



planck



# Lessons learned from the Planck optical system

**J. Tauber, on behalf of the Planck Collaboration**

**B-modes workshop, Tokyo, Dec 2015**

J. Tauber, B-modes Workshop 2015

European Space Agency

## Lessons learned related to optics

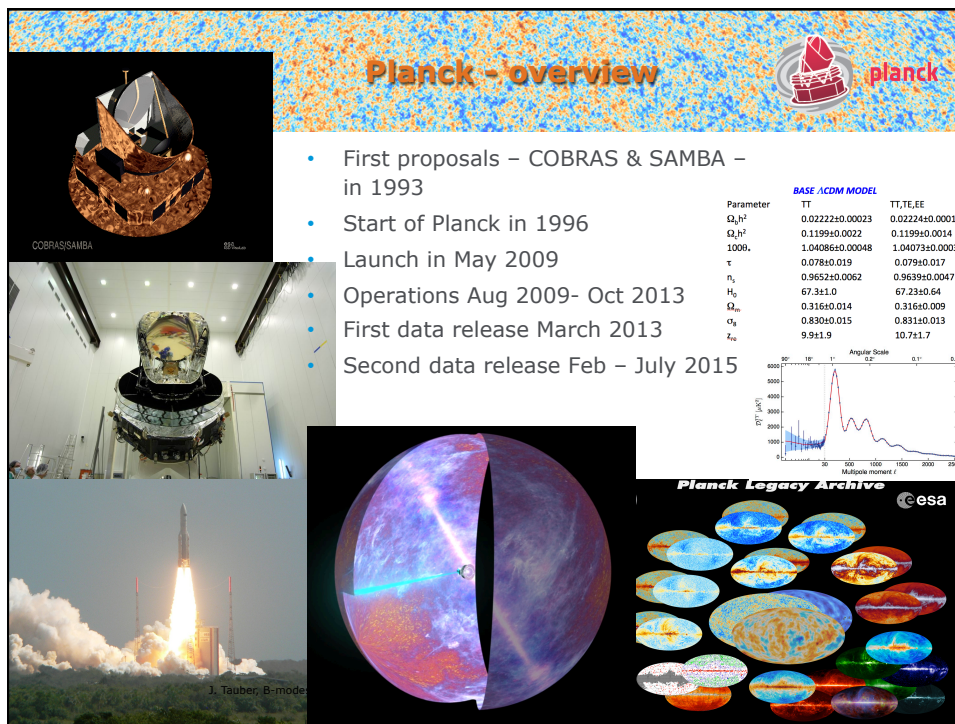


1. Background
2. Requirements & design
3. Telescope
  - a. Technology
  - b. Verification on ground
4. Horns & Detectors
5. Modelling
6. Performance in flight – recovery of parameters
7. Some misc issues
8. Summary



