Calibration strategy and mitigation of systematic effects in the QUIJOTE MFI wide survey

José Alberto Rubiño-Martín (IAC), on behalf of the QUIJOTE Collaboration

GOBIERNO DE ESPAÑA
MINISTERIO DE CIENCIA E INNOVACIÓN
UNIÓN EUROPEA
Fondo Europeo de Desarrollo Regional
"Una manera de hacer Europa"
Ref. de la ayuda: ICTS-2019-03-IAC-12

CMB Systematics and Calibration focus workshop
Kavli IPMU, 29 November -2 December 2020

The QUIJOTE Collaboration

(http://research.iac.es/project/cmb/quijote)

The QUIJOTE experiment

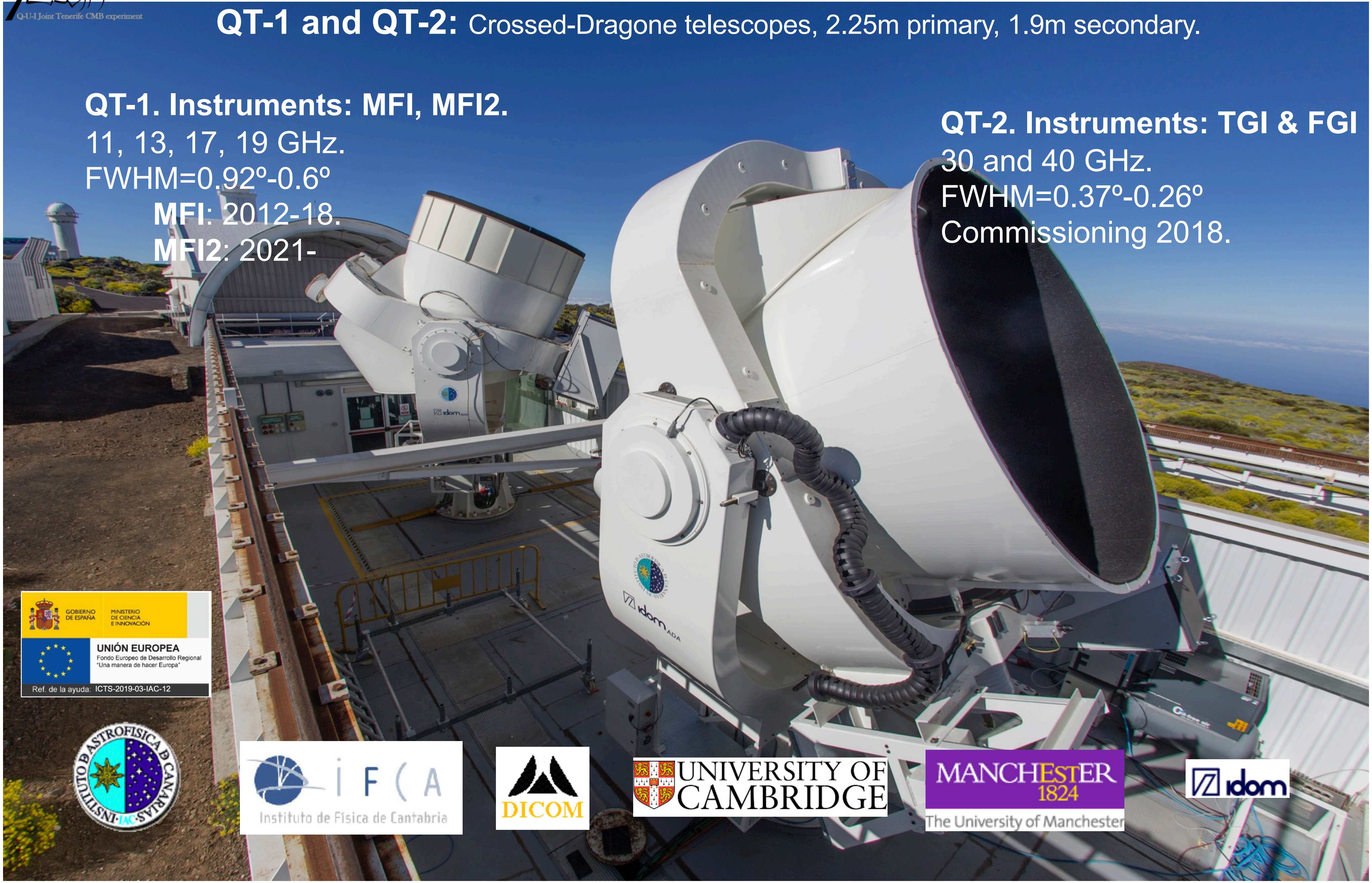
Quijote
Q-U-I Joint Tenerife CMB experiment

RADIO FOREGROUNDS

QT-1 and QT-2: Crossed-Dragone telescopes, 2.25m primary, 1.9m secondary.

QT-1. Instruments: MFI, MFI2.
11, 13, 17, 19 GHz.
FWHM=0.92º-0.6º
MFI: 2012-18.
MFI2: 2021-

QT-2. Instruments: TGI & FGI
30 and 40 GHz.
FWHM=0.37º-0.26º
Commissioning 2018.



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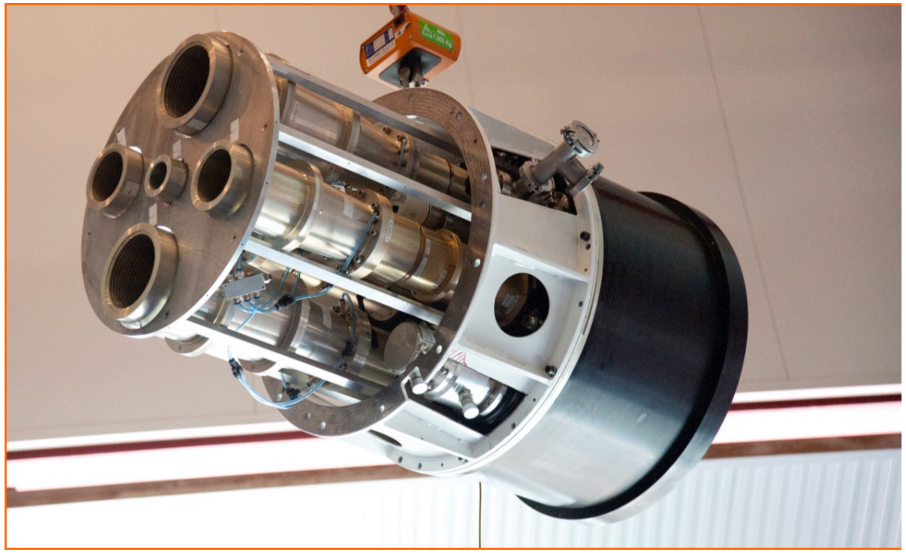
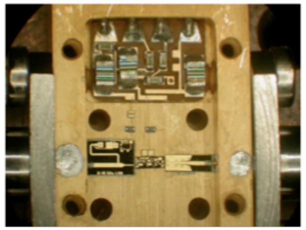
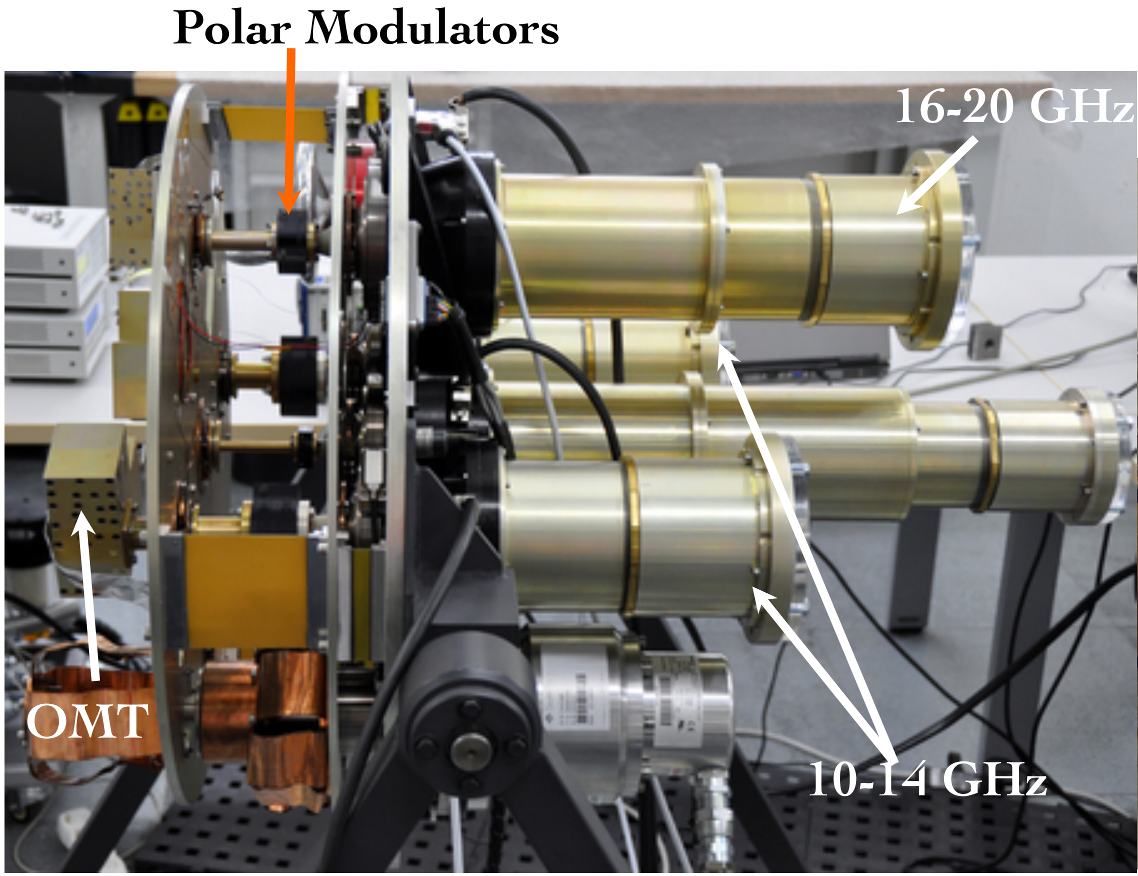
Quijote
Q-U-I Joint Tenerife CMB experiment

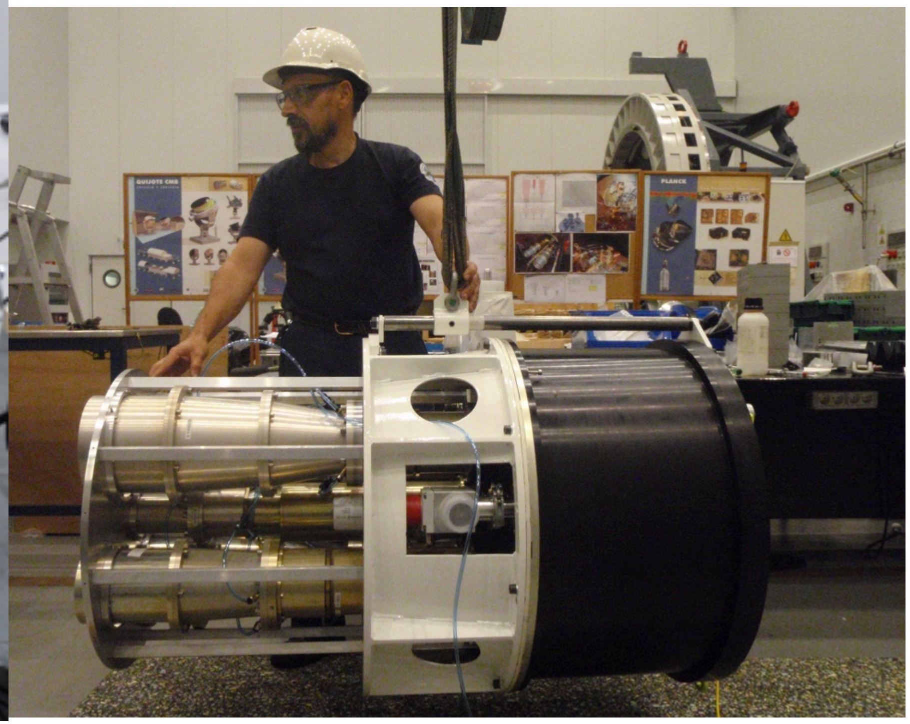
MFI Instrument (10-20 GHz)



