TITLE: **LFI REQUIREMENTS FOR RFQM PERFORMANCE VERIFICATION TEST**

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1 INTRODUCTION AND SCOPE

Scope of this document is to define LFI requirements for the beam pattern measurements will be performed on the Planck RFQM telescope / FPU assembly by the Planck Industry contractor. The requirements are presented for the measurement of the main beam, the intermediate zone, the spillover zone, and the straylight region, respectively. These regions (in position and shape) have been identified for each considered beam pattern, in the S/C coordinate system. The accuracy level to be reached in the measurement of each region is reported.

The current requirements result from a compromize between *i)* the acquisition time, the duration, the feasibility, and the cost of the test campaign and *ii)* the need to verify that phenomena possibly not included in the numerical model – like misalignment effects on spillover, dust, surface tolerances and deformations, influence of mirror supporting structures, and higher order MrGTD contributions – are not critical for science.

We also address the specific requirements on polarisation measurements for the main beams.

2 APPLICABLE DOCUMENTS

[AD 1] F. Villa, M. Sandri, C. Burigana, *LFI requirements for RFQM pattern measurements,* Issue 1.0

3 REFERENCE DOCUMENTS

[RD 1] J.Ph. Bernard, C. Chamayou, I. Ristorcelli, J. Brossard, E. Gleeson, A. Murphy, V. Yurchenko, J.M. Lamarre, Y. Longval, B. Maffei, *HFI requirements for the RFQM performance verification test*, Issue 1, November 2003

[RD 2] *Planck Telescope Design Specification*, SCI-PT-RS-07024, Issue 1, August 2000

[RD 3] *Planck/LFI: Main Beam Locations and Polarization Alignment for the LFI Baseline FPU*, PL-LFI-PST-TN-027

[RD 4] *LFI Pointing Requirements* Issue/Rev. 1.2, PL-LFI-PST-TN-023_1.2

[RD 5] *LFI Optical Interfaces*, PL-LFI-PST-TN-034

[RD 6] C. Burigana, P. Natoli, N. Vittorio, N. Mandolesi, M. Bersanelli, *Straylight Contamination from Internal Solar System Bodies in PLANCK/LFI Observations*, Int. Rep. ITeSRE 272/2000, April 2000

[RD 7] M. Sandri, F. Villa, R. Nesti, C. Burigana, M. Bersanelli, N. Mandolesi, 2003, *Trade-off between angular resolution and straylight contamination in CMB anisotropy experiments. I. Pattern simulations*, A&A, submitted, astro-ph/0305152

[RD 8] C. Burigana, M. Sandri, F. Villa, D. Maino, R. Paladini, C. Baccigalupi, M. Bersanelli, N. Mandolesi, 2003, *Trade-off between angular resolution and straylight contamination in CMB anisotropy experiments. II. Straylight evaluation*, A&A, submitted, astro-ph/0303645

[RD 9] C. Burigana, P. Natoli, N. Vittorio, N. Mandolesi, M. Bersanelli, *In-flight main beam reconstruction for PLANCK/LFI*, (2002), Experimental Astronomy, 12/2, 87-106, 2001

[RD 10] K. Pontoppidan, *Technical description of GRASP8*, TICRA, March 2002

[RD 11] *PLANCK RFQM test requirements*, H-P-3-ASP-SP-0561

4 RFQM CONFIGURATION

The RFQM will be very close to the flight design, including QM reflectors, QM telescope structure, part of the cryo-structure (3rd groove + baffle) in order to provide a characterization of the RF performance.

4.1 LFI FOCAL PLANE LAYOUT

The LFI Focal Plane layout for the RFQM test campaign is reported in Figure 1: the feed horn #18 at 70 GHz, the feed horn #24 at 44 GHz, and the feed horn #27 at 30 GHz.