J. Tauber, B-modes Workshop 2015

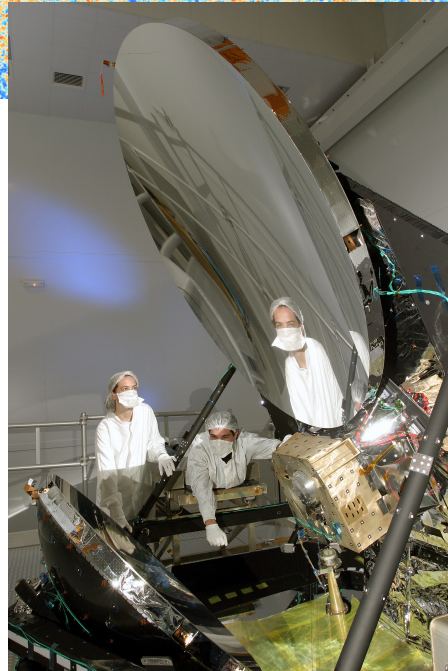
European Space Agency



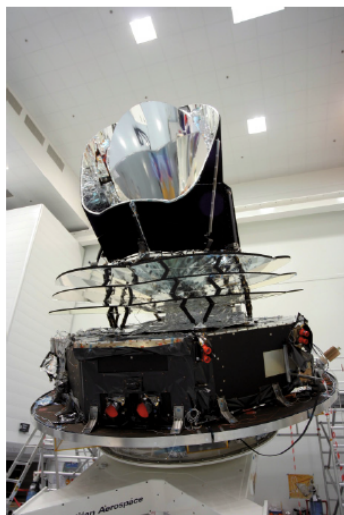


## Planck Telescope

1. Optimized offset gregorian
2. Primary: 1.50 x 1.89 m ellipsoid (CFRP)
3. Secondary: 1.02 x 1.04 m ellipsoid (CFRP)
4. System:
  - a. 1.5 m circular projected aperture
  - b. Total  $\varepsilon < 0.01$
5. Operates at 40 K !
  - a. *System cannot easily be measured on the ground in flight conditions*
6. Reflectors were developed by EADS Astrium (Friedrichshafen, D), under lead of ESA and a Consortium of danish institutes led by the Danish Space Research Institute
7. System architect: Alcatel Alenia Space (Cannes, F)
  - a. Structure
  - b. Baffle
  - c. ...

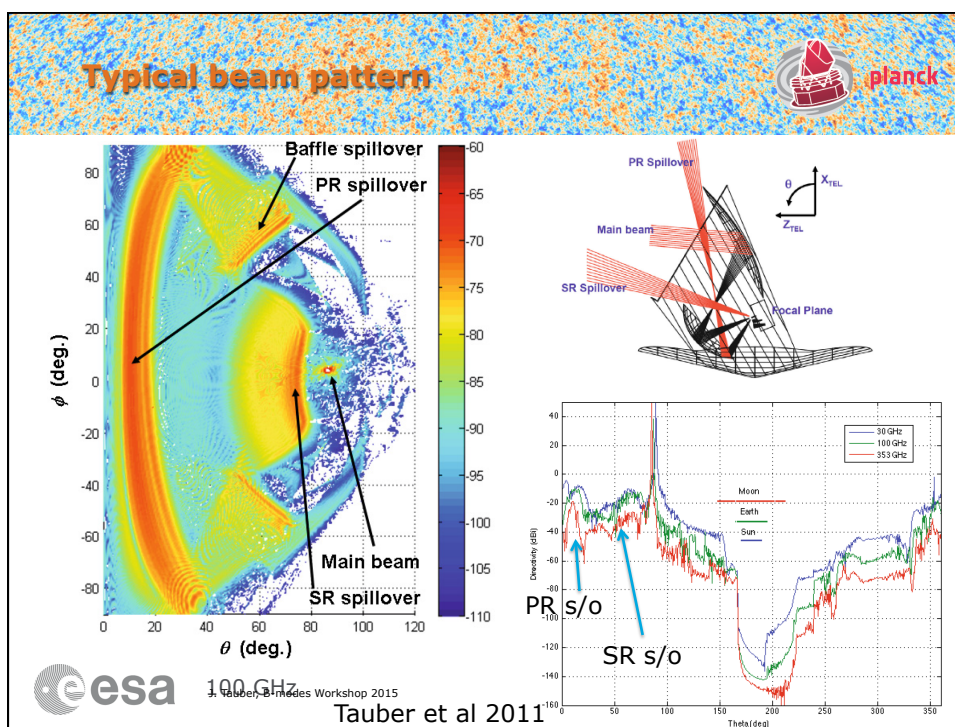
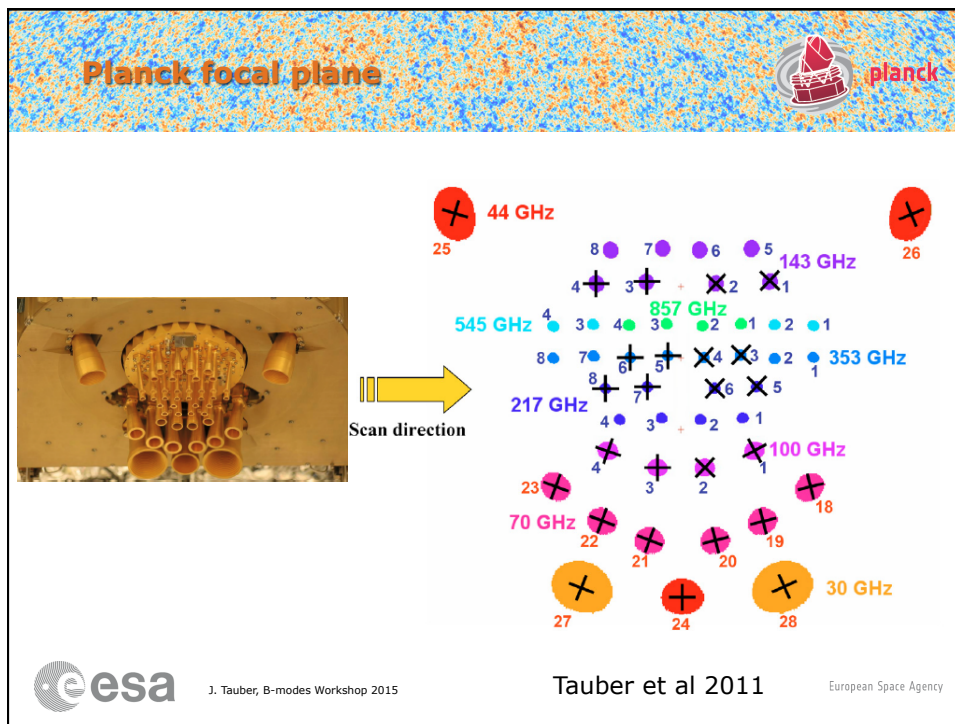