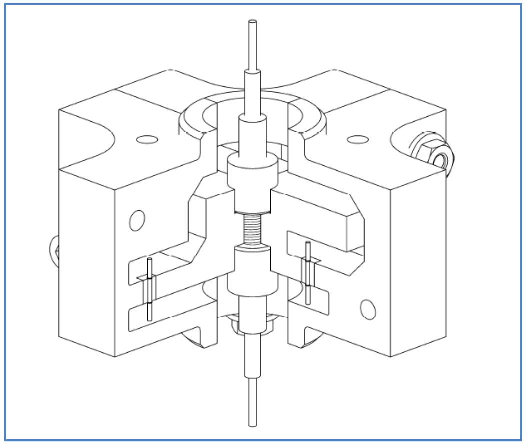
- **Operation**: Nov. 2012 – Dec. 2018.
- 4 horns, 32 channels. Covering 4 frequency bands: 11, 13, 17 and 19 GHz.
- **Sensitivities**: ~400-600 μK $s^{1/2}$ per channel.

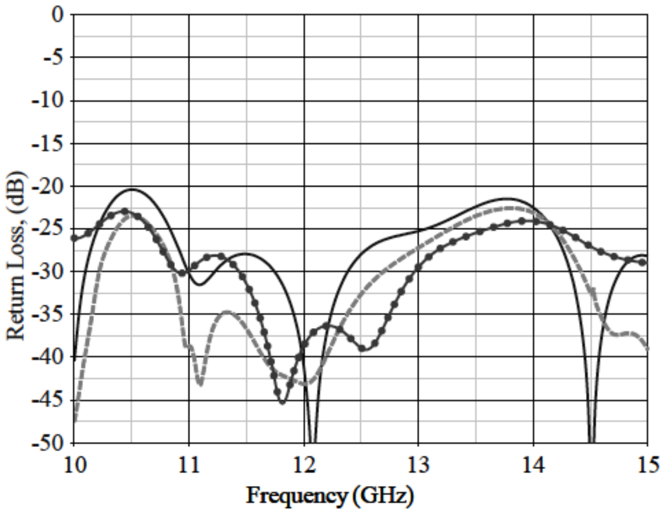

LNA

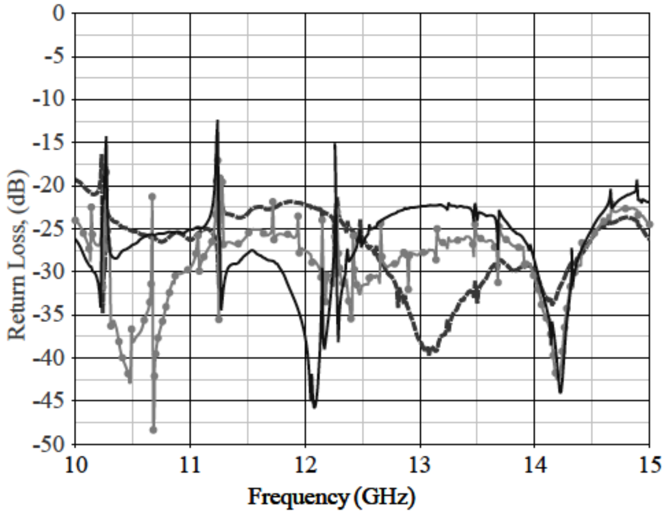


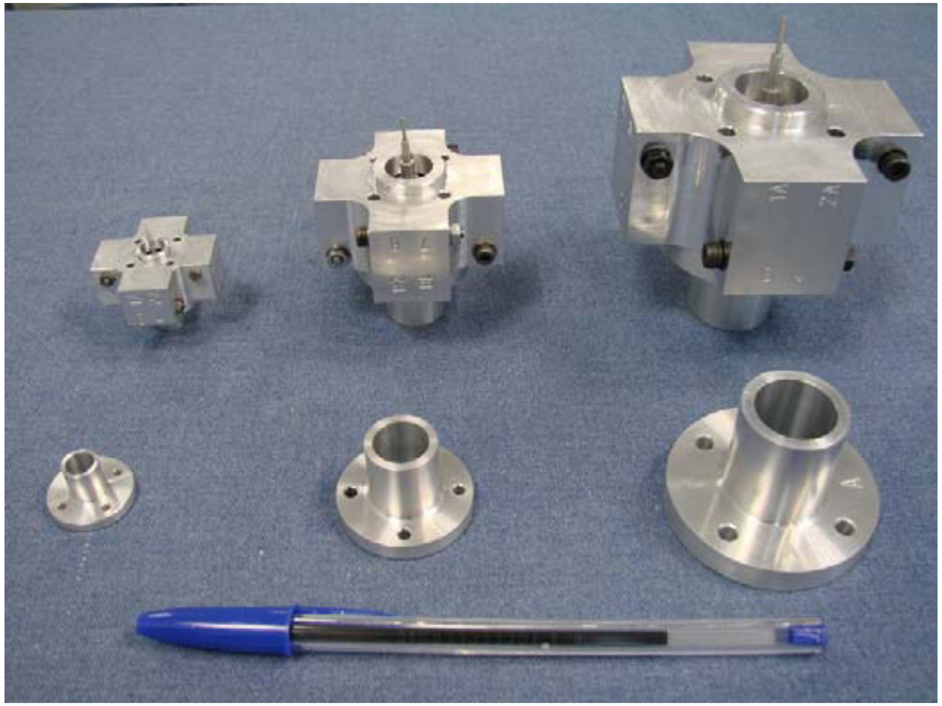


MFI Instrument (10-20 GHz). Polar modulator.

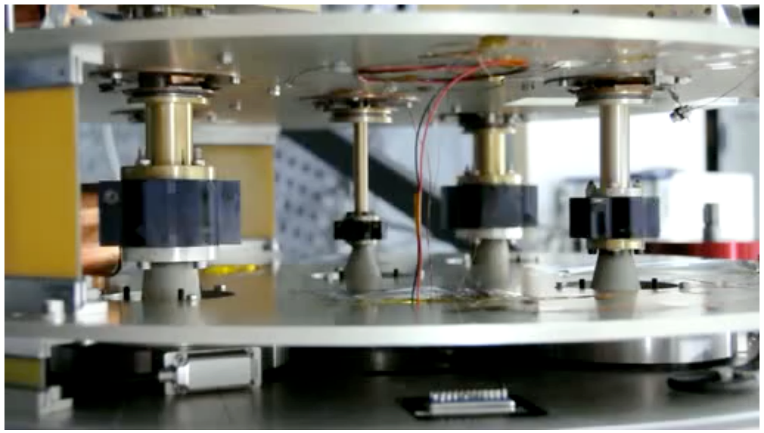








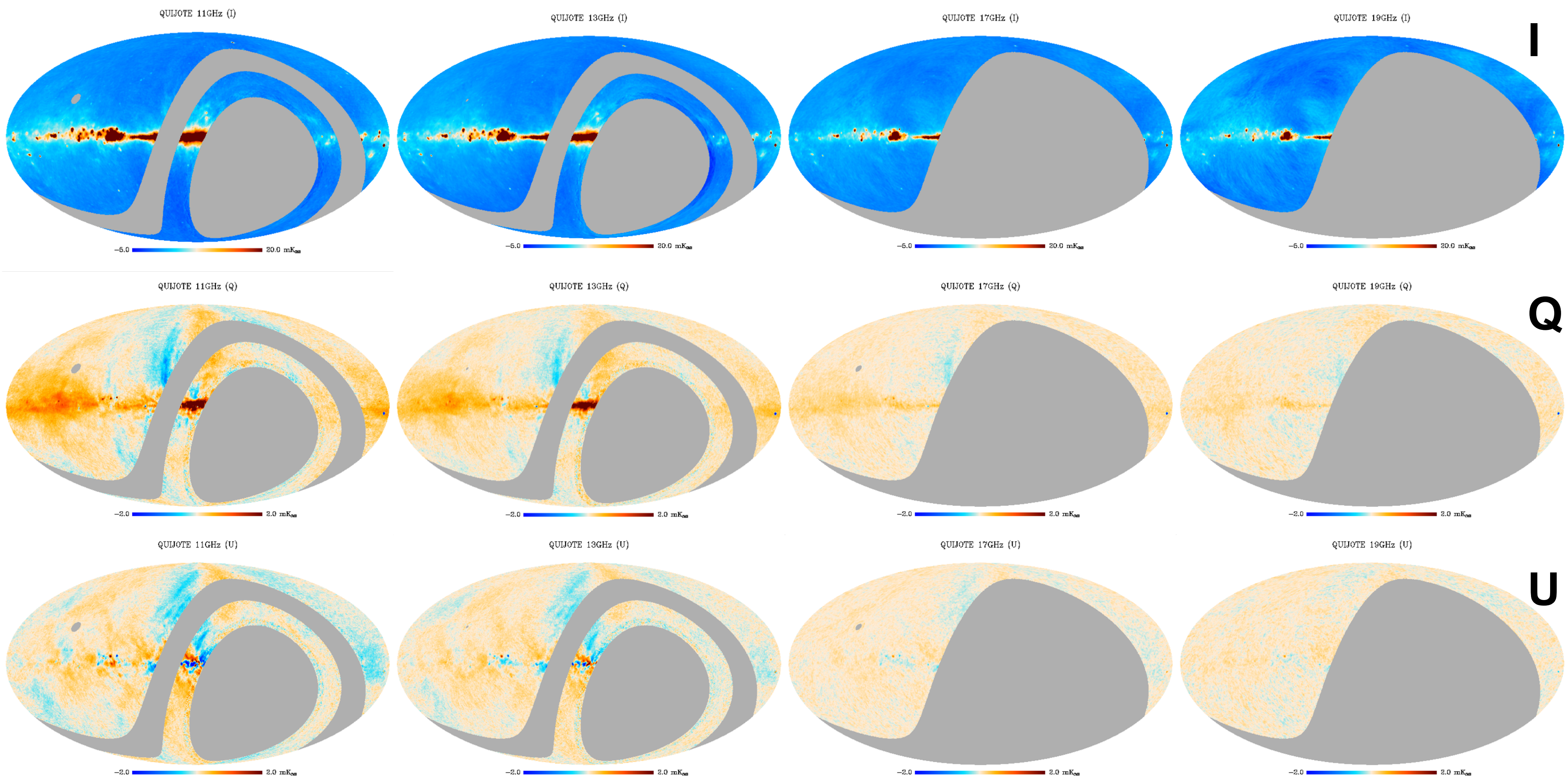
"HWP": a polar modulator based on a turnstile junction, in waveguide. Advantages: broad band, cooled down in the criostat, and high performance (Return Losses < -20dB, insertion losses < -0.15dB, isolation < -40 dB) .