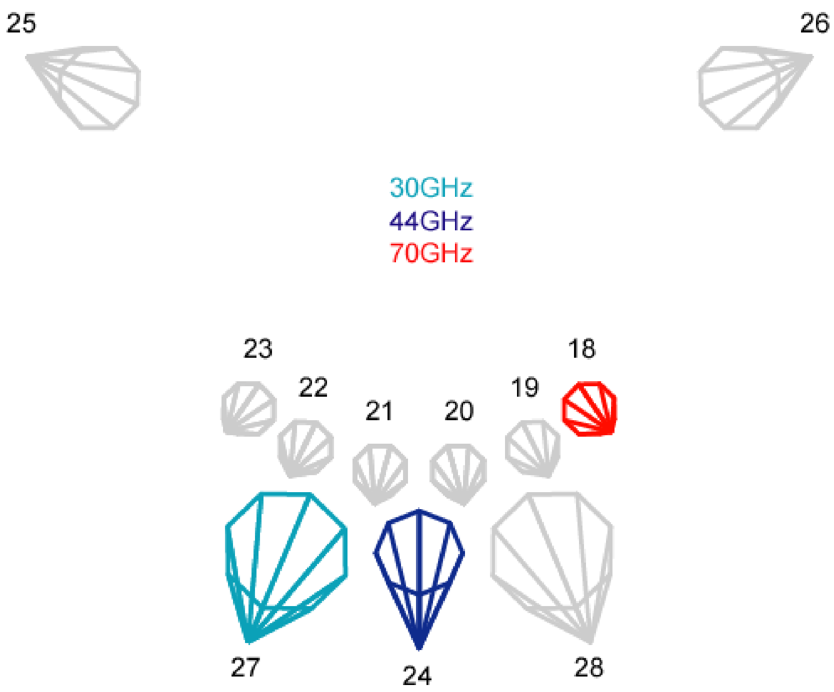

Figure 1: LFI focal plane layout. The horns will be used for RFQM test are in colour.

4.2 REFERENCE FRAME

The angular requirements are reported in the S/C coordinate system [RD 2], in order to harmonize requirements with HFI [RD 1], whereas in the original note they were defined in the Main Beam coordinate system [AD 1].

5 MAIN BEAMS

Each main beam shall be measured in a spherical regular grid defined in the S/C coordinate system, in the co– and cross– polar basis. The predicted (θ_{SC},φ_{SC}) values for the centre of each beam are reported in Table 1. These values should be coincide with the power peak of the beam. This latter would be derived from the measurements with an uncertainty smaller than 0.5 arcmin (i.e. the final pointing accuracy).

Table 1 Spherical field grid centre definition for each main beam measurement.

Main Beam	$\theta_{(SC)}$ (°)	$\varphi_{(SC)}$ (°)
LFI 27	88.8957	–1.9310
LFI 24	89.0536	0.0000
LFI 18	87.2024	2.4600

Table 2 Angular region and angular step for main beam measurements.

Beam	θ range (°)	φ range (°)	Δθ (°)	Δφ (°)	N. pts θ	N. pts φ
LFI 27	[87.4, 90.4]	[-3.4,-0.4]	0.01	0.01	301	301
LFI 24	[87.5, 90.5]	[-1.5,1.5]	0.01	0.01	301	301
LFI 18	[86.2, 88.2]	[1.5,3.5]	0.007	0.007	287	287

We would like to measure the main beam in an extended angular region where we would map the aberrations due to the optics at a level lower than –30 dB. The angular step is close to the final pointing accuracy requirements in order to cross-check the on-ground and in-flight measurements without any additional systematics, like interpolation.

5.1 dB – LEVEL ACCURACY

In order to assess the accuracy for main beam measurements three considerations are needed. First of all the uncertainty on the measurements will reflects in the uncertainty on the FWHM estimation or equivalently on the estimation of the beamwidth, σ, if Gaussian profile is assumed. Secondly the uncertainty on σ will reflect on the error on the power spectrum reconstruction, specially at high multipoles. Finally the requirement on the beamwidth shall not exceed the uncertainty derived from the in–flight beam reconstruction for which the pointing accuracy impacts substantially (see [RD 4] and [RD 6]).