## Planck telescope

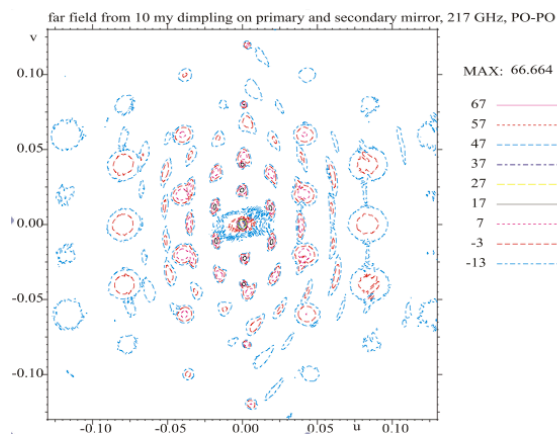
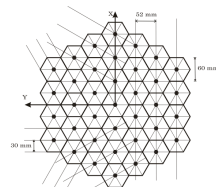
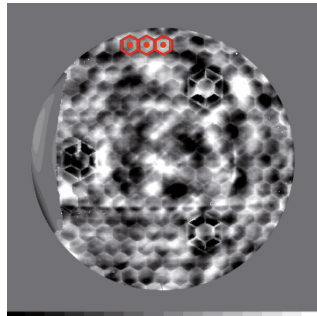


J. Tauber, B-modes Workshop 2015

European Space Agency



## Reflector features: print-through and dimpling



J. Tauber, B-modes Workshop 2015

European Space Agency

## Requirements



1. The main requirements set at system level were related to internal straylight (leading to thermal fluctuation reqts)
2. At telescope level, a geometrical design was imposed
  - a. The telescope was designed iteratively
    - Starting point was an offset Gregorian / D-M system
    - CodeV was used to optimize the WFE across the focal plane (not the final one)
    - GRASP was used to check straylight levels and adjust horn tapers
  - b. Once the telescope configuration was defined, it was used to
    - at telescope level, set geometrical requirements and optical requirements (WFE, peak gain degradation, ellipticity), etc etc
    - At reflector level, set mechanical requirements: rms distortion levels by "rings", "dimpling", and roughness