Wide survey with the QUIJOTE MFI (10-20 GHz)

Preliminary maps

(Smoothed to 1º)

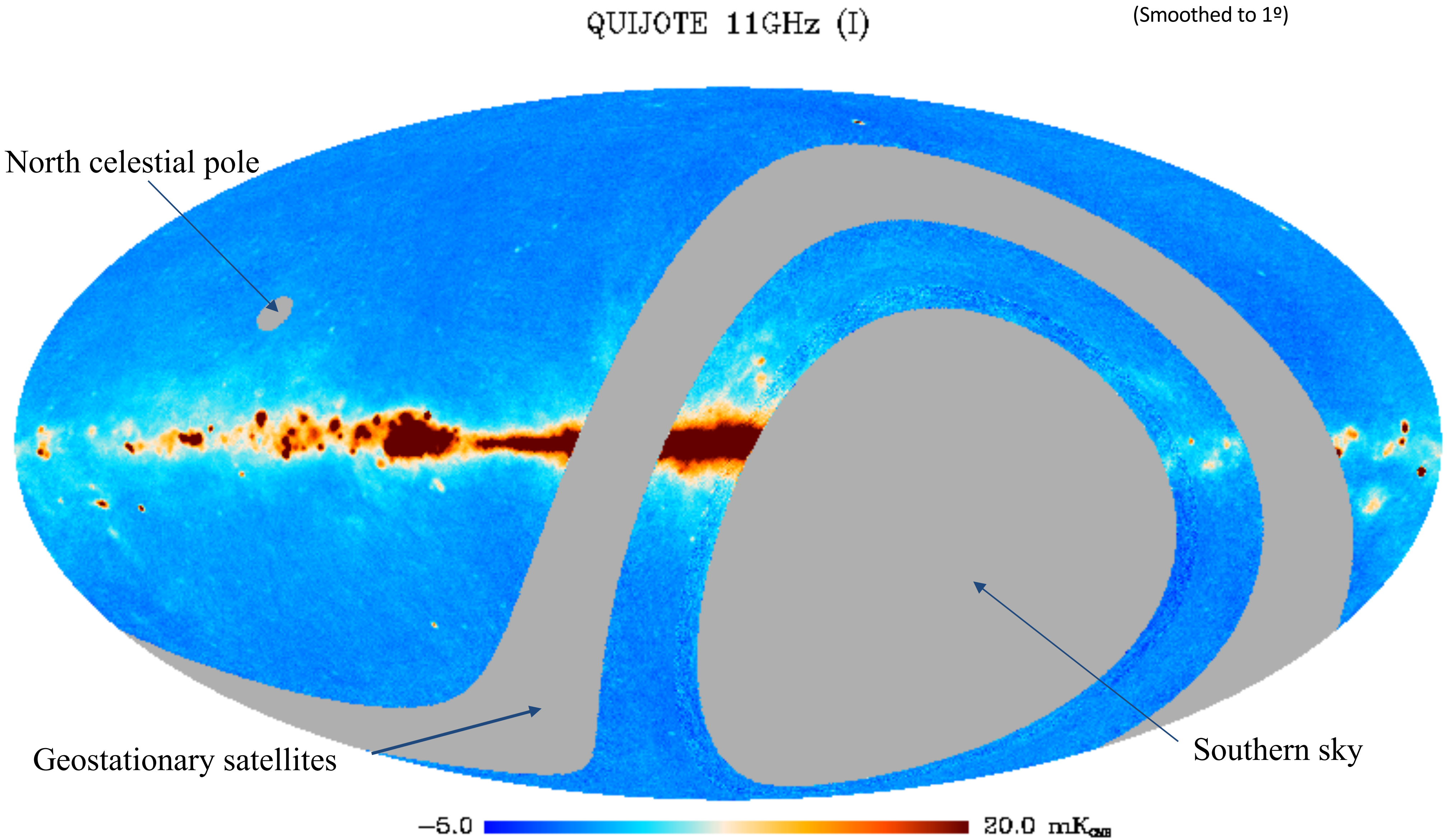


QUIJOTE 11GHz **QUIJOTE 13GHz** **QUIJOTE 17GHz** **QUIJOTE 19GHz**

Scans at constant EL (12deg/s). ~10,000 hrs. Sensitivities in polarization (Q,U): ~45 μK/deg.

Wide survey with the QUIJOTE MFI (10-20 GHz)

Preliminary maps
(Smoothed to 1º)



Wide survey with the QUIJOTE MFI (10-20 GHz)

Preliminary maps

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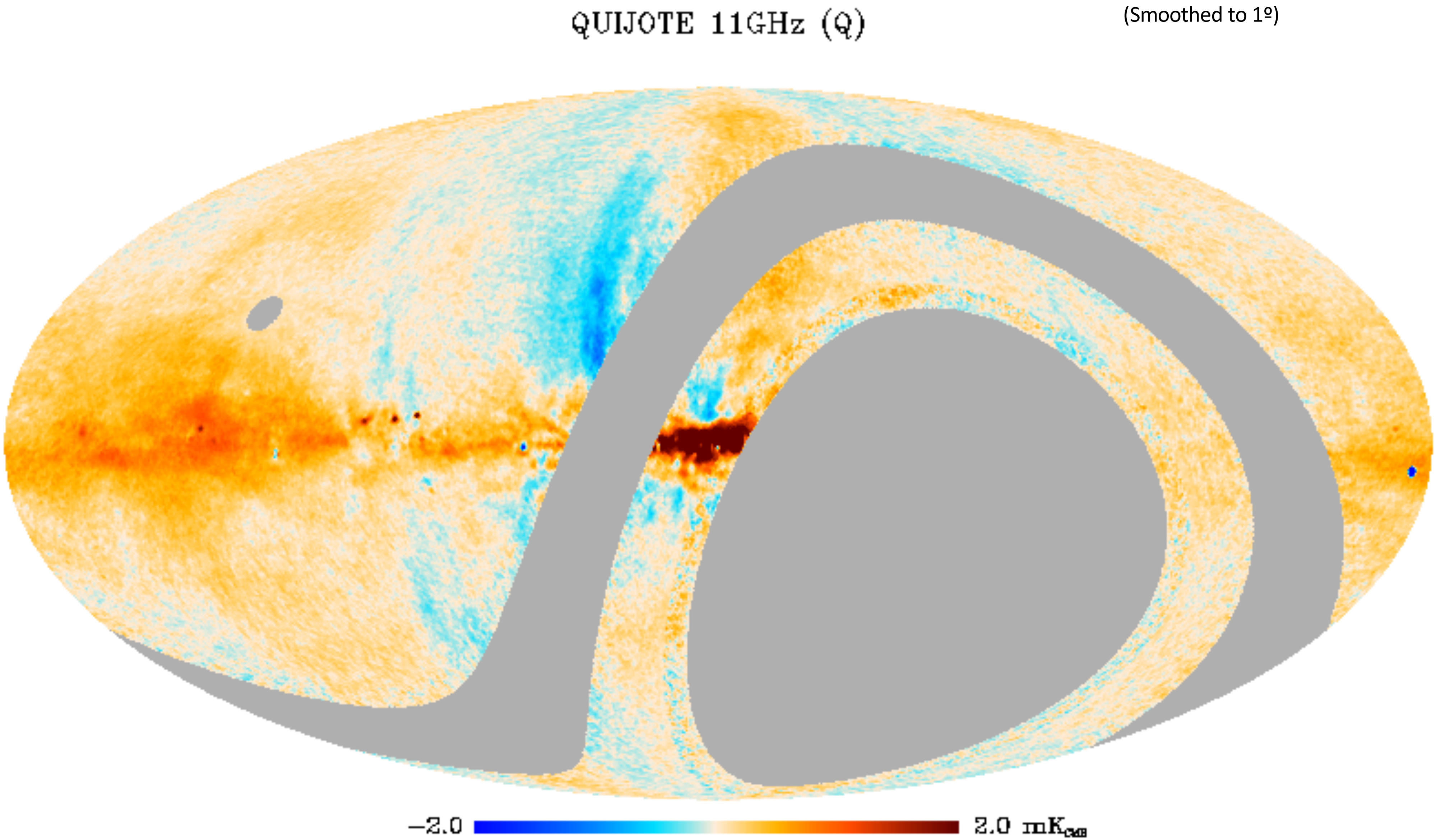
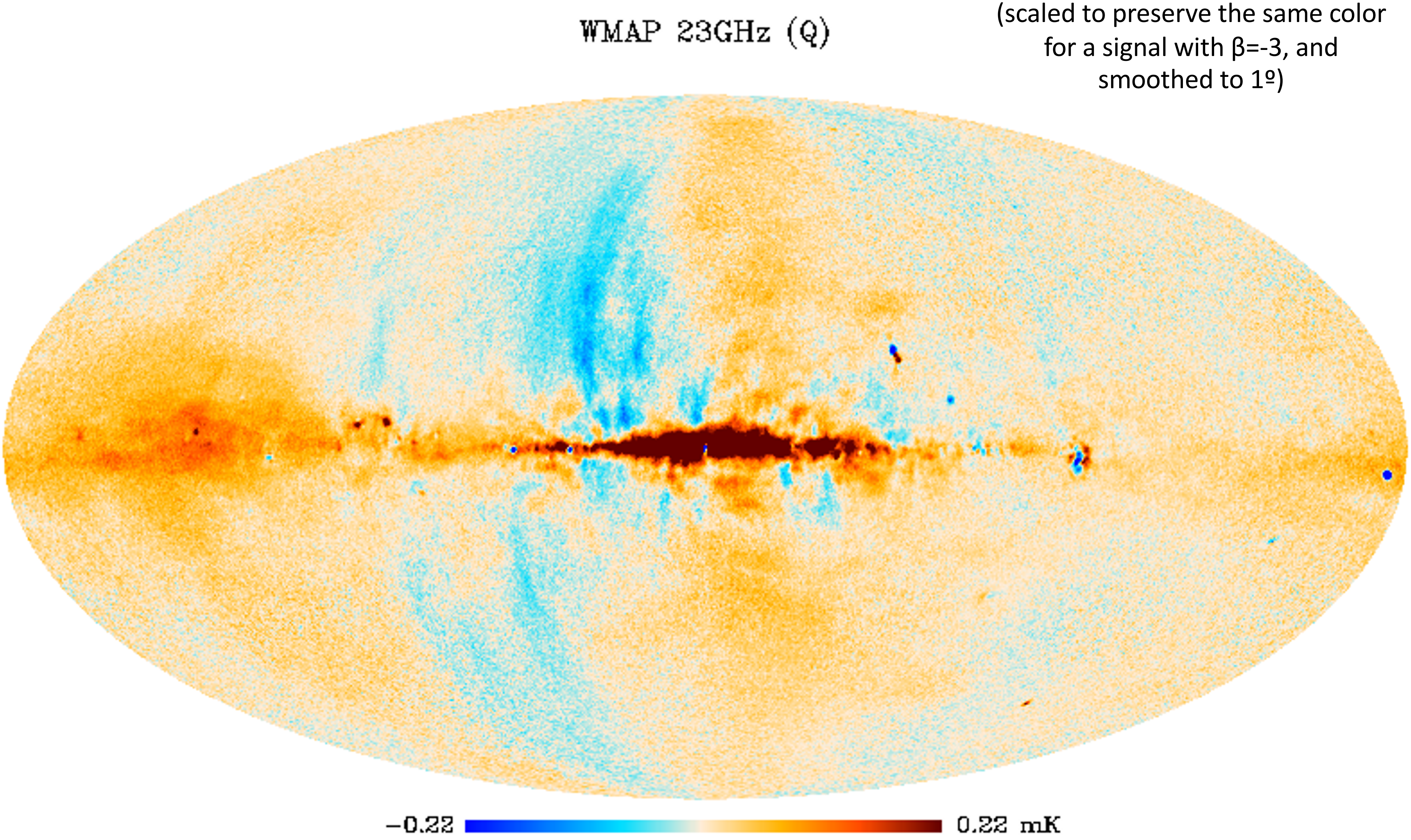


