Thermal design and modeling of the Tenerife Microwave Spectrometer: towards high precision spectral measurements of the microwave sky at 10-20GHz

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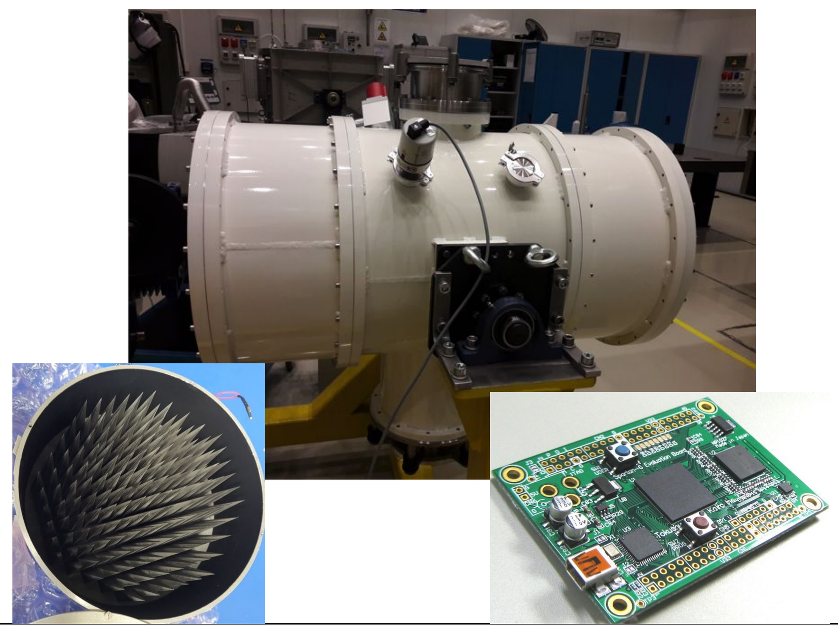
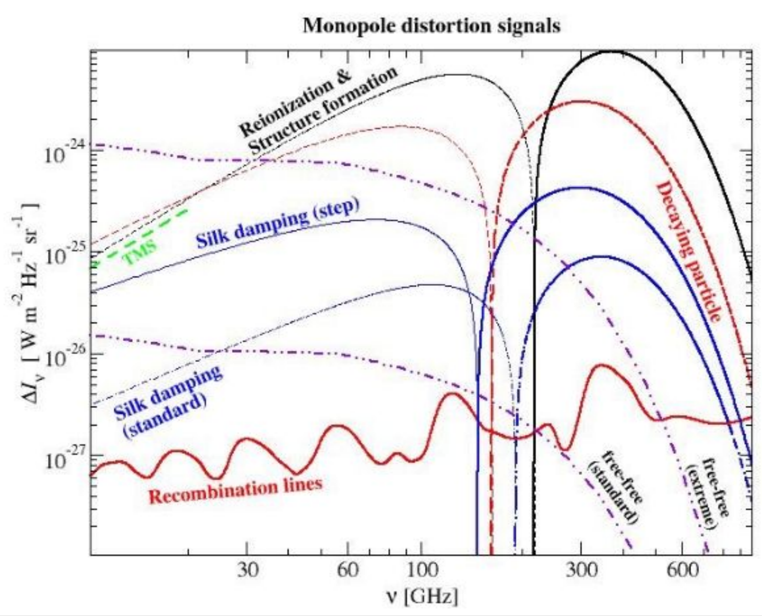
Abstract

According to the ΛCDM model, spectral distortions of the CMB from a perfect blackbody shape are expected. The COBE experiment was the first to measure the absolute spectrum of the CMB in the 1 to 95 cm⁻¹ frequency range, but it did not detect any deviations from a pure blackbody. Absolute measurements of the CMB at longer wavelengths than those covered by COBE have been performed by a few ground-based and balloon-borne experiments. Notably, ARCADE2 detected an unexplained excess of radio emission with a synchrotron-like spectrum — the so-called radio synchrotron background — which might potentially be explained by dark matter models (e.g., axions, sterile neutrinos, superconducting cosmic strings, etc.). The Tenerife Microwave Spectrometer (TMS) is a new ground-based microwave experiment to be installed at the Teide Observatory (Tenerife, Spain). TMS will take precise measurements of the absolute sky spectrum (at the level of uK) in the frequency range between 10 to 20 GHz, with the sensitivity to characterize the spectral dependence of the radio synchrotron background. TMS uses a pseudo-correlation scheme, similar to the Low Frequency Instrument (LFI) on board the PLANCK satellite, which simultaneously compares two input signals, one coming from the sky, and one coming from a stable reference black body load at cryogenic temperatures. At the output of the radiometer, the difference between both signals will be recorded and deviations from the blackbody curve will be measured. TMS requires a detailed characterization of every part of the radiometric chain to predict the possible systematic effects that will impact the final measurements and to design the calibration strategy. In this talk, we present a detailed forecast of the instrument performance, by obtaining the temperature contributions due to the non-ideality of the radiometric components. These results are used, together with a Jones matrix analysis, to perform realistic simulations of the instrument to consolidate the calibration scheme.