J. Tauber, B-modes Workshop 2015

European Space Agency



## Requirements



The Planck approach was due mainly to the complicated contractor scheme.  
What we SHOULD have done but did NOT (*formally*) do

- Set optical requirements at high level, based on scientific reqts, and taking into account in-flight "calibration" and use of optical information
- Flow them down to subsystem level
- Set knowledge requirements
- Assess in detail ground requirements early enough

The lack of system reqts and "ownership" led to serious problems:

- Confusion due to "duplicate" reqts (some due to language)
- (not) Meeting some requirements, e.g. the figures and alignment
- Verifying the whole system

A-posteriori, it is clear that

- Some requirements were too tight (had little influence on performance)
- Other requirements were missing (some knowledge aspects)

Overall, the balance between performance and knowledge was not right



J. Tauber, B-modes Workshop 2015

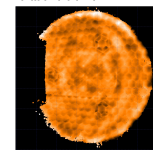
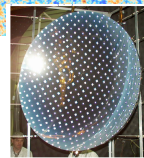
European Space Agency

Simulations

## Verification – main measurements



1. At reflector level
  - a. Videogrammetry down to 95 K
  - b. Interferometry at  $\lambda 10\mu\text{m}$  down to 40 K (only successful for SR)
2. At telescope level
  - a. Videogrammetry down to 95 K
  - b. Theodolite to tie all subsystems together
3. At system (telescope + FPU) level
  - a. Initial plan for cryo-Shack-Hartmann at  $\lambda 10\mu\text{m}$  not implemented
  - b. Extensive CATR testing on RFQM (ambient temperature)
  - c. Cryogenic "RF check" on FM



The initial verification plans were only partially fulfilled. Final on-ground verification was largely by extrapolation and analysis.



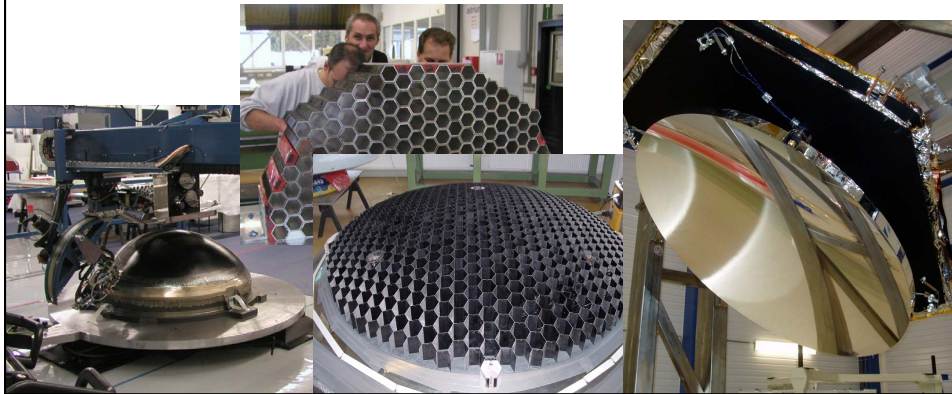
J. Tauber, B-modes Workshop 2015

European Space Agency

## Telescope technology



1. CFRP was selected for many reasons, including the usual ones (CTE, mass, stiffness, ...)
2. The manufacturer was ASED in Germany – heritage from Herschel
3. A proprietary fiber/resin combination and facesheet lay-up technique was developed
4. The reflectors met all the surface quality requirements



