are the Sun, the Moon, the Earth, and the Galactic plane. As an example of the very low levels of rejection which need to be achieved, the Sun signal becomes important when the angular response is larger than ~-100 dB from peak.

The final performance will be degraded by a number of factors:

- the alignment of the system (reflectors and focal plane) will not be perfect.
- the reflector surfaces are not perfect, and suffer from a number of mechanical defects which cover length scales from sub-millimetres to metres. These defects are caused by the manufacturing process [2], and grow in amplitude as the telescope is cooled from room-temperature to operating temperatures (~50 K). In addition, some of these defects are quasi-regularly distributed:
    - the honeycomb-type structure on which the front surface lies imprints a regular quilt-like structure with ~6 cm periodicity

- the isostatic mounts on the back of the reflector induce a triangular deviation on the front surface.

- Many reflective and partially absorptive structures exist all around the main reflectors, all of which have an effect on the angular responsivity of the system at the very low levels of interest. Some of these structures are indeed an integral part of the optical design, such as the large baffle surrounding the telescope, whose main optical purpose is to shield the detectors from self-emission from the satellite.

All of the above factors may have an influence on the final performance of the optical system in flight. Unfortunately there are few possibilities in flight to measure its performance. The only well-known observable sources in the sky are the major outer planets (Jupiter, Saturn, Mars), which will be scanned by all detectors and will therefore provide a measure of the shape of the main beam (down to ~30 dB from peak in the best of cases). Other sources exist, but they are either not very bright (e.g. extragalactic point sources) or poorly known at the operating wavelengths (e.g. the galactic plane). Because Planck will map the whole sky, it will be possible to model such sources and iteratively estimate their combined contributions and refine the source and measurement model; however, the final accuracies achievable in this process are currently quite uncertain. In this context, it is obvious that the knowledge on the beam shapes in flight, in particular the sidelobes, will be based in large measure on what is learned during testing on the ground.

The photometric calibration of the detectors also requires specific knowledge of the beam shapes. The main calibrator to be used is the dipolar (Doppler) signal on the sky caused by the motion of the Solar System with respect to the Cosmic Microwave Background. This signal is easily detectable, however in order to extrapolate the calibration from the very large angular scales (~180$^{o}$) of the dipole signal to the size scales of interest in the maps (<1$^{o}$) requires a very accurate knowledge of the distribution of power across the 4π beam pattern.

## 5. OPTICAL TESTING

Testing of the optical system on the ground poses a number of difficult challenges:

- The in-flight operating temperature of the telescope (~50 K) cannot be easily produced for an optical test environment of such a large object. Indeed some aspects must be tested at room temperature and then the behavior extrapolated by models to operating temperatures.
- Antenna measurement techniques at sub-mm wavelengths are not well developed, and indeed at the highest frequencies no measurements have ever been made of such large flight antennas in a controlled test environment.
- The reflector surface characteristics (high local slopes) imply large scattering at optical wavelengths and limit the range of wavelengths which can be used to infrared and longer.
- The flight hardware cannot be exposed to uncontrolled conditions and this limits the types of facilities which can be used.

The above challenges have as a consequence that the verification and characterization of the optical system of Planck is composed of a significant number of individual tests in different environments and conditions, which must a-posteriori be coherently integrated by means of mathematical models into a prediction of flight performance. This prediction will essentially consist of a GRASP model of the optical system at many individual frequencies, which includes aspects learned from each of the tests. This integration process is complex and constitutes one additional challenge in the whole process. Below we provide a list of each of the tests currently planned in the overall verification and characterization campaign, with some remarks on the special difficulties and characteristics of each.

### 5.1 Reflector Characterisation

Each of the Planck reflectors is characterized individually prior to integration into the telescope. The main objectives are to understand and measure the large-scale behavior of the reflectors as they cool down to operating temperatures, and to characterize the surface irregularities at small and intermediate length-scales. Currently three kinds of measurements are carried out on each reflector:

- 3D metrology is carried out at room temperature by means of a contacting probe which measures the location of each node of a (typically) 1 cm grid with an accuracy of a few μm.
- interferometry at a wavelength of 9.25 and 10.6 μm is performed in a vacuum chamber, both at room temperature and at a number of temperatures down to ~40 K. Cooling is achieved by means of liquid Nitrogen and Helium shrouds, while the interferometer is kept at room temperature outside the chamber. The method is in practice

limited by light scattering from high local slopes on the surface being measured; for the Planck reflectors, high local slopes are located at the edges of the honeycomb structures, near the isostatic mount locations, and near the edges of the reflectors. In the areas affected by these large slopes, no information is recoverable on the surface shape; in addition these blind areas can inhibit the recovery of large scale surface information by breaking up the recovered phase maps into small coherent patches. Recovery of the large scale surface deformations is further complicated by a lack of information about changes of the interferometric cavity during reflector cool-down (principally differential contraction of the isostatic reflector mounts). Global wavefront deformations induced by e.g. a tilt of the reflector cannot easily be distinguished from a large-scale deformation of the reflector. The situation is ameliorated when a smaller area of the surface is imaged, as this effectively increases the amplitude of the resolvable slopes.

