Design, optimization, and characterization of multi-beam optical systems

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Introduction

• The performance of an optical system can be quantified by two main quantities:
  1. Image quality/efficiency:
     • PSF/Strehl ratio (optical)
     • Beam/efficiency (radio and mw)
  2. Ability to point it in the right direction

• Image quality is determined by a proper design of the optical system, as well as accuracy and alignment of the manufactured optics.

Design and optimization of multi-beam optical systems
Overview of sub-efficiencies

\[ \eta_{ap} \sim \eta_t \cdot \eta_{sp} \]

(see Cappellen 2007)
Spillover and taper efficiencies

- The taper efficiency and the spillover efficiency are complementary: as the taper increases, the spillover will decrease (and thus increases $\eta_{sp}$), while the taper efficiency $\eta_t$ decreases.
- The trade-off between $\eta_{sp}$ and $\eta_t$ has an optimum solution: -11 dB.
Some examples of ET (radio)

ALMA $\Rightarrow$ -12 dB

GBT $\Rightarrow$ -14 dB

VLA $\Rightarrow$ -12 dB

SRT $\Rightarrow$ -12 dB
Some examples of ET (cmb)

Planck $\Rightarrow -30$ dB

WMAP $\Rightarrow -20$ dB

The taper used in the CMB experiments are rather different because we have strong requirements in the straylight rejection due to the fact that straylight contamination, originated by the signal entering the feed horns through the sidelobes of the radiation patter, could be higher than the CMB signal when the sidelobes points towards the Galactic plane.

Trade-off angular resolution and straylight
Single beam optics

- Far-field pattern is the Fourier transform of aperture plane electric field distribution:
  - Uniform illumination $\Rightarrow$ sinc function
  - Gaussian illumination $\Rightarrow$ Gaussian function

- Software packages for precise modelling of reflector antennas and beam simulations (GRASP)

$$P_{\text{sky}} = \text{Optics}(P_{\text{feed}})$$
Multi-beams optics

\[ P_{sky} = \text{Optics}(P_{feed}) \]

\[ \hat{r}_{sky} = \text{Optics}(x_{feed}, y_{feed}) \]
\[ z_{feed} = z(x_{feed}, y_{feed}) \]

- Illumination (ET)
- Beam pointing
  - Feed locations
  - Tilting
- Feed mechanical coupling
- Feed e.m. coupling
- Constrains in array dimensions
Single and multi – beam (feed) systems

- Off-focus feeds reflect in
  - beams offset wrt LOS
  - increase of aberrations (mainly coma, astigmatism)

- The study of the focal region of the telescope is mandatory:
  - feed location
  - pointing
Focal plane surface arrays

Single feed at focus: feed boresight along telescope chief-ray

Concave focal surface

Convex focal surface

A strategy to locate and tilt the feeds is required
Focal plane surface arrays

- There is not a consolidated strategy to calculate the best location and tilting of the feed horns.
- Minimization of the RMS of the wave front deformation (i.e., WFE) at the focus or at the aperture plane is one of the possible methods.
- The RMS of the WFE is an average quantity and is directly related to main beam properties such as gain and FWHM.
Shape of the focal surface
What does optimisation mean?

- Minimise the main beam distortions
- Minimise the straylight contamination
- Improve the angular resolution
- Make the focal surface as flat as possible
- Fit the telescope/focal plane into the fairing (space)
QUIET Telescope
Planck Telescope
Summarizing...

- Multi beam systems are widely used to improve image capabilities for millimeter and radio-telescopes (sky coverage and sensitivity)
- The complication is that feed dimensions are not negligible so that off-axis aberrations may degrade the beam patterns rapidly
- Location and pointing of feeds need to be carefully studied to minimize illumination losses and spillover radiation
- Complicated system w.r.t single feed optics especially in polarization since the polarization capabilities degrades far from optical axis.
Planck: a case study. Why?

- Planck is a multi-beam, multi-frequency telescope
- High performance, low systematics focal plane instrumentation spanning in frequency from 27GHz to 1THz with 74 detectors and 47 corrugated feed horns
- Almost 10 years of telescope and focal plane optimization activity to satisfy the demanding performances required by precision CMB measurements
- It has been characterized very well (on-ground and in-flight) to remove the systematic effects
The Planck Optics

REFERENCES
Telescope design and optimization

- (1996) We started with a Dragone-Mizuguchi 1.3 meter aperture Telescope (Gregorian off-axis configuration)
- (1998) We moved towards a quasi Dragone-Mizuguchi 1.5 meter aperture Telescope
- (1999) We demonstrated that Aplanatic (optical) condition may optimize the main beam shape
- (2000) We optimized the optics using traditional ‘optical’ software at various Planck frequencies (APLANATISATION).
- (2000-2002) We designed the focal plane and the corrugated feed horns to satisfy the angular resolution and the straylight requirements
- (2004) focal plane unit design frozen after re-optimization (including polarisation)
Focal plane, feed pattern and illumination

LFI footprint on the secondary mirror

LFI footprint on the primary mirror

10 dB contours
Trade-off between AR and spillover

10 dB of ET degradation ~ factor of 10 in the Galactic straylight
Where sidelobes come from?
SS2 – SS1, 30 GHz Straylight Simulations
SS2 – SS1, 30 GHz dDX9
SS2 – SS1, 30 GHz dDX9 - Sim
Optical tuning
Lesson learned from Planck

- Requirements should be properly defined taking into account
  - bandpass response
  - asymmetric illumination typical of multi-beam systems (the edge taper is not a number but it is a curve)
- Beam simulations are a fundamental tool from design phase to sky measurements
  - to guarantee correct gain values in the calibration pipeline
  - to remove systematics from the maps
- Polarization purity degrades in multi-beam optics
  - cross-polarization is quite impossible to be properly characterized with celestial sources
  - beam simulations are mandatory to model the beam polarization
- Good optical simulations require excellent measurements of the optical components (feed, reflector surfaces, alignment)