TMS Experiment

The Tenerife Microwave Spectrometer (TMS) is a **new ground-based microwave experiment** to be installed at the Teide Observatory (Tenerife, Spain). TMS will take **absolute measurements of the distortions of the sky spectrum (at the level of uK)** in the frequency range between 10 to 20 GHz [1]. TMS uses a **pseudo-correlation scheme**, similar to the Low Frequency Instrument (LFI) on board the PLANCK satellite [3].



TMS Science Goals

1. Measure the **absolute sky spectrum in the 10-20 GHz range**, reaching a sensitivity of 10 - 20 Jy/sr.
2. **Provide an absolute calibration scale for QUIJOTE experiment**, and accurate relative calibration scale to QUIJOTE MFI frequencies. (11, 13, 17 and 19 GHz)
3. Provide **information of the spectral properties of the synchrotron and AME from our Galaxy** (in particular, tp confirm or discard the excess of emission detected by ARCADE 2. **Radio Synchrotron Background [4]**).

Methods

Jones Matrices and Stokes Parameters

In astrophysical instrumentation, the propagation of radiation across a receiver may be characterized by a Jones matrix **J.** The components of the electric field of a light beam emerging from a device are linearly related to those of the incident light beam [2].

E_{out}: Total output radiation; E_{in} : Incoming radiation

$$\boldsymbol{E}_{\text{out}} = \mathbf{J}\boldsymbol{E}_{\text{in}}$$

Noise Temperature of an Attenuator

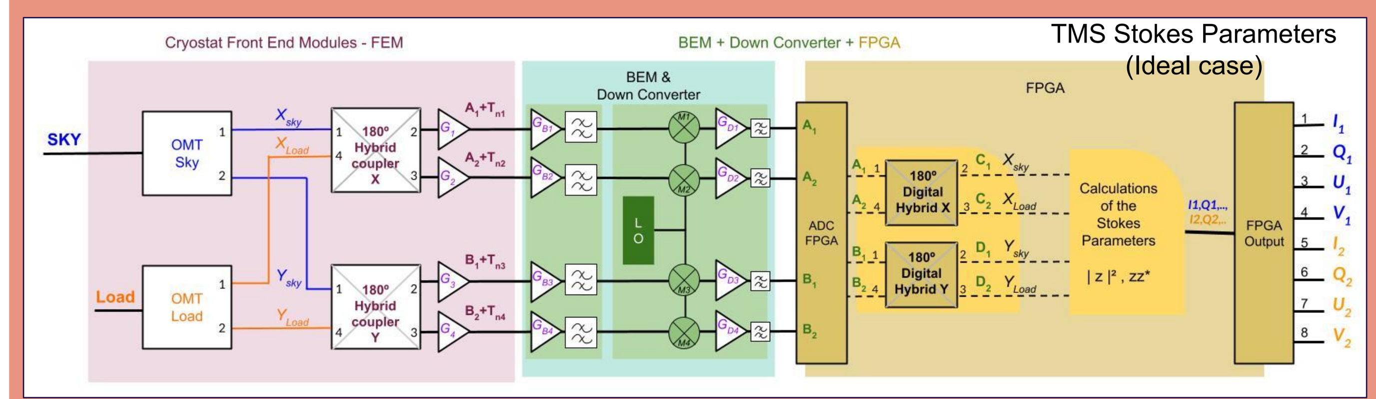
When 2-port devices are connected in series with a matched generator, the noise temperature of the receiver-transmission-line combination is expressed by the following equation:

$$T_{RT} = (L-1)\,T_{LP} + L\,T_R$$

where L denotes the loss factor of the attenuator, T_{LP} represents its physical temperature, and T_R the noise temperature of the receiver

Systematic Error Characterization: Jones matrices

The diagram illustrates how the electrical signal propagates through the RF components and the FPGA of the TMS, from which the total (I_{Tot}) and Q-polarization (Q_{Tot}) signals are obtained, as illustrated by the following equations.