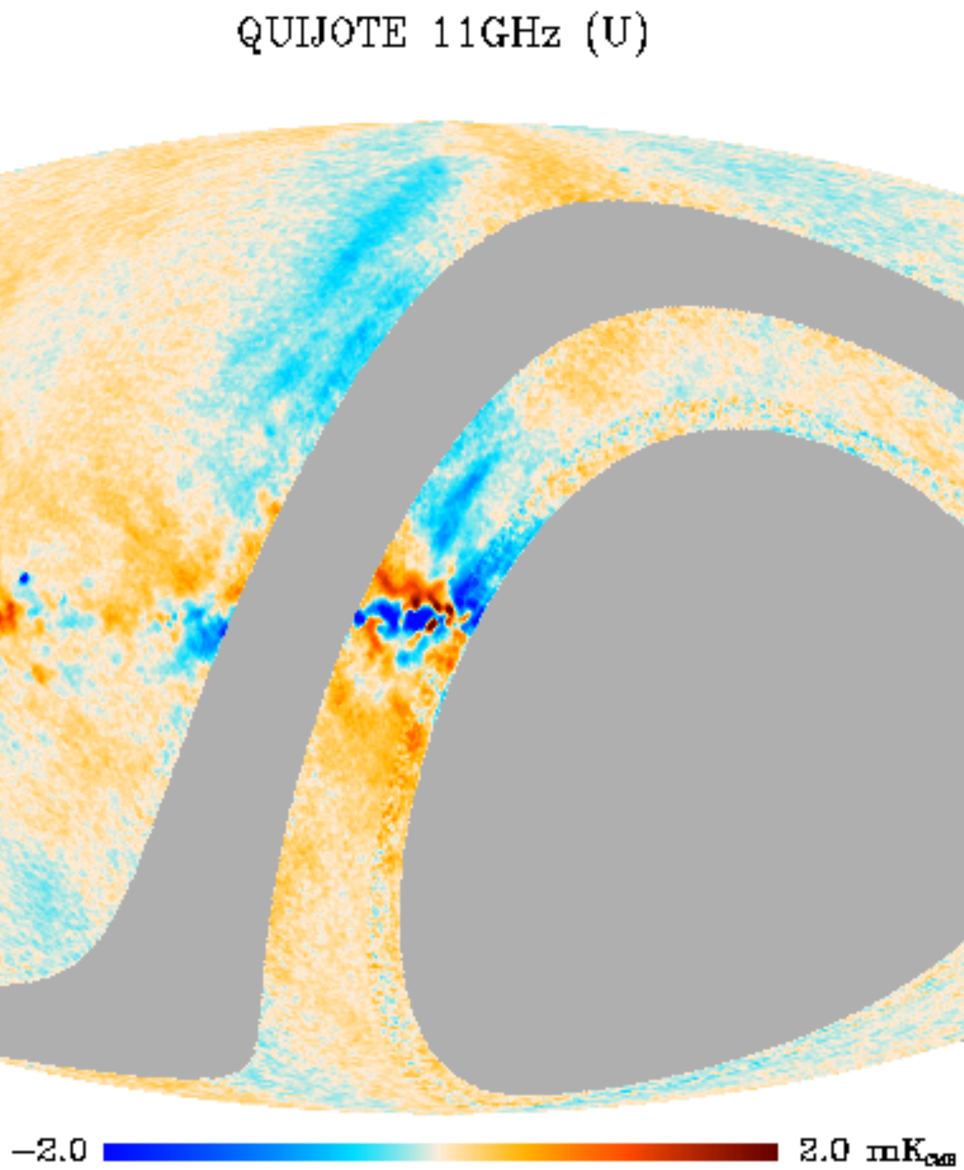
Wide survey with the QUIJOTE MFI (10-20 GHz)

(scaled to preserve the same color for a signal with β=-3, and smoothed to 1º)



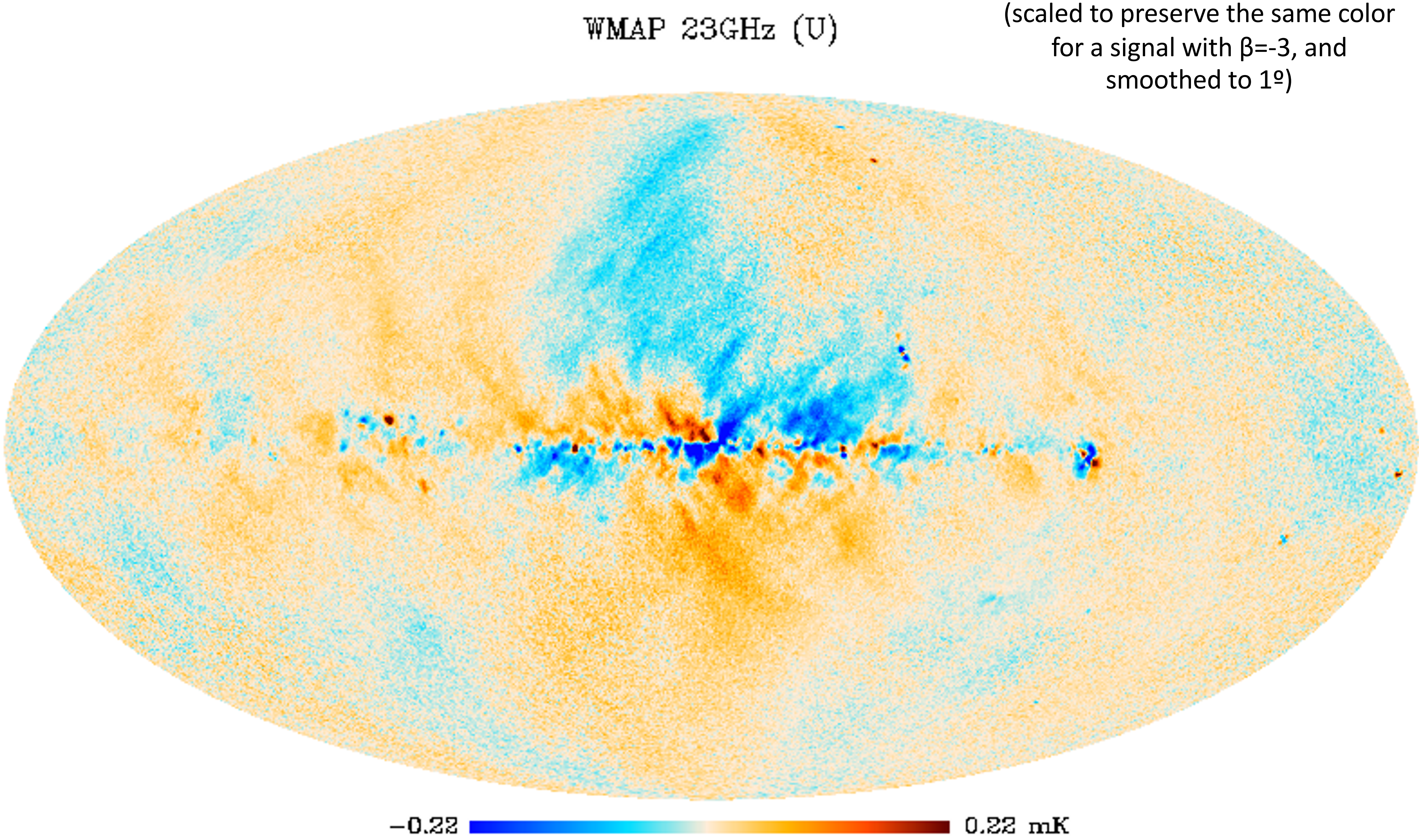
Wide survey with the QUIJOTE MFI (10-20 GHz)

Preliminary maps
(Smoothed to 1º)



Wide survey with the QUIJOTE MFI (10-20 GHz)

(scaled to preserve the same color for a signal with β=-3, and smoothed to 1º)



Wide survey with the QUIJOTE MFI (10-20GHz)

Calibration and systematic effects

(Rubino-Martin et al. in prep; Genova-Santos et al. in prep)

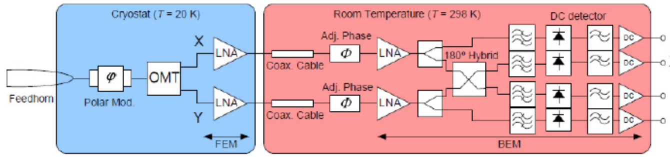
- **Calibration. Gain modelling.**
  - Primary. Point sources (CRAB, CASS-A).
  - Secondary. Calibration diode.

- **Beam model.**
  - Description of the full beam based on simulations (CST). Verified on maps (radial profile of point sources). Satellites.
- **RFI and atmosphere**
  - Mode at constant declination due to scanning strategy.
- **Polarization angle and polar efficiency**.
- **Validation of wide survey maps**
  - **Null tests.**
  - **CMB signal.** CMB detected via cross-correlation QUIJOTE x Planck (SMICA). **11GHz**: 1.01+-0.04 in l=100-200 (0.98+-0.05 in l=30-200).
  - **CMB dipole.** Dipole signal detected via direct measurement and also with cross-correlations. Error: 10%. **11GHz**: 0.91±0.10
  - **Radiosources and planets**.

Calibration. Gain modelling

$$G(t) = G_0 + \delta G(t) = G_0\left(1 + \frac{\delta G(t)}{G_0}\right)$$

- **Primary (absolute). G_0.** Point sources (CRAB, CASS-A).
  - Model for calibrators from WMAP (Weiland et al. 2011).
  - Daily observations (> 600 observations).
  - Recalibration in the final map (1/f noise).
  - Internal consistency: <1% (null tests).