A 0.5' of pointing requirement permits to measure the beamwidth with an accuracy of ±6 arcsec. This gives directly the requirement. At 70 GHz (13' of FWHM or σ = 5.52) means an error of 1.8%.

In order to translate this error in accuracy of iso–dB levels, we use the approximation that the beam can be model by a symmetric Gaussian function:

$$R(\theta) = e^{-\frac{1}{2}\frac{\theta^2}{\sigma^2}}$$

In decibel (dB) the response can be written as

$$R^{(dB)}(\theta) = -\frac{5}{\ln(10)} \cdot \frac{\theta^2}{\sigma^2}$$

We can estimate the uncertainty on R by

$$\delta R^{(dB)} = \sqrt{\left(\frac{\partial R^{(dB)}}{\partial \sigma}\right)^2 \delta\sigma^2} = 2 \cdot \frac{R^{(dB)}(\theta)}{\sigma} \delta\sigma$$

we used also

$$\theta^2 = -\frac{\ln(10)}{5} R^{(dB)}(\theta) \cdot \sigma^2$$

Then, we obtain that

$$\frac{\delta R^{(dB)}}{R^{(dB)}} = 2 \cdot \frac{\delta\sigma}{\sigma} = 2 \cdot 1.8\% = 3.6\%$$

In the accuracy we require for the main beam measurements is reported. The accuracy is given in dB for each iso–dB level of interest below the main beam peak. The values in table shall be applied to all the LFI channels.

Table 3 Accuracy requirements for main beam measurements.

Iso–Level dB	Accuracy dB
–3	± 0.1
–5	± 0.2
–10	± 0.4
–15	± 0.5
–20	± 0.7
–40	± 1.4
–60	± 2.2

At these levels only these measurements will permit us a good knowledge of the pattern with a real telescope and check the simulations, since the in flight main beam measurements with a good resolution will be limited to about –(20 ÷ 30) dB.

5.2 REQUIREMENTS ON POLARIZED MAIN BEAMS

For the feed horn LFI27 and LFI18, the co– and cross– polar components shall be measured in amplitude and phase, for the two polarization X and Y. For X and Y polarization measurements we will provide OMT.

The definition of the orientation axis is described in Table 4. For example, for the feed horn 27, the co–polar component shall be measured along the direction at 157.5° while the cross– polar component along the direction at 67.5°, for the X arm and viceversa for the Y arm.

With the six parameters required (co– and cross– polar amplitude for main arm, co– and cross– polar amplitude for side arm, co– polar to cross– polar phase difference for main arm, and co– polar to cross–polar phase difference for side arm) we can recostruct the Jones matrix.

The phase accuracy has to be better than few degrees of phase. This is based on the fact that we should detect the cosmological E-mode with a signal-to-noise of 10:1 or so in the binned C_l spectrum, implying the requirement of systematic phase errors <~ 0.1 radian. Of course, the phase measurements have to be calibrated: the "zero" of the phase of the cross– polar component has to be the same of the co– polar one.

Table 4 Definition of the axis where shall be measured the polarized main beam.

Beam	co– polar	cross– polar
LFI 27	157.5°	67.5°
LFI 24	0°	90°
LFI 18	22.3°	112.3°

The requirements specifically on polarization measurements (cross– polar component) are the same of those reported for the co– polar component. In terms of accuracy, this means that the accuracy required in the cross– polar component measurement (normalized to the co– polar component maximum) is the same of that required in co– polar measurement.

6 FAR SIDE LOBES

As for the main beam measurements, the amplitude of two orthogonal components of the field shall be measured during the test. Three different zones have been identified:

1. Intermediate Zone
2. Spillover Zone
3. Straylight Zone

In addition, 13 high resolution cuts would be required.