## Problems with use of CFRP



- The estimated mechanical parameters of the composite were (well) outside the ones expected from the fiber/resin combination
  - FEM behavior with temperature did not match the measured one
  - Figure (k, R) at op temp had to be extrapolated from videogrammetry at 95 K
- The shape of the “dimples” was more pronounced and more complex than expected from FEM
  - The dimples scattered too much light and broke up the double-pass interferometric images of the PR
    - Single-pass interferometry on the PR was too difficult
  - SR was measured w/ interferometry, PR had to be guessed
- Fortunately Planck was quite forgiving as an optical system



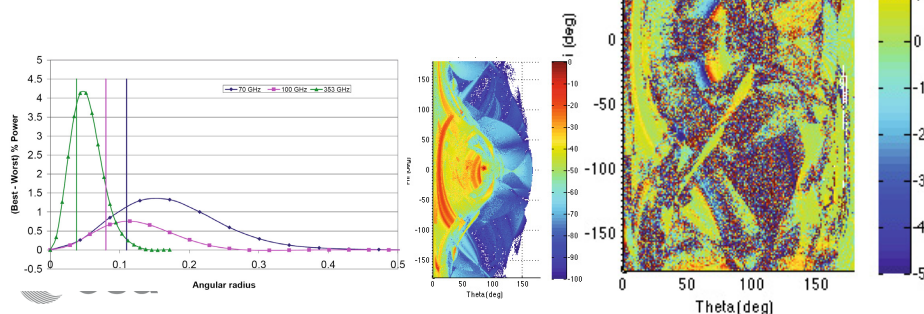
J. Tauber, B-modes Workshop 2015

European Space Agency

## Mechanical uncertainties



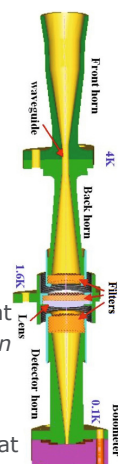
1. A "best-worst" GRASP model gives an idea of the uncertainties on the predicted pattern due to mechanical alignment uncertainties from the ground
2. It is clear that if one wants sub-percent accuracy, then one has to "calibrate" the optical response in flight



## Horns and detectors



1. Corrugated horns, high tapers
  - a. straightforward to design
  - b. Broad-band nature is a complicating factor, e.g. phase-center
2. LFI design very clean – feeds two orthogonally polarized LNAs via OMT
3. HFI design quite complex, feeds spider-web bolometers in a cavity
  - a. Back-to-back horns, filters, cavity etc
  - b. Coupling of radiation to bolometer in the cavity
  - c. Bolometer time response *very* complex
  - d. Multi-moding (545 and 857 GHz) not well understood
4. Monochromatic single-mode measurements on the ground indicate that the beam pattern models of corrugated horns are quite good - *except in polarization*
  - a. Beware manufacturing tolerances at high frequencies !
5. Bottom line: no measurement was made of detector angular response at operating temperature...



a. All GRASP modelling used "ideal" horn beams

J. Tauber, B-modes Workshop 2015

European Space Agency



## Modelling



1. GRASP has been the modelling workhorse for Planck (PO for main beam, PO+MultiGTD for sidelobes)
2. It has some serious limitations
  - a. It requires experts to run it
  - b. It is quite slow and not easily parallelisable
    - at high frequencies
    - for complex geometries
  - c. It is expensive
3. Some implications:
  - a. Geometry designed to make modelling easier
  - b. Modelling very selective, especially at high freqs
4. Other tools we used:
  - a. CodeV (wherever many iterations are needed)
  - b. Zemax: for quick&simple analysis
  - c. ASAP for some straylight calculations