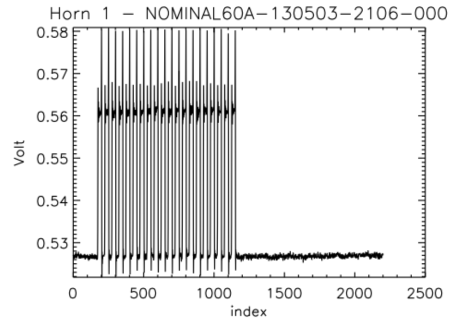
$$V_x + r_u V_y = s_x g_1^2 I$$

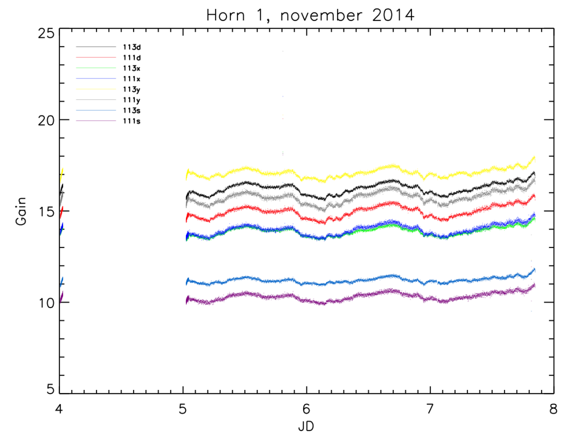
$$V_x - r_u V_y = s_x g_1^2 (Q\cos(4\theta) - U\sin(4\theta))$$

$$V_{x+y} + rV_{x-y} = s_{x+y}\left(\frac{g_1^2 + g_2^2}{2} I + \frac{g_1^2 - g_2^2}{2}(Q\cos(4\theta) - U\sin(4\theta))\right)$$

$$V_{x+y} - rV_{x-y} = s_{x+y} g_1 g_2 (Q\sin(4\theta) + U\cos(4\theta))$$

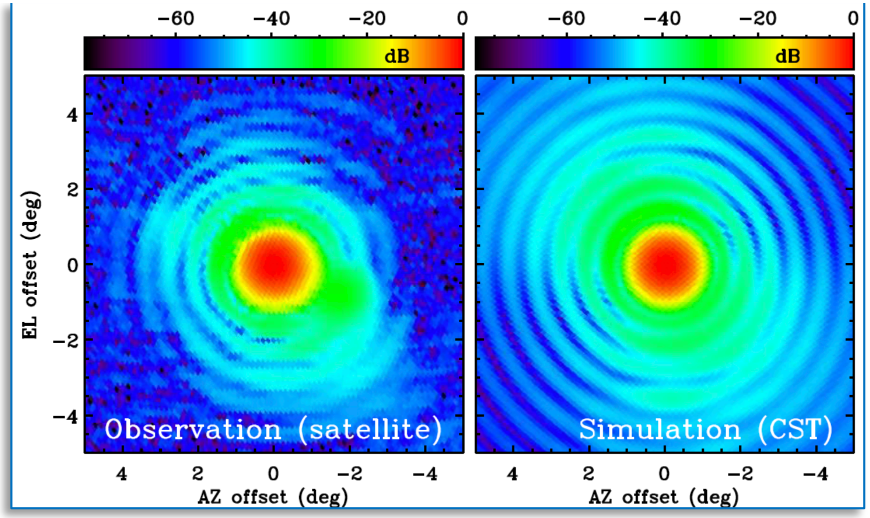
- **Secondary (relative). $\delta G(t)$.** Calibration diode.
  - Heritage of other CMB experiments at Teide.
  - Thermally stable reference.
  - Injected during 1s every 30s, rapid switch 20Hz.
  - Ratio of the two gains is very flat and constant in time → global correction ($g_1 = K\, g_2$, so $G \sim g_1^2$).
  - RMS of calibrators after correction: **< 3-5%,** but limited by noise. Correlation with external Tbem (HK) effectively removed → no residual gain variation at TOD level.
  - Smoothing the time-variable gain for the wide survey.
    - Gain stable in period of hours.
    - Smoothing kernel: 30min-2hrs (depending on SNR).



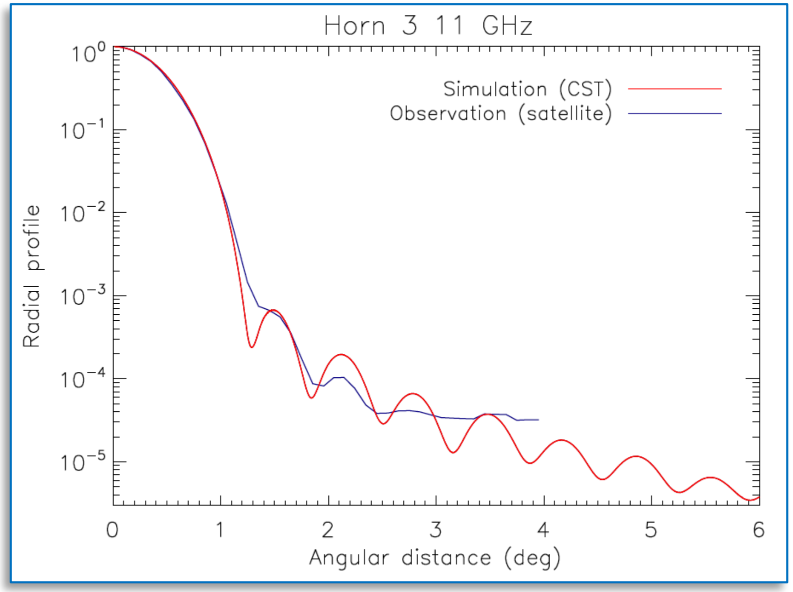


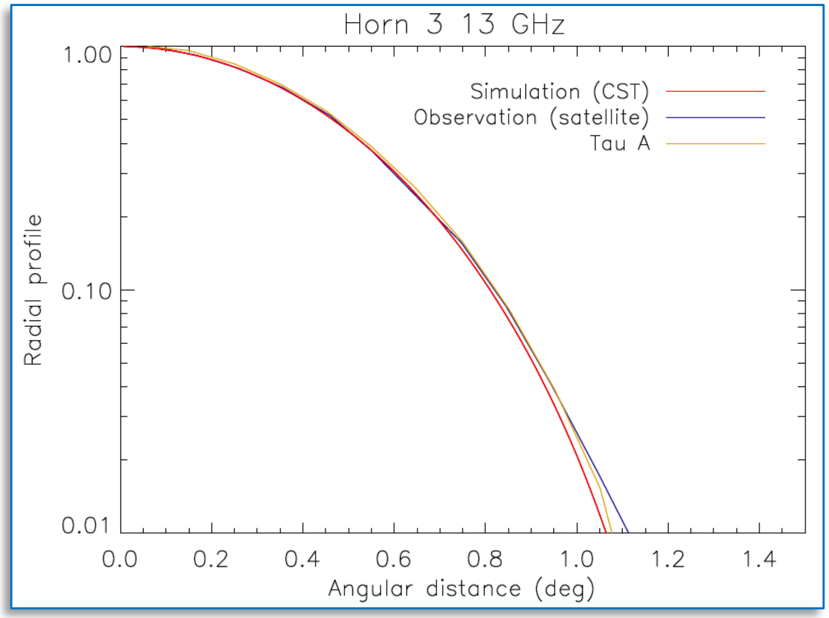
Beams. Intensity.

- Detailed modelling (in the design phase GRASP, later CST) and measurements in laboratory.
  - Excellent cross-pol (<-35dB)
  - Near sidelobes.
  - Far sidelobes (→RFI).



- **Calibration on-sky with bright sources**. Using geo-stationary satellites for the low-frequency channels (10-14 GHz) → down to 40-45dB.

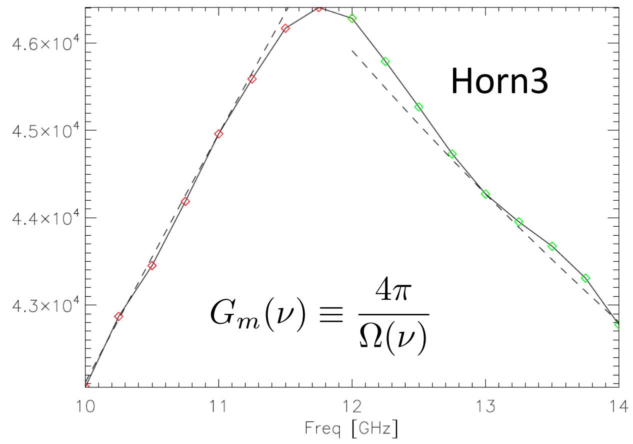




The comparision with final beam in maps (which includes pointing errors) is reasonable → adopting simulated CST beams as reference.

Beams. Frequency dependence and polarization properties

Modelling with CST

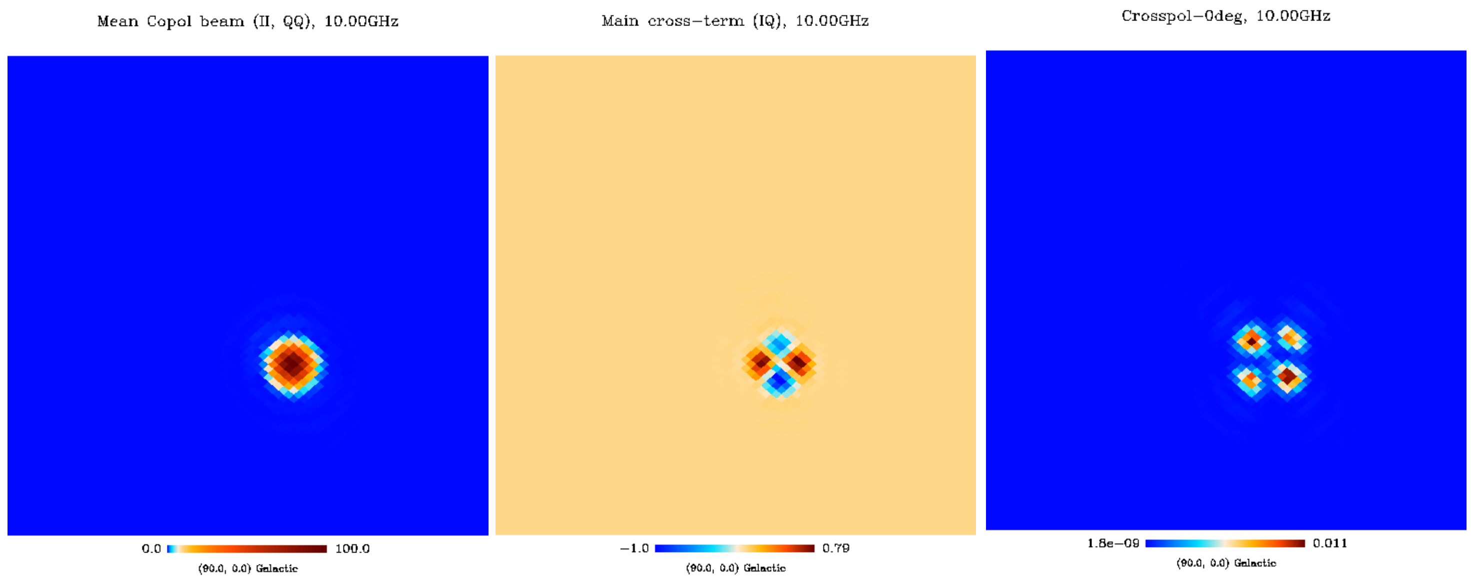


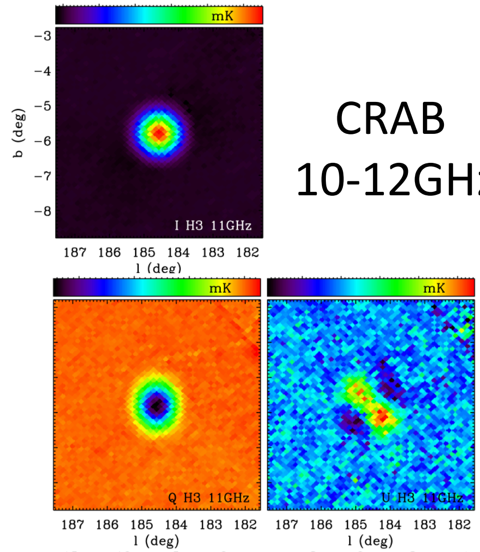
- Main beam solid angle. Peak-to-peak +/-4% change across the band (2% in the FWHM) → < 1% for colour corrections.
- Mueller matrix formalism, similar to Leahy et al. (2010). Intensity to polarization leakage in point sources due to the difference ellipticities of copolar beams a 0º and 90º.

$$\mathbf{J} = \frac{1}{\sqrt{4\pi}} \begin{pmatrix} \text{Copolar}\,0^\circ(\nu) & \text{Crosspolar}\,0^\circ(\nu) \\ \text{Crosspolar}\,90^\circ(\nu) & \text{Copolar}\,90^\circ(\nu) \end{pmatrix}$$

- Cross-polarization <-35dB in the full band.
- M_IQ: leading term is $M_{IQ}(\nu) = \frac{C_{0^\circ}(\nu) - C_{90^\circ}(\nu)}{2}$

- 1% p-p. Seen in bright sources (CRAB, CASS).
- Negligible impact in photometry (< 0.1% for AP and BF) → angle determination.