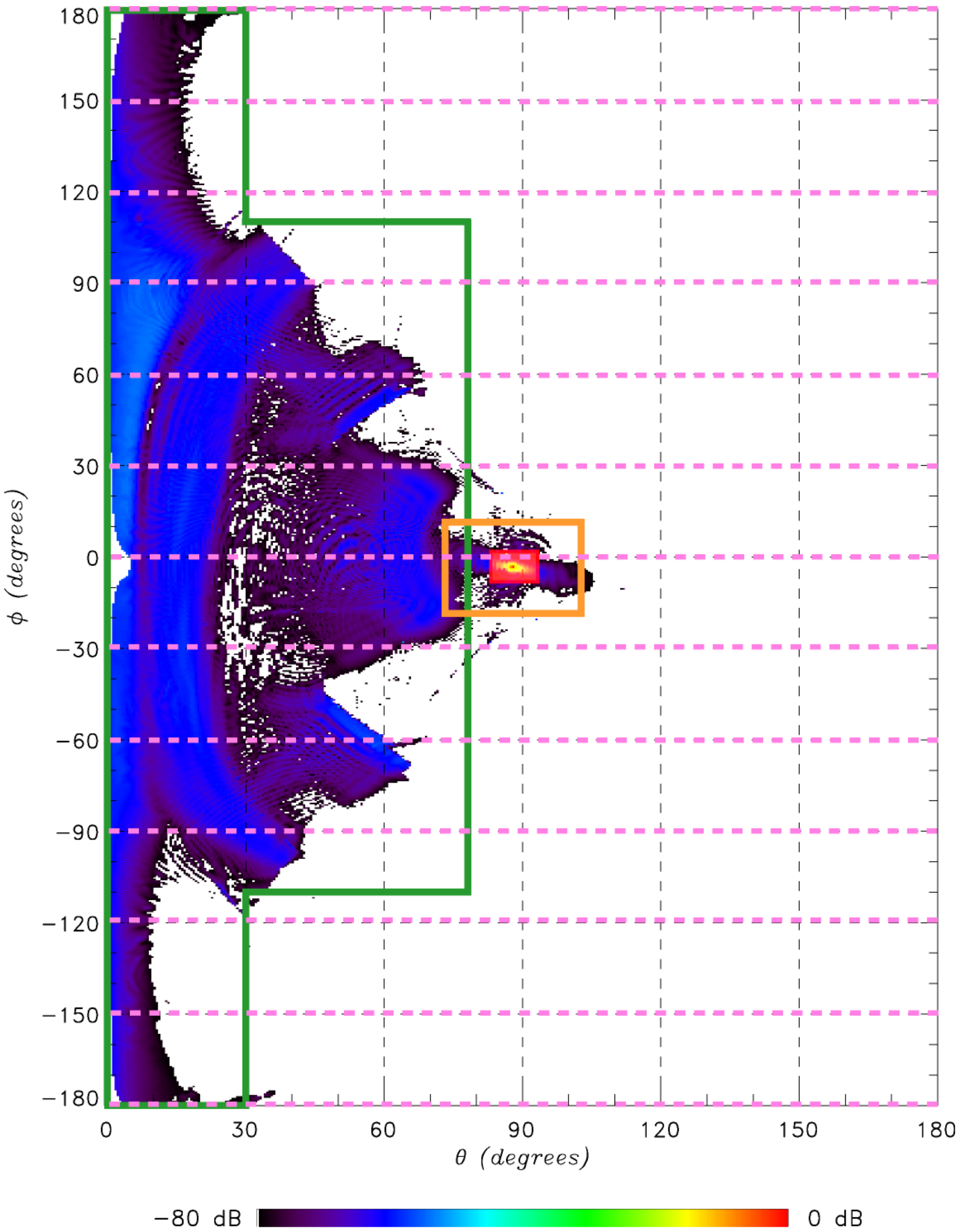

Figure 2 Spillover and intermediate zone identified for the LFI 27 beam pattern.