$$I_{tot}(t) = I_1(t) - I_2(t) = \left(|C_1+n_x|^2 + |D_1+n_y|^2\right)(t) - \left(|C_2+n_x|^2 + |D_2+n_y|^2\right)(t)$$

$$Q_{tot}(t) = Q_1(t) - Q_2(t) = \left(|C_1+n_x|^2 - |D_1+n_y|^2\right)(t) - \left(|C_2+n_x|^2 - |D_2+n_y|^2\right)(t)$$

$$\mathbf{J}_{\text{att},k} = \begin{pmatrix} A_x & 0 \\ 0 & A_y e^{i\phi_k} \end{pmatrix}$$

$$\mathbf{J}_{\text{omt},k} = \begin{pmatrix} (1+O_x^k) & O_a^k e^{i(\theta_2^k+\theta_3^k)} \\ O_a^k e^{i\theta_2^k} & (1+O_y^k)e^{i\theta_3^k} \end{pmatrix}$$

$$\mathbf{J}_{\text{hyb},k} = \frac{1}{\sqrt{2}} \begin{pmatrix} (1+B_2^k)e^{i\beta_1^k} & (1+B_a^k)e^{i(\beta_a^k+\beta_2^k)} \\ e^{i(\beta_a^k+\beta_1^k)}(1+B_a^k) & -e^{i\beta_2^k}(1+B_3^k) \end{pmatrix}$$

$$\mathbf{J}_{\text{lna},k} = \begin{pmatrix} g_i & 0 \\ 0 & g_{i+1} e^{i\psi_{i+1}} \end{pmatrix}, \quad \mathbf{J}_{\text{BD},k} = \begin{pmatrix} g_i^{\text{BD}} & 0 \\ 0 & g_{i+1}^{\text{BD}} e^{i\phi_{i+1}} \end{pmatrix}$$

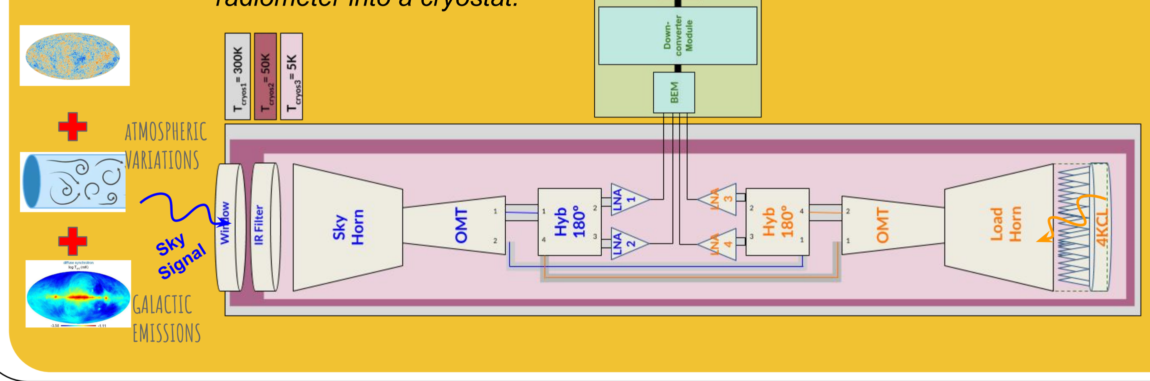
$$\mathbf{n}_{\text{lna},k} = \begin{pmatrix} n_i \\ n_{i+1} \end{pmatrix}, \quad \mathbf{n}_{\text{BD},k} = \begin{pmatrix} n_i^{\text{BD}} \\ n_{i+1}^{\text{BD}} \end{pmatrix}$$

Non-ideal Jones matrices employed to calculate the TMS stokes parameters.

Systematic Error Characterization: Physical temperature variation effects

The radiometric architecture of TMS use a pseudo-correlation scheme which use a cold-load to compare the sky signal with a known reference value. We have obtained the general Friss equations of TMS using the schematic shown below.

Schematic of the optical, passive and active RF components of the TMS radiometer into a cryostat.



$$\Delta T = T^b_{sky} - T^b_{load} = T_{sky}\,\overbrace{(2\beta^{Ts}_{A2} + 2\beta^{Ts}_{B2})}^{\beta^{\Delta T}_{Sky}} + T_{load}\,\overbrace{(2\beta^{Tl}_{A2} + 2\beta^{Tl}_{B2})}^{\beta^{\Delta T}_{Load}} + T^{eff}_{off} + T^{eff}_{n}$$

ΔT represents the radiometric response of TMS in terms of brightness temperature. This response includes: sky and cold-load input temperatures; effective losses (T_{off}) generated by Insertion Loss, Return Loss, SPO for each system component; and noise temperature (T_n) of each amplifier.