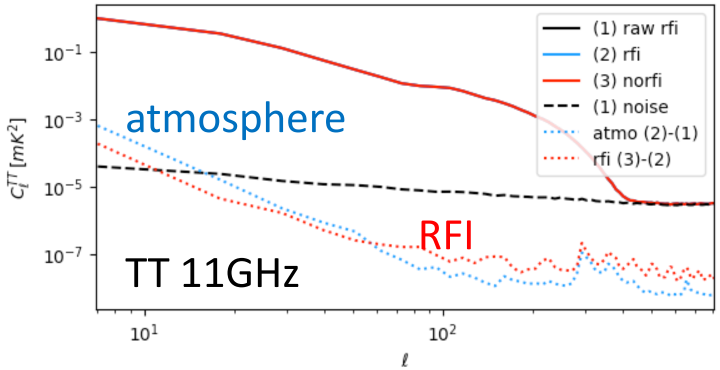


CRAB
10-12GHz

RFI and atmospheric emission

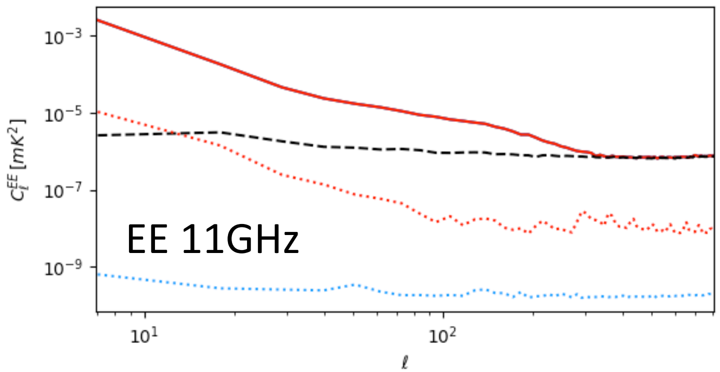
RFI:

- Far sidelobes in crossed Dragone (triple reflection, spillover lobe at 70º) → **shielding (**far sidelobes decrease -60dB to <-80 dB**)**. Well-known issue (e.g. LSPE-STRIP, talk of S. Realini; QUIET, Bischoff et al. 2013).
- Main RFI for QUIJOTE: geo-stationary satellites (far sidelobes). Mainly affecting 10-14 GHz band.
- RFI appears at fixed AZ locations → removed using f(AZ) templates.
- **Issue**: when projected on sky, the mode at constant declination is missing. Affecting low multipoles (l<15).



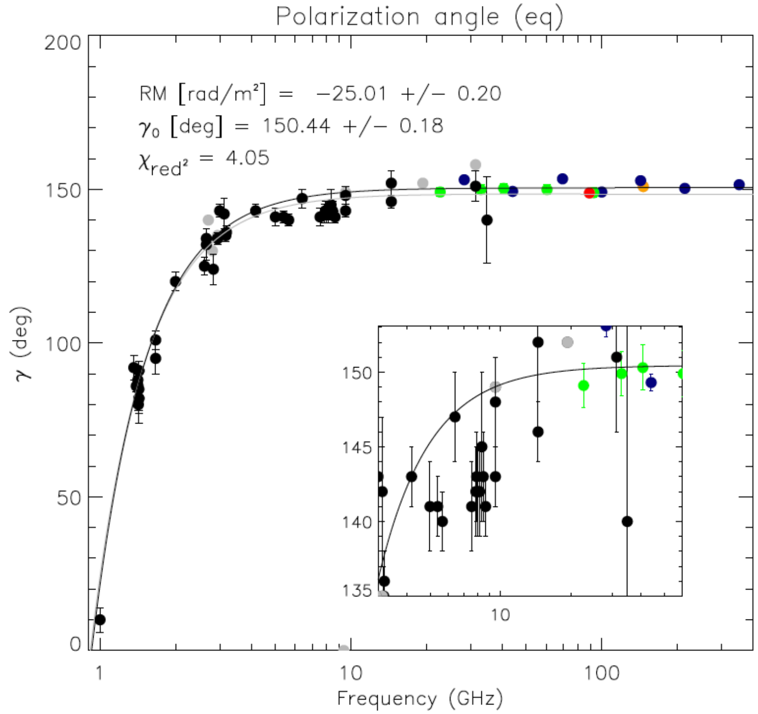
Atmospheric emission:

- Observations at constant EL. But still some variations due to changes in pwv along different l.o.s.
- Correlated between different horns and frequencies → PCA used to extract common large-scale modes.
- Relevant in intensity (l<15). Negligible impact in polarization (→ unpolarized atmospheric emission).



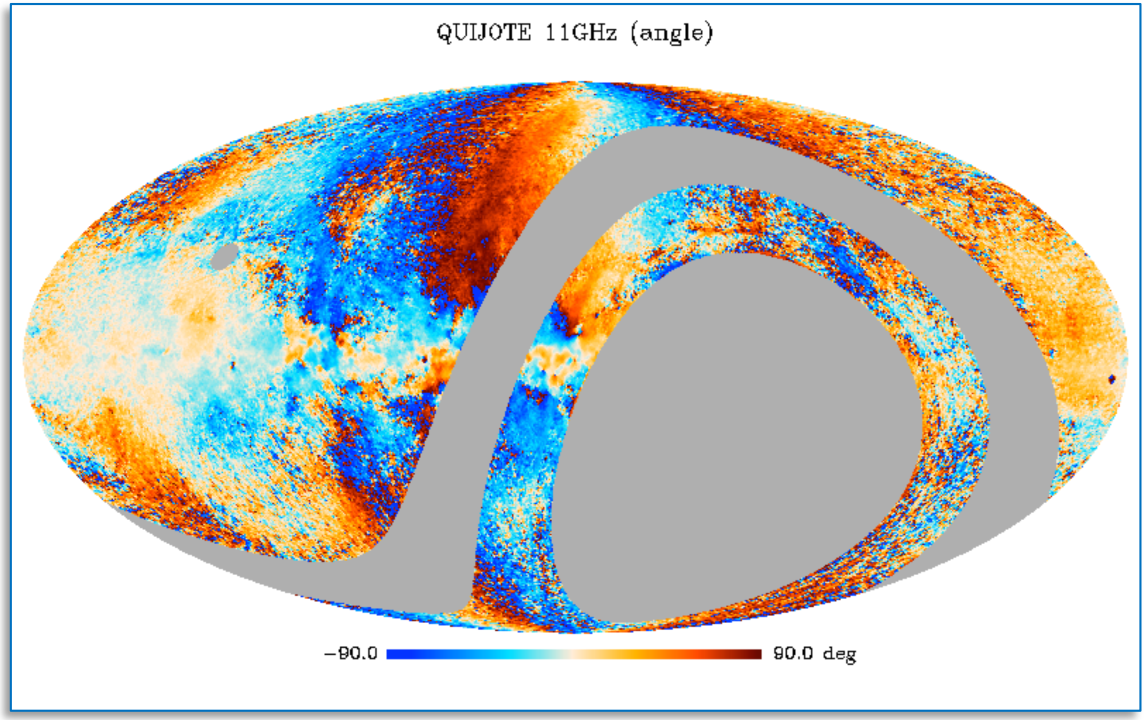
Polarization angle

- Reference calibrator: **CRAB.** $\gamma = \gamma_0 + RM\lambda^2$
- Ref angle changes across the band (and from band to band) →each frequency calibrated separately (although two frequencies share the same polar modulator).
- Daily calibration gives polar angle for CRAB with **error 0.3º** in a period. But daily calibration might suffer from 1/f noise or other effects →final maps are recalibrated.



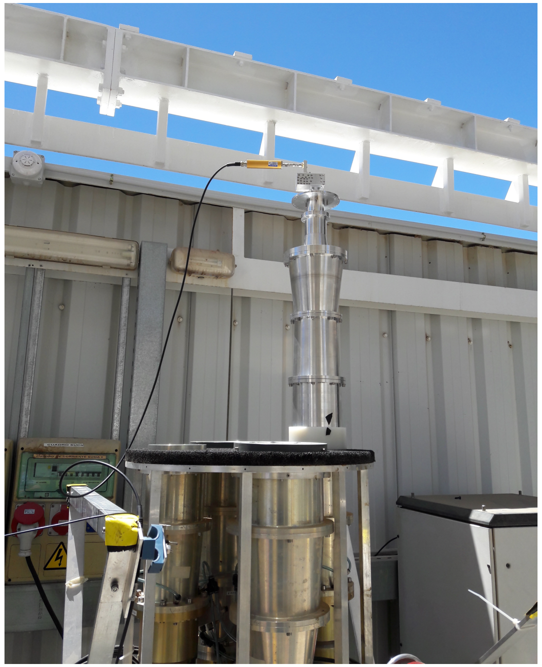
Validation: Comparison to WMAP and PLANCK in high SNR regions, excluding calibrators (CRAB) and high FR regions (galactic center):

- Median difference MFI11GHz-LFI30: 0.3º (error ~0.5º)
- Median difference MFI11GHz-WMAP-K: 1.1º (error ~0.5º).



Quijote
Q-U-I Joint Tenerife CMB experiment

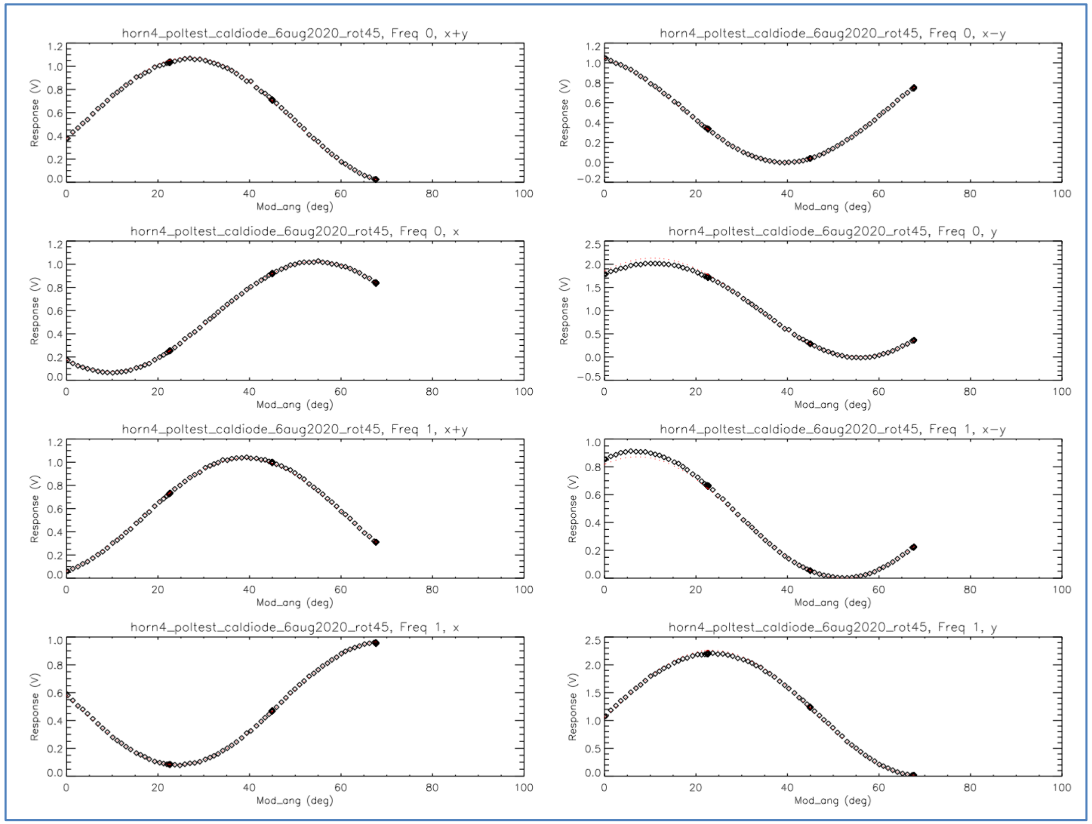
Polarization efficiency



- Measured for each channel individually (8 chan/horn, 4 horns).
- Injecting linearly polarised source (noise diode) with a horn coupled to the MFI horns. Signal switching at 20Hz to avoid 1/f.
- Sweeping all modulator angle positions in steps of 22.5º (from 0º to 67.5º). Rotating also the input signal (0º, 45º, 90º, 135º) to minimise systematic effects. Time for one measurement: 1-2 min.
- Error: 1% (scatter of measurements; two methodologies).