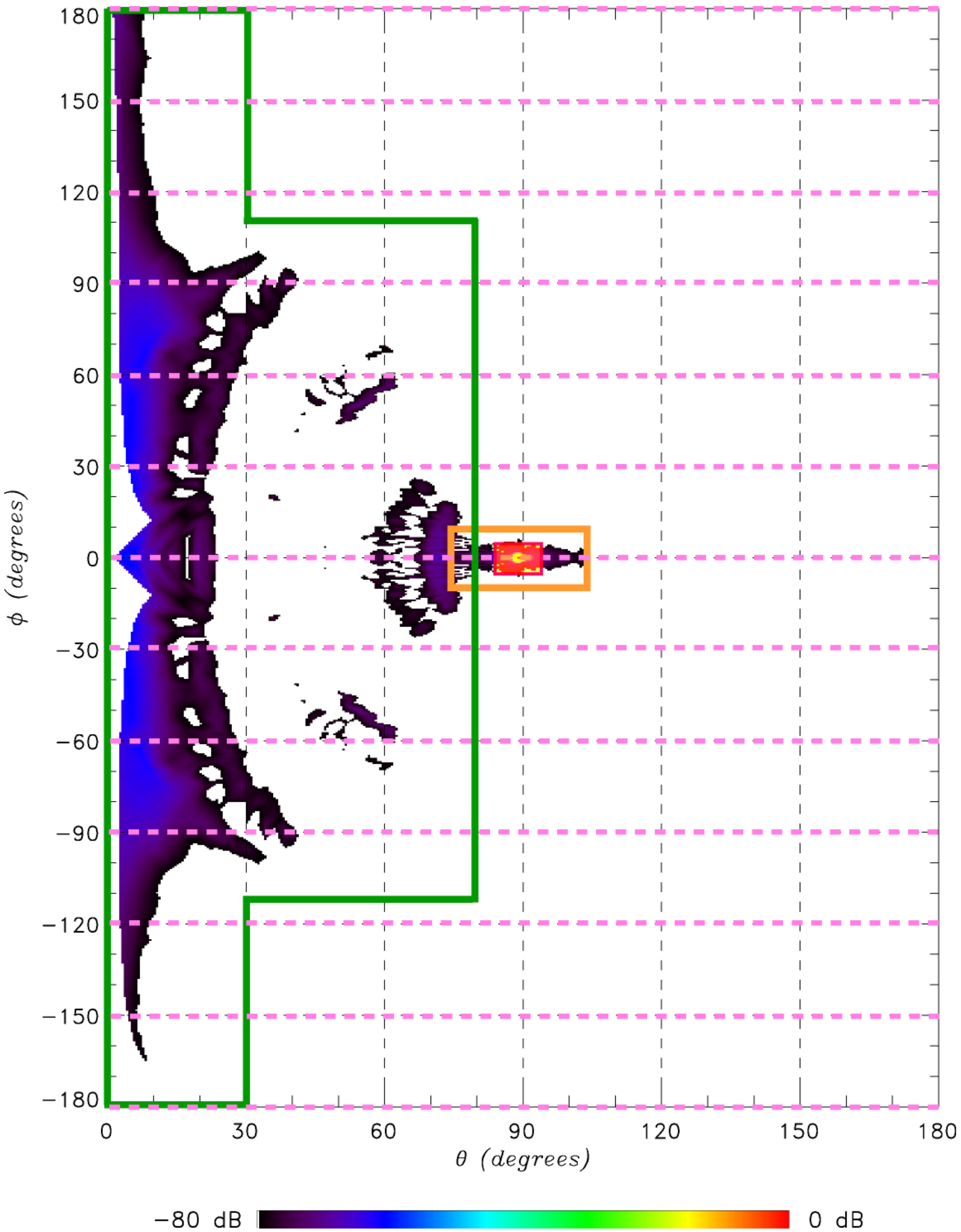

Figure 3 Spillover and intermediate zone identified for the LFI 24 beam pattern.