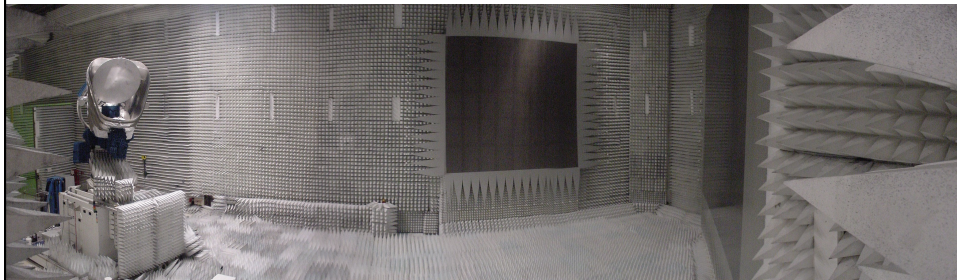
J. Tauber, B-modes Workshop 2015

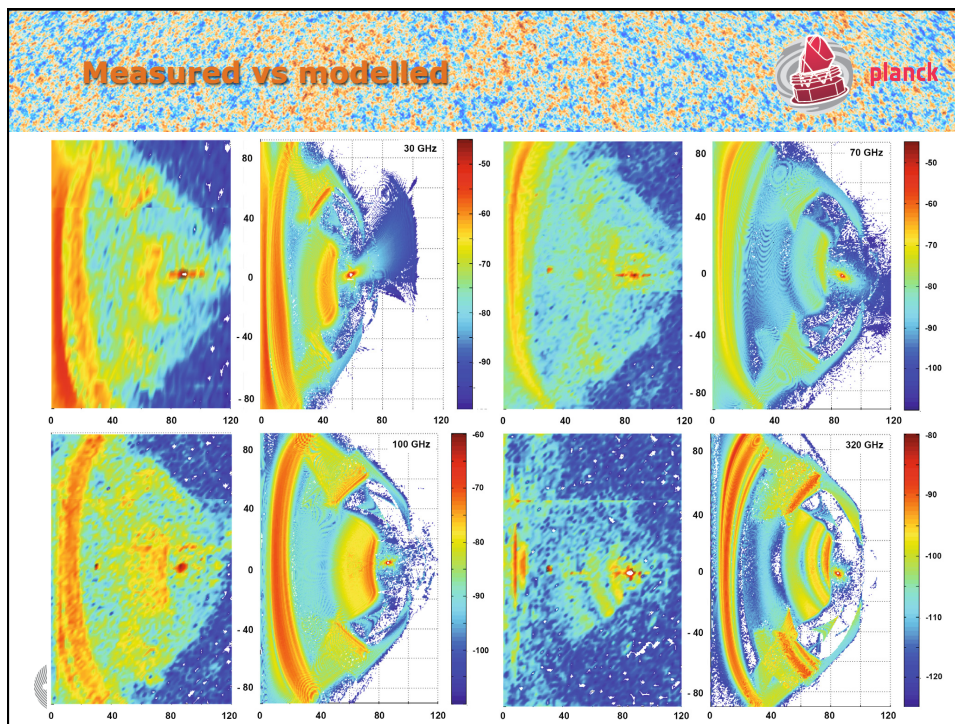
European Space Agency

## Validation of the Planck GRASP model



1. A huge amount of work was put into this validation
2. The GRASP models work quite well but not perfectly
  - a. Main beams can be modelled to an accuracy of a few % in total power
  - b. The highest sidelobe levels differ from the model by a few dB, even after special corrections are made
  - c. Polarization was *not* “validated”
3. Note that even though the Planck analysis relies largely on measured beams, GRASP models enter the analysis in various ways





## Performance in flight

1. Far sidelobe features have consequences on calibration, are detectable in the maps (not at all frequencies) and removed during map-making
  - a. LFI detailed models indicates the importance of broadband
2. Main beams are measured in flight on planets during the surveys (*no dedicated observations*)
  - a. LFI uses Jupiter, 8 passes
  - b. HFI uses Saturn, Jupiter, Mars, 4-5 passes
    - Brendan's talk on time constant deconvolution
3. Even stacking multiple seasons, there isn't enough SNR in the measurements – for scientific analysis "hybrid" beams are built which combine measurements and models
4. There is only one bright *polarized* source in the submm sky: the Crab - it is unfortunately somewhat extended - there are still significant untreated issues in the recovery of polarization angle with respect to ground measurements
  - a. requirements on knowledge of e.g. det pol angle are quite low