$$V_x = \frac{s_x g^2}{2}\left(I - \rho_x\left[Q\cos(4\theta) - U\sin(4\theta)\right]\right)$$

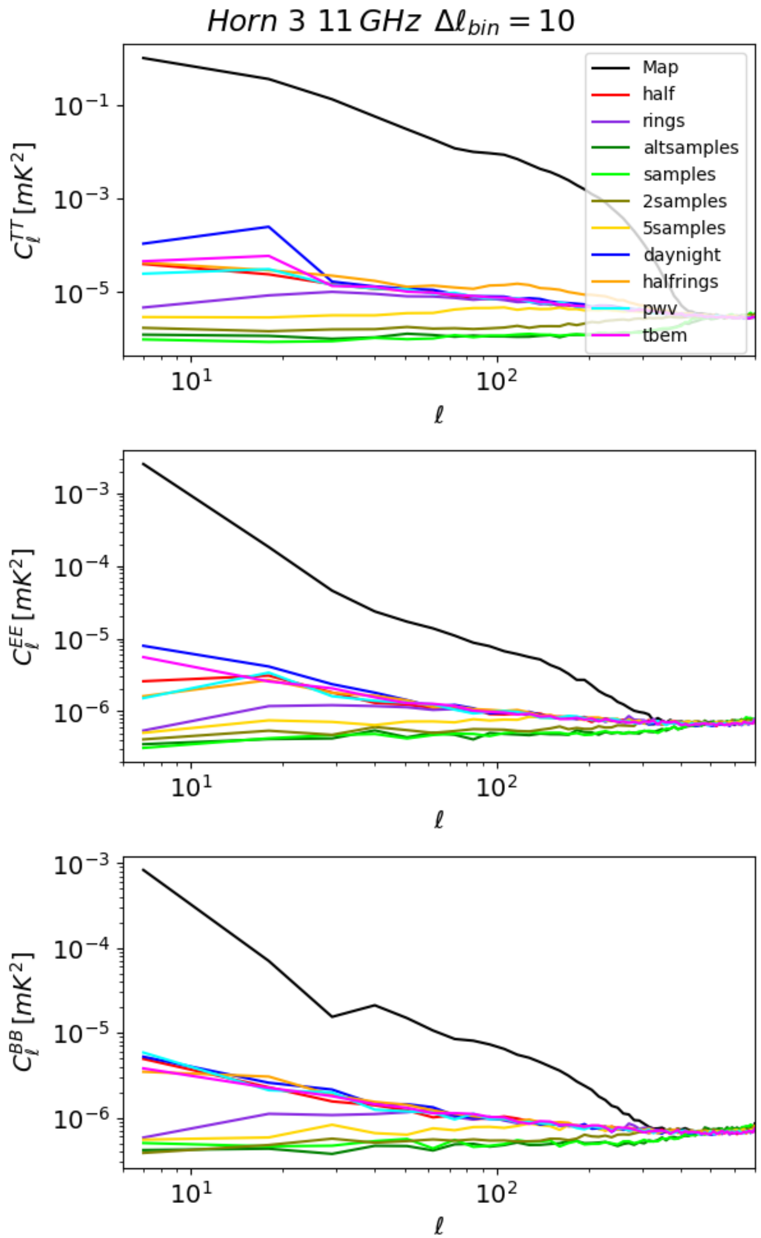
Horn, Freq	Corr	Uncorr
2, 17GHz	0.84	0.98
2, 19GHz	0.86	0.96
3, 11GHz	0.89	0.98
3, 13GHz	0.83	0.97
4, 17GHz	1.00	0.93
4, 19GHz	0.99	0.91



Validation of the MFI wide survey maps

Null-tests

- **Half mission**. The full database is divided in two halves. The separation is done according to the calendar date inside every period, producing maps labelled as “half1” and “half2”.
- **Rings**. Odd (“rings1") and even (“rings2”) rings.
- **Samples**. Odd (“samples1”) and even (“samples2”) samples, each one of 40ms. Used for testing white noise levels. Similarly, we separate in blocks of **2samples** and **5samples.**
- **Halfrings**. Dividing each ring in two halves. “Halfring1” (telescope azimuth values AZ ≤ 180º) and “halfring2” (data with AZ > 180º). These maps are significantly noisier (less crossings) but useful to find residual RFI.
- **Daynight**. Day (“daynight1”) and night (“daynight2”). We define here “day” as all observations from 8AM to 8PM.
- **PWV**. Based on GPS measurements of PWV at the Teide Observatory. Low (“pwv1”, median=2mm) and high (“pwv2”, median=5.2 mm).
- **Tbem**. Global gain strongly correlated with physical temperature at BEM. Monitored every 1s as part of HK data. “Tbem1” low versus “tbem2” high.

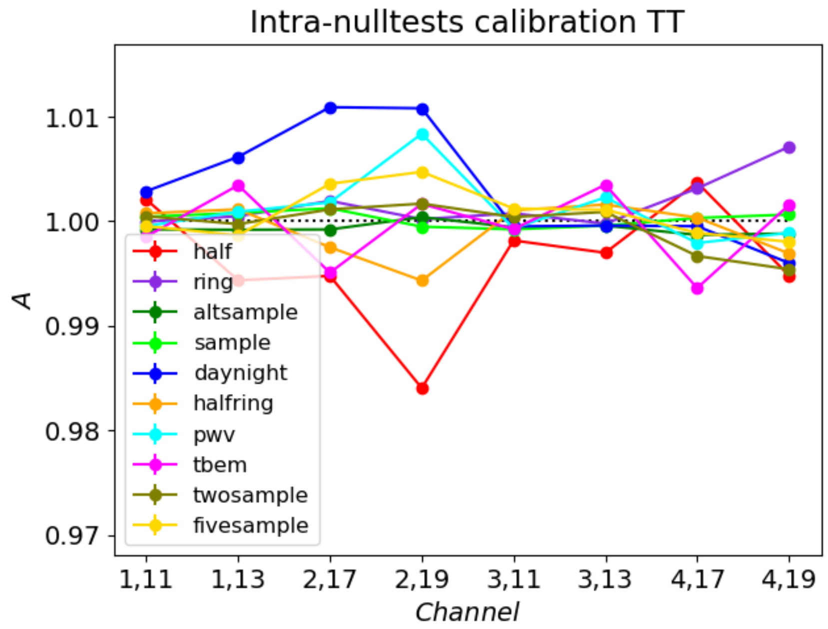


Validation of the MFI wide survey maps

Intensity calibration

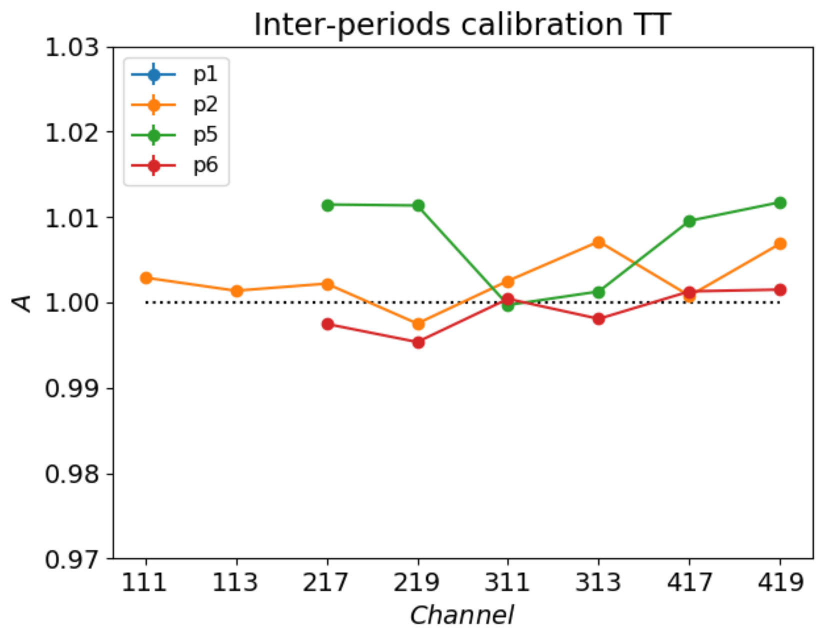
- **Intra-nulltest calibration**. Comparison of relative calibration between the two null-tests, at the power spectrum level. Following Planck, we use cross-spectra in the multipole range [30,200]. Here "other" runs over uncorrelated channels and external maps (WMAP, Planck).

$$A_{1,2} = \frac{C_\ell^{1\times \mathrm{other}}}{C_\ell^{2\times \mathrm{other}}}$$



- **Inter-period calibration**. Comparing MFI calibration as a function of time (period 1 to 6).

Period	1	2	5	6
Year (eff)	2013.7	2014.9	2016.7	2017.8



- **Conclusion**: internal consistency better than 1% (rms) in intensity. However, the global calibration uncertainty is limited by the modelling of the calibrators (5%).

Validation of the MFI wide survey maps

Polarization calibration

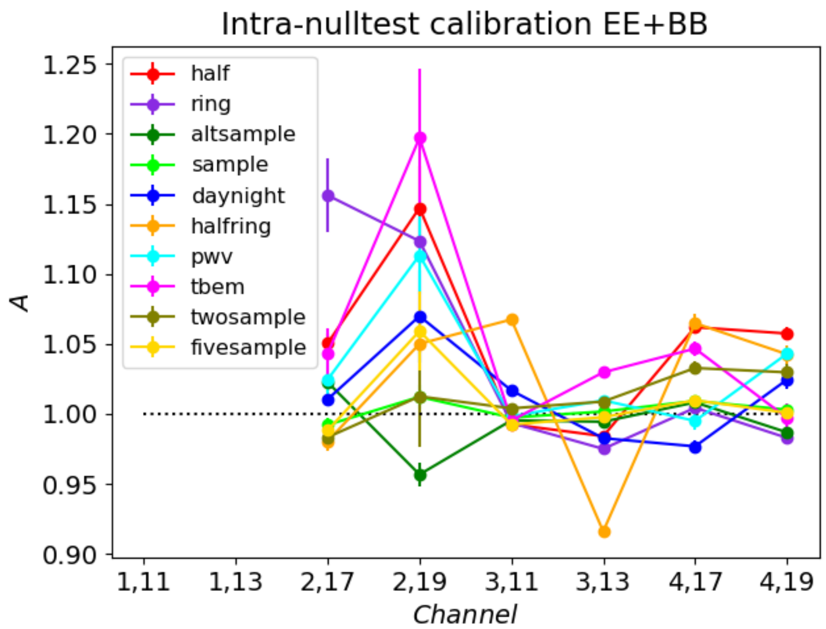
- **Intra-nulltest calibration**. Comparison of relative calibration between the two null-tests, at the power spectrum level. Following Planck, we use cross-spectra in the multipole range [30,200]. Here "other" runs over uncorrelated channels and external maps (WMAP, Planck).