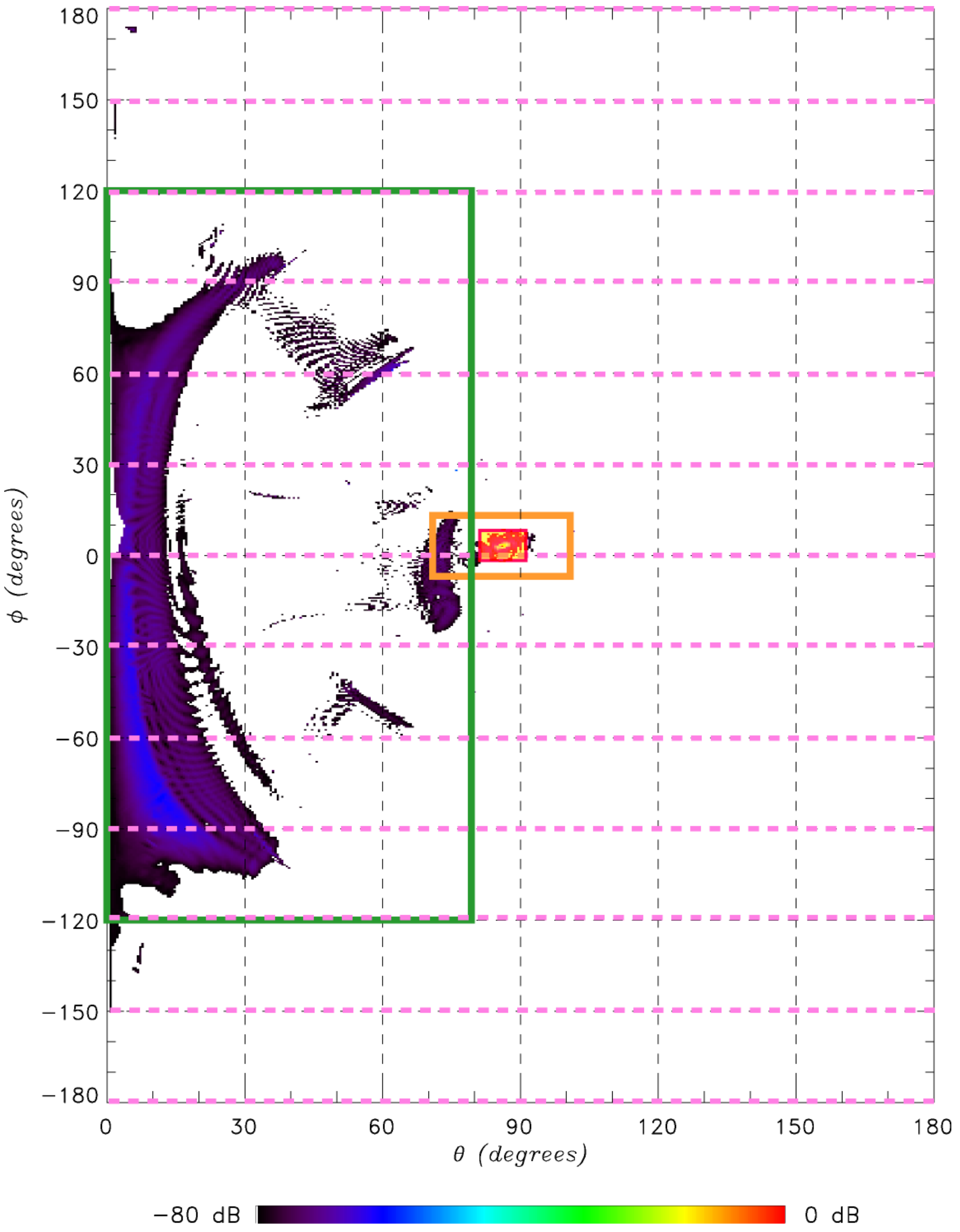

Figure 4 Spillover and intermediate zone identified for the LFI 18 beam pattern.