J. Tauber, B-modes Workshop 2015



European Space Agency



## In-flight retrieval



An attempt to recover a single physically-motivated geometrical configuration that fits all Planck planet measurements has had only moderate success

1. Estimation of the small-scale properties of the reflector surfaces
  - a. Based on the near side lobes at 217 – 857 GHz:
    - “ruze envelope”
    - “grating lobes”
  - b. Requires very high SNR measurements
    - Measure beams on planets
    - Stack many planet epochs
  - c. Uses additions to GRASP
2. Estimation of the large-scale geometry of the optical system: alignment of SR, PR, FPU; and large-scale reflector deformations
  - a. Based on shape of main beams at 30-353 GHz
  - b. Uses iterative fitting of GRASP models based on POS



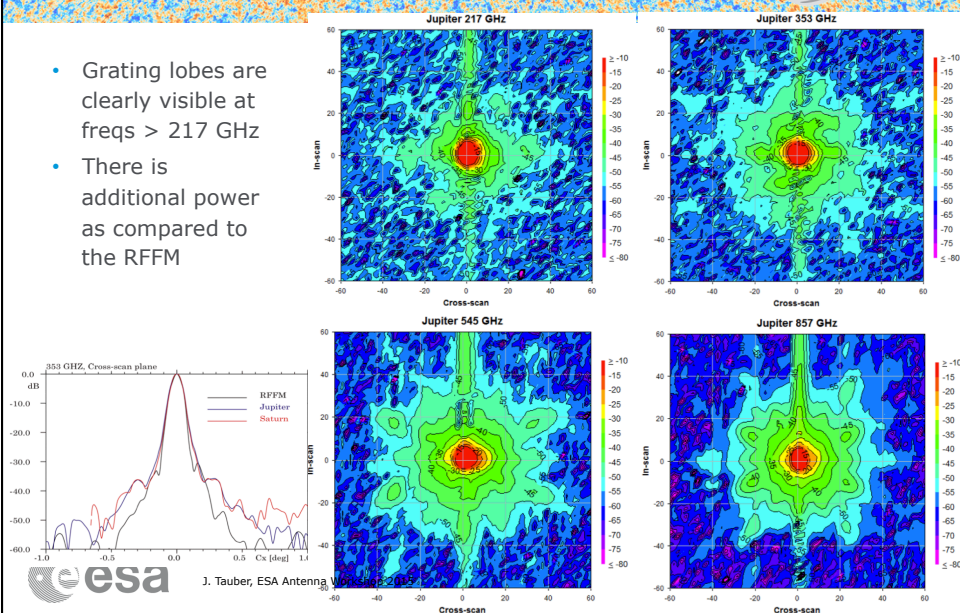
J. Tauber, B-modes Workshop 2015

European Space Agency

## The stacked measurements



- Grating lobes are clearly visible at freqs > 217 GHz
- There is additional power as compared to the RFFM



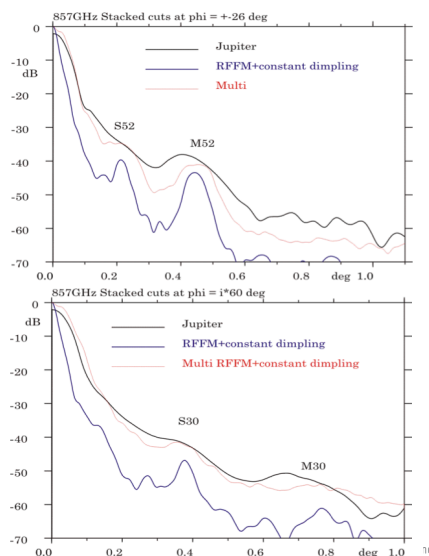
J. Tauber, ESA Antenna Workshop 2015



## Multi-moding



1. The 545 and 857 GHz horns are multi-moded
2. Modelling shows that multi-moding acts to increase the power in the grating lobes, qualitatively explaining the discrepancies at 545 and 857 GHz
3. The model is not understood well enough to allow quantitative fitting