Results

Slightly unbalanced radiometer and correlated noise: FEM: non-ideal LNAs

$$I_1 = \frac{I_{sky}}{8}\left[\sum_{k=1}^{4} g_k^2 + 2(g_1g_2\cos\psi_2 + g_3g_4\cos\psi_4)\right] + \frac{I_{load}}{8}\left[\sum_{k=1}^{4} g_k^2 - 2(g_1g_2\cos\psi_2 + g_3g_4\cos\psi_4)\right] + \frac{Q_{load}}{8}\left[\sum_{k=1}^{4} C_k g_k^2 - 2(g_1g_2\cos\psi_2 - g_3g_4\cos\psi_4)\right] + \frac{Q_{sky}}{8}\left[\sum_{k=1}^{4} C_k g_k^2 + 2(g_1g_2\cos\psi_2 - g_3g_4\cos\psi_4)\right] + \frac{1}{2}\left[\sum_{k=1}^{4} g_k^2 N_k\right]$$

$$I_2 = \frac{I_{load}}{8}\left[\sum_{k=1}^{4} g_k^2 + 2(g_1g_2\cos\psi_2 + g_3g_4\cos\psi_4)\right] + \frac{I_{sky}}{8}\left[\sum_{k=1}^{4} g_k^2 - 2(g_1g_2\cos\psi_2 + g_3g_4\cos\psi_4)\right] + \frac{Q_{load}}{8}\left[\sum_{k=1}^{4} C_k g_k^2 + 2(g_1g_2\cos\psi_2 - g_3g_4\cos\psi_4)\right] + \frac{Q_{sky}}{8}\left[\sum_{k=1}^{4} C_k g_k^2 - 2(g_1g_2\cos\psi_2 - g_3g_4\cos\psi_4)\right] + \frac{1}{2}\left[\sum_{k=1}^{4} g_k^2 N_k\right]$$

FPGA output response for the sky (I1) and load (I2) intensities. (g) indicates the gain of the four LNAs in the TMS, and ψ the phase difference between the X- and Y-branch amplifiers (ψ_2 and ψ_4).

$$I_{tot} = \frac{I_{sky}}{2}[g_1g_2\cos\psi_2 + g_3g_4\cos\psi_4] - \frac{I_{load}}{2}[g_1g_2\cos\psi_2 + g_3g_4\cos\psi_4] + \frac{Q_{sky}}{2}[g_1g_2\cos\psi_2 - g_3g_4\cos\psi_4] - \frac{Q_{load}}{2}[g_1g_2\cos\psi_2 - g_3g_4\cos\psi_4]$$

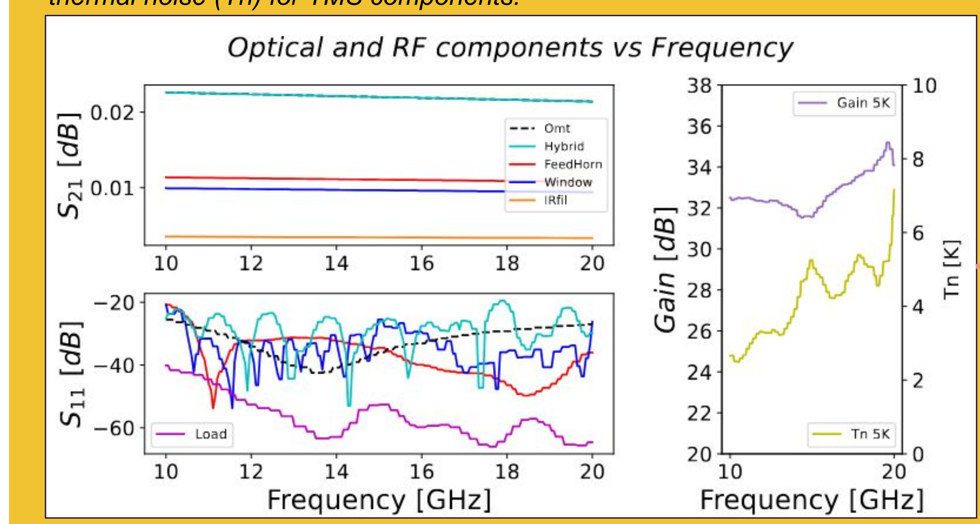
$$Q_{tot} = \frac{Q_{sky}}{2}[g_1g_2\cos\psi_2 + g_3g_4\cos\psi_4] - \frac{Q_{load}}{2}[g_1g_2\cos\psi_2 + g_3g_4\cos\psi_4] + \frac{I_{sky}}{2}[g_1g_2\cos\psi_2 - g_3g_4\cos\psi_4] - \frac{I_{load}}{2}[g_1g_2\cos\psi_2 - g_3g_4\cos\psi_4].$$

Total response of I and Q of the TMS instrument.

To accurately measure the sky intensity or Q polarization, we obtain that, the system requires **balanced gains and zero phase shift between the amplifiers,** since spurious signals originating from the load and sky polarization can otherwise contaminate the total output.
Furthermore, **thermal noise (N) contribution is canceled out** when the total intensity (I1-I2) or total Q-pol (Q1-Q2) is obtained.

Impact of Physical Temperature in TMS instrument