6.1 INTERMEDIATE ZONE: ANGULAR RESOLUTION AND STEP

The intermediate zone is defined as the antenna pattern area surrounding the main beam. Inside the intermediate zone, two regions have been identified, as shown in Figure 2, Figure 3, and Figure 4.

Beam	θ range[1] (°)	φ range (°)	Δθ (°)	Δφ (°)	N. pts TOT
LFI 27	$\lvert\theta_r\rvert > 5 \wedge \lvert\theta_r\rvert \le 15$	$\lvert\varphi_r\rvert > 5 \wedge \lvert\varphi_r\rvert \le 15$	0.5	0.5	3280
	$\lvert\theta_r\rvert \le 5$	$\lvert\varphi_r\rvert \le 5$	0.1	0.1	10201
LFI 24	$\lvert\theta_r\rvert > 5 \wedge \lvert\theta_r\rvert \le 15$	$\lvert\varphi_r\rvert > 5 \wedge \lvert\varphi_r\rvert \le 10$	0.4	0.4	3200
	$\lvert\theta_r\rvert \le 5$	$\lvert\varphi_r\rvert \le 5$	0.1	0.1	10201
LFI 18	$\lvert\theta_r\rvert > 5 \wedge \lvert\theta_r\rvert \le 15$	$\lvert\varphi_r\rvert > 5 \wedge \lvert\varphi_r\rvert \le 10$	0.2	0.2	12650
	$\lvert\theta_r\rvert \le 5$	$\lvert\varphi_r\rvert \le 5$	0.1	0.1	10201
$\sum_v$ N. pts = 49733					

Table 5 Angular region and angular step for the intermediate region measurements.

6.2 SPILLOVER ZONE: ANGULAR RESOLUTION AND STEP

Beam	θ range (°)	φ range (°)	Δθ (°)		Δφ (°)		N. pts θ		N. pts φ	
			Req	Goal	Req	Goal	Req	Goal	Req	Goal
LFI 27	[0,30]	[-180,-110] U [110,180]	5	2	5	2	7	16	30	72
	[0,80]	[-110,110]	2	–	2	–	41	–	111	–
LFI 24	[0,30]	[-180,-110] U [110,180]	5	2	5	2	7	16	30	72
	[0,80]	[-110,110]	2	–	2	–	41	–	111	–
LFI 18	[0,80]	[-120,120]	2	–	2	–	41	–	121	–
$\sum_v$ N. pts = 14483 (Req) – 16367 (Goal)										

Table 6 Angular region and angular step for the spillover region measurements.

[1] With $\theta_r = \theta_{sc} - \theta_{sc\_max}$ and $\varphi_r = \varphi_{sc} - \varphi_{sc\_max}$ where θ_{sc_max} and φ_{sc_max} are the coordinates of the main beam peak (see **Table 1**). Between the two coloums "**θ range**" and "**φ range**" a logic OR has to be applied.

6.3 Stray Light Zone: Angular Resolution And Step

Beam	θ range (°)	φ range (°)	Δθ (°)		Δφ (°)		N. pts θ		N. pts φ	
			Req	Goal	Req	Goal	Req	Goal	Req	Goal
LFI 27	[140,180]	[0,360]	5	2	5	2	9	21	73	181
LFI 24	[140,180]	[0,360]	5	2	5	2	9	21	73	181
LFI 18	[140,180]	[0,360]	5	2	5	2	9	21	73	181
$\sum_v$ N. pts = 1971 (Req) – 11403 (Goal)										

Table 7 Angular region and angular step for the straylight region measurements.

6.4 High Resolution Cuts

Beam	θ range (°)	| φ | (°)	Δθ (°)		N. pts θ	
			Req	Goal	Req	Goal
LFI 27	[0,180]	0, 30, 60, 90, 120, 150, 180	1	0.5	2353	4693
LFI 24	[0,180]	0, 30, 60, 90, 120, 150, 180	1	0.5	2353	4693
LFI 18	[0,180]	0, 30, 60, 90, 120, 150, 180	1	0.5	2353	4693
$\sum_v$ N. pts = 7059 (Req) – 14079 (Goal)						

Table 8 High resolution cuts with angular step.