  - For the secondary reflector, the interferometer beam is injected at one focal point and recovered (after passing through the reflector) at the second focus, for combination with the reference beam and imaging of the resulting interferogram onto an infrared camera; this constitutes a co-called single-pass configuration. The quality of the recovered interferograms is good down to operating temperatures, though it is not yet clear how much of the large-scale information is preserved due to the problems mentioned above.
  - For the primary reflector, interferometry is performed in a so-called double-pass configuration, in which the beam is injected at one focal point and recovered through the same point, having passed twice through the reflector itself (note that in this setup the beam it is returned by a specifically designed spherical mirror which could introduce its own errors). In this configuration the high slopes problem is amplified by the multiple passes, and the quality of the recovered interferograms is not high. In fact, up to today it has not been possible to measure images of the Planck primary at temperatures below ~210 K, even when only a small part of the reflector is imaged.

- Videogrammetry: because of the problems experienced using interferometry to recover the large-scale deformations of each reflector, it was decided lately to add videogrammetry to the reflector test programme. It is implemented within a vacuum chamber which can be cooled down to nitrogen temperatures (~100 K on the reflector), and uses a large-format camera on a rotating arm to image a set of several hundred targets placed on the surface of the reflector. The accuracy estimated to be achievable for each target is of order 20 μm, though several aspects of this measurement are being currently tuned to enable this performance.

**5.2 Telescope Structure Characterisation**

The large scale deformation of the telescope structure determines to a large extent the location of the focal plane, as it changes the relative location of the two reflectors. In order to determine the motion of the structure as it cools down, videogrammetry has been carried out on a qualification model of the structure. The setup and achievable accuracy are similar to the ones for reflector-level videogrammetry.

**5.3 Telescope Optical Characterisation and Alignment**

The telescope is tested as a whole (structure plus reflectors) in order to verify that it behaves as a system in the way predicted by the mathematical model, and consistently with the measurements at reflector and structure level. This test is also carried out by means of videogrammetry. The setup is similar to the one for reflector-level videogrammetry, i.e. the physical temperature achieved on the elements is in the range ~100 K; however, the accuracy achievable will be lower than for the reflectors, since the camera must image the set of targets at very steep angles. In principle this measurement will provide the location of the telescope's focal surface at operational temperatures. This is a very critical measurement since the flight focal plane containing the detector feedhorns will be placed at the location determined in this way. An important plus for this method is that it also allows to place the focal plane within the measurement setup and to measure its deformations during the cool-down (this test would not be performed otherwise).

It should be noted that the choice of videogrammetry was not the initial one, but a fallback solution due to the failure of other conceptual arrangements (at cryogenic temperatures). Among the discarded choices were sequential Shack-Hartmann (was very complex and difficult to implement), and "Best Focus" search at 10.6 μm via Point-Spread-Function fitting (which was not accurate enough due to the poor wavefront quality of the telescope arising from the reflector surface errors, as well as largely incompatible with the thermal setup).

The reflectors and focal plane are aligned to each other using classical optical means: theodolite triangulation to optical marks placed in each element (focal plane, reflectors, structure), and shimming to bring the whole assembly into the correct location (predicted such that at cryo-temperatures the focal plane will be correctly aligned).

### 5.4 Radio Frequency Characterisation

The mathematical prediction exercise requires high confidence in the ability of GRASP to model the RF behavior of these large structures. A special hardware model has been designed and built to validate this aspect, consisting of qualification models of the reflectors, telescope structure, baffles, and feed-horns; all being assembled into a model of the satellite which is virtually identical (from the RF point of view) to the flight one. This assembly will be placed in a Compact Antenna Test Range, where the far-field radiation pattern of the system will be measured at frequencies between 30 and 350 GHz. Naturally these measurements can only be made at room temperature, and for this reason the alignment of the model is not identical as that of the flight telescope (which is indeed not in alignment at room temperature). Nonetheless, these measurements will verify the predictive ability of GRASP and will allow to estimate the uncertainties associated to GRASP modeling of the various phenomena involved in determining the response at very low levels (~-100 dB from peak at low frequencies and ~50 dB from peak at higher frequencies). This test campaign is technologically very demanding, and will be breaking new ground for sub-mm CATR measurements.

### 5.5 End-to-end Test

Since the instruments cannot be operated nominally at ambient temperature, and in a cryogenic facility it is not possible to make meaningful RF measurements (due to the small volume and lack of absorptive walls), the overall system is never subjected to an End-to-end test before flight (by this we mean a test where the optical response pattern of the detector/telescope combination is measured in a flight-like configuration). The alignment in particular is made using elaborate prediction tools, and there is a certain fear that if a mistake creeps into the process, it would go undetected until flight. Therefore provision has been made for a specifically designed test which can at least partly allay this risk. It consists of a dedicated detector placed in the focal plane of the flight satellite, which can be operated at room temperature in a CATR-like environment. This detector will operate at 350 GHz, and will be used to measure the shape of the main beam at that frequency. Models indicate that the beam shape is rather sensitive to misalignments, and therefore this measurement will detect any gross misalignments in the system.

## 6. CONCLUSIONS AND OUTLOOK

The scientific objectives of the Planck satellite imply demanding performance requirements on its optical system, which in turn are forcing new ground to be broken in many areas of antenna testing. Each of the tests in the Planck programme has its own peculiarities, and all the results need to be coherently assembled into a final prediction of in-flight behavior. Some of the test methods adopted required considerable refinement to reach the performances needed, while others failed altogether. It is clear that for the next generation of satellites seeking to measure the Cosmic Microwave Background, such requirements will be exceeded and therefore the testing programmes may have to be rethought from scratch.

## 7. ACKNOWLEDGMENTS

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