J. Tauber, ESA Antenna Workshop 2015

## Summary of the near-sidelobe analysis



1. Analysis of the in-flight measured grating lobes yields an improved model of the telescope geometry
  - a. Amplification of SR deformations by  $\times 1.2$
  - b. Addition of "constant" dimpling of amplitude  $\sim 4 \mu\text{m}$  to the PR
  - c. Addition of ISM-related sinusoidal deformation on the SR of amplitude  $\sim 4 \mu\text{m}$
2. No evidence for additional "random" (Ruze-like) components on the reflectors
3. Multi-moding can account for the increase in power in the grating lobes at freqs  $> 545$  GHz, but the current understanding of multi-moding is not detailed enough to allow to use this quantitatively
4. The grating lobes add significant power to the near-sidelobes (e.g.  $\sim 0.1\%$  at 217 GHz)
1. Overall the mechanical behavior of the Planck reflectors in flight is as predicted – some of the differences could be due to the (anomalous) in-orbit cooldown
5. There remain differences between measurement and model which are of the same order as the new elements of the model... e.g. at 217 GHz the integrated pattern difference is  $\sim 0.1\%$  over angles  $< 1^\circ$  from peak



J. Tauber, B-modes Workshop 2015

European Space Agency

## Overall geometry recovery



1. In principle you can use the fact that many detectors use the same telescope at different frequencies and focal plane locations to recover the properties of the telescope
2. In practice
  - a. There are quite a lot of degeneracies in the geometrical parameters
  - b. A single-parameter merit function is quite crude
  - c. The LFI is not very sensitive to small deformations
  - d. The HFI response is seriously complicated by the bolometer time response
    - the HFI “map-making” beams are *not* optical beams
    - The bolometer time response is “measured” in flight
    - Only one Mars pass was designed to separate optical from time response (satellite spin-up)
3. We can converge on a reasonable configuration
  - a. Focal plane and reflectors are where expected (within 0.5 mm)
  - b. it represents all measurements only up to a few x0.1% (TBC)



J. Tauber, B-modes Workshop 2015

European Space Agency

## Misc issues



1. Broad-band aspects have probably been underestimated
  - a. Sidelobes
  - b. Polarization leakage
2. Vocabulary is a big issue
  - a. Meeting of many different disciplines – optical & RF engineers, radio and FIR astronomers
  - b. Requirements were set in different languages
  - c. “Calibration” did not mean the same to different people
3. Coordinate systems were not used consistently across teams
  - a. Polarization is particularly painful
4. Data and model results were not fully utilized (the “ownership” problem)
5. Contamination and emissivity: not an issue for Planck
6. Transformation of optical information into something useable for science is a complex process: optical beam -> scanning beam -> effective beam -> window function – it is quite slow and one of the significant cogs in the data analysis machine...



J. Tauber, B-modes Workshop 2015

European Space Agency

## Some lessons learned – in view of next generation CMB missions



1. Optics is a system issue: institute a single "authority" for all optical aspects, and include them all, starting at design level
  - a. Manufacture, *on-ground validation*, transition to in-orbit
  - b. "calibration" in flight – need for dedicated measurements ?
  - c. Use of optical information in flight
2. CFRP technology is at the limit of what Planck could accept
  - a. It has serious mechanical predictability issues
  - b. On-ground characterization (in the IR) is complex
3. HFI-like optics are very difficult to characterize and simulate accurately
4. The time response of bolometers complicates significantly the understanding of optics
5. Broad-band aspects should not be underestimated
6. GRASP is a great tool but
  - a. It is complex and heavy to operate
  - b. It has some prediction shortcomings



Polarization has hardly been touched by Planck from an optical point of view....

J. Tauber, B-modes Workshop 2015

European Space Agency