6.5 dB – Level Accuracy

For each spillover zone the maximum has been found. The requirement on the accuracy of the spillover zone measurements is motivated by the necessity to provide a reasonably accurate check of optical simulations to be able to reliably subtract the Galactic straylight contamination in the time ordered data during the data analysis. From recent accurate studies [RD 7][RD 8] and very recent simulations and 70 GHz, the expected peak-to-peak (RMS) Galactic straylight contamination is of about 6–7 μK (0.3–1.3 μK) both from the intermediate pattern region and the far sidelobes at 30 GHz, and of about 3μK (0.3 μK) at 70 GHz. Of course, only if the beam pattern is accurately known this spurious signal can be reduced in the data analysis by simulating the effect on the sky maps derived from Planck. An uncertainty of 3 dB (a factor 2) on the pattern measurement in the spillover zone would imply in practice that the correction for this effect will be affected by an uncertainty level similar to level of the effect that has to be subtracted. Our requirements should be then significantly better, particularly close to the maximum spillover zone.
The accuracy is set to be 1 dB maximum at the maximum level of the spillover reported in Table 9. At various dB – isolevel the accuracy requirements are listed in Table 10.

This requirements assure that, assuming the same pattern in flight, the straylight effect can be reduced during the data analysis to about 25% of the unsubtracted one, i.e. in terms of peak-to-peak signal to few uK at 30 GHz and to less than 1 μK at 70 GHz, which is the best cosmological channel for LFI.

Beam	Max dBi	Max dB below the peak	(θ,ϕ) coordinates	Accuracy at this level
LFI 27	–3.52	–54.45	(7°,54°)	1 dB
LFI 24	–5.59	–59.65	(3°,0°)	1 dB
LFI 18	–5.33	–63.71	(12°,-75°)	1 dB

Table 9 Maximum spillover signal and accuracy at maximum for each beam.

Channel	dB level below the peak	accuracy dB
LFI 27	54 ÷ 66	1
	67 ÷ 70	2
	71 ÷ 80	3
LFI 24	60 ÷ 66	1
	67 ÷ 70	2
	71 ÷ 80	3
LFI 18	64 ÷ 66	1
	67 ÷ 70	2
	71 ÷ 80	3

Table 10: Accuracy requirements at various dB – isolevels for the far sidelobes and intermediate zone measurements.

Of course, an accuracy of 1dB is required in each spillover region where, possibly, the measured response is larger than 54, 60, 64 dB respectively for LFI 27, 24, 18.

Down to –80 dB, for each frequencies, an accuracy of 3 dB in the measurement has to be reach in the straylight zone, according to the statement: "The sensitivity of the measurement shall be such as to verify the stray requirements with a margin of -3 dB", as reported in the MoM of the TWG #7, page 11. In particular, we need to be confident that the pattern is quite flat at level close to the requirement, reported in Table 11 for each channel.

Channel	Rejection from Sun dB	dB level below the peak	accuracy dB
LFI 27	94	94	3
LFI 24	96	96	3
LFI 18	101	101	3

Table 11 Accuracy required for stray light zone measurements

7 TOTAL NUMBER OF MEASUREMENT POINTS

	LFI 27	LFI 24	LFI 18	TOTAL
Main Beam (dual pol, co and cross)	181202	90601	164738	436541
Intermediate Zone	13481	13401	22851	49733
Spillover Zone	4761 (5703)	4761 (5703)	4961	14483 (16367)
Straylight Zone	657 (3801)	657 (3801)	657 (3801)	1971 (11403)
High Resolution Cuts	2353 (4693)	2353 (4693)	2353 (4693)	7059 (14079)
TOTAL	202454 (208880)	111773 (118199)	195560 (201044)	**509787** (**528123**)

Table 12 Summary of the number of measurement points required for the RFQM test for each channel and sky zone (between parenthesis the goal is reported).