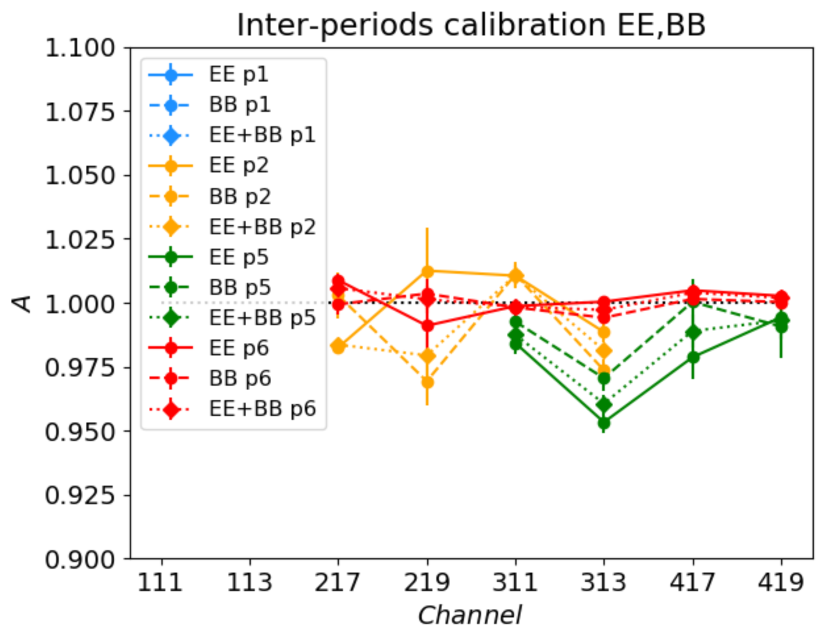
$$A_{1,2} = \frac{C_\ell^{1\times \mathrm{other}}}{C_\ell^{2\times \mathrm{other}}}$$

- **Inter-period calibration**. Comparing MFI calibration as a function of time (period 1 to 6).

Period	1	2	5	6
Year (eff)	2013.7	2014.9	2016.7	2017.8

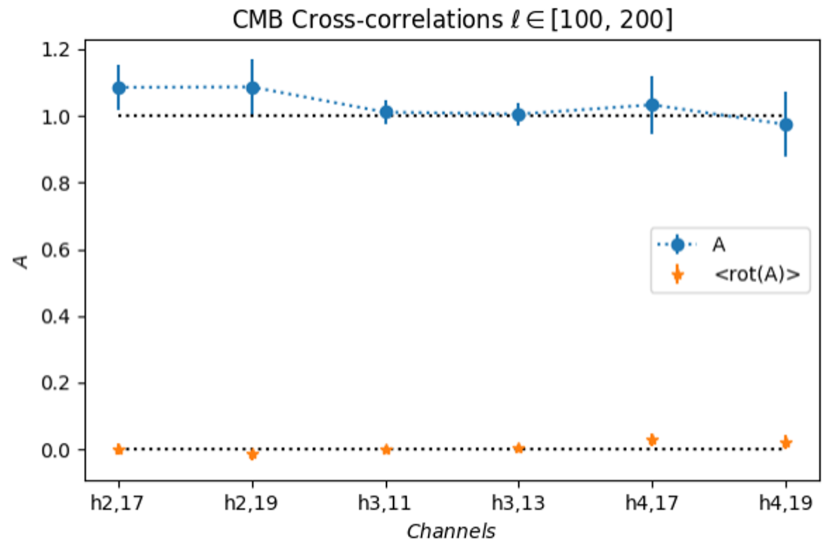
- **Conclusion**: internal consistency better than 3% (rms) in polarization. In some channels (H2, 19GHz), the test is limited by noise. The global calibration uncertainty is 5-6%.

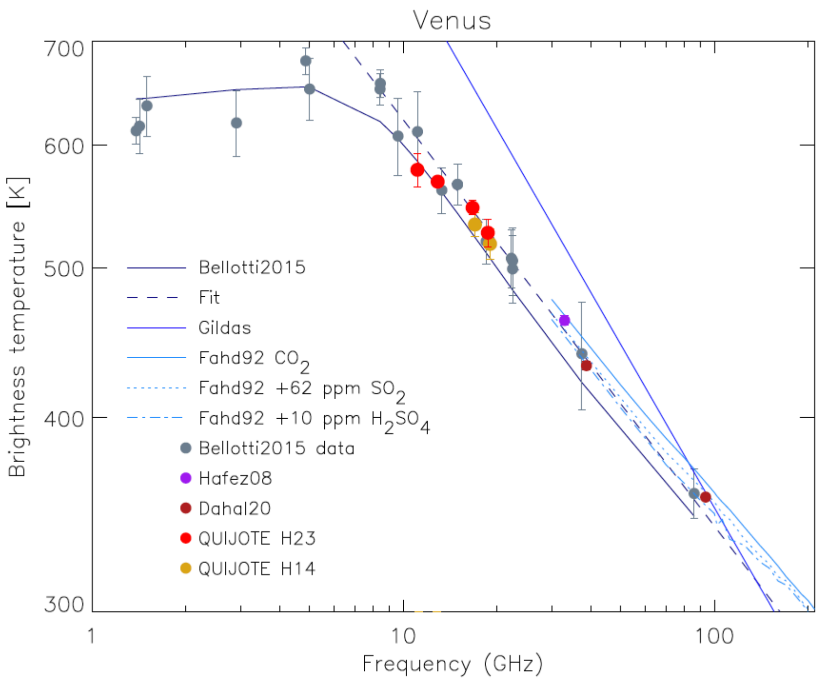


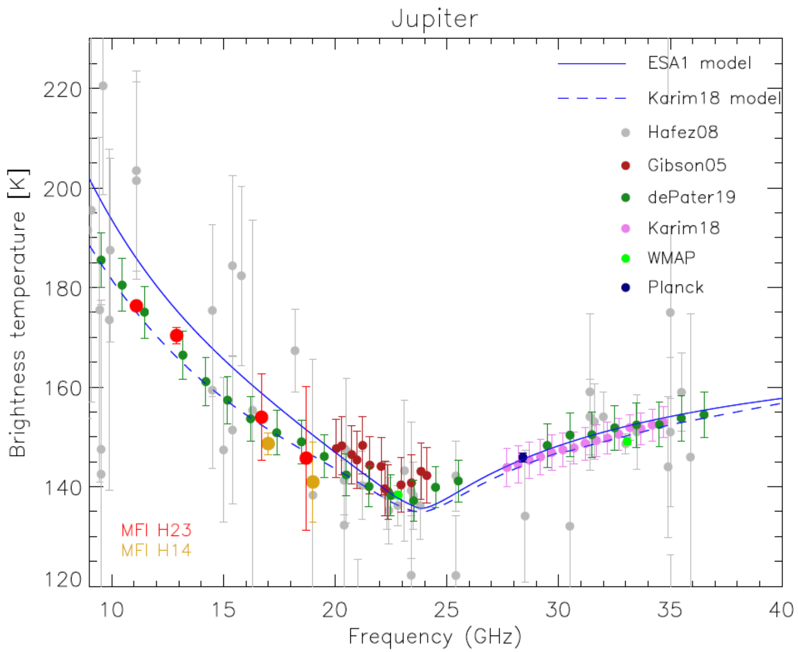


Validation of the MFI wide survey maps (II)

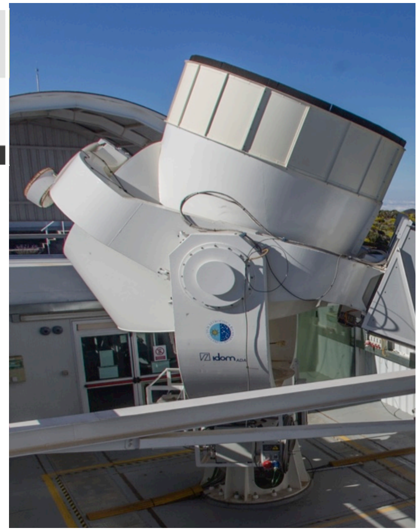
- **CMB anisotropies** (calibration to Planck). Cross-correlation between QUIJOTE intensity maps and SMICA. At **11GHz**: 1.01±0.04.
- **CMB dipole.** Dipole signal detected via direct measurement and also with cross-correlations. Error: 10%. **11GHz**: 0.91±0.10.
- **Planets** (Jupiter, Venus). Consistency.
- **Radiosources** (Cass-A, Cygnus-A). Consistency <5%.







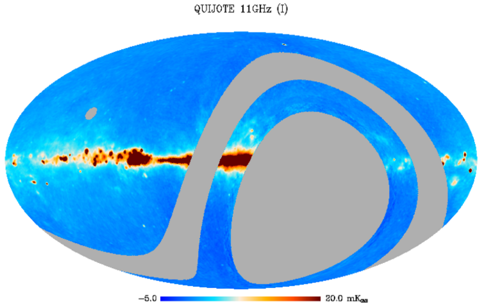
Summary and conclusions

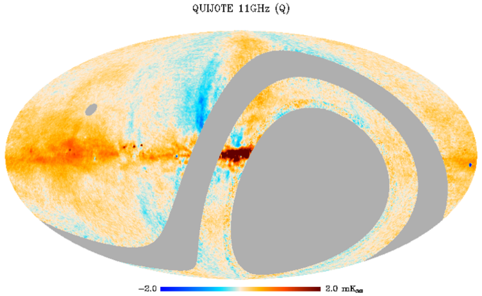


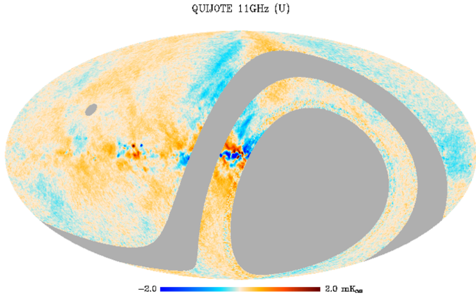
QUIJOTE MFI 10-20 GHz (2012-2018). Wide survey (>10,000h) completed. Four maps at 11, 13, 17, 19GHz, with sensitivities ~45 µK/beam in polarization. Data release will happen soon (10 papers). Legacy value (e.g. Litebird).

Calibration and systematic effects for MFI instrument (Rubiño-Martin et al. in prep; Genova-Santos et al. in prep).

- **Calibration. Gain modelling.**
- **Beam model.**
- **RFI and atmosphere.**
- **Polarization angle and polar efficiency**.
- **Validation of wide survey maps** (Null tests. CMB cross-correlation. CMB dipole. Planets, radio-sources).







Lessons learned.

- Characterization of the instrument is essential. Important to have independent routes to measure some parameters (beams, polar efficiency, polar angle).
- Testing, testing, testing. Null-tests are key tool.
- Better is the enemy of "good enough".
- Atmosphere is not a limiting factor for these measurements in Tenerife → we can recover large angular scales (l~20). But missing mode (constant dec).
- RFI is serious issue for ground-based obs. Digital back-end (FGPA)→ **MFI2**.
- Major limitation is **calibration**: model for CRAB, or sources in general: ~3%. → see talk A. Ritacco. In the future we'll have **TMS** (spectrometer at 10-20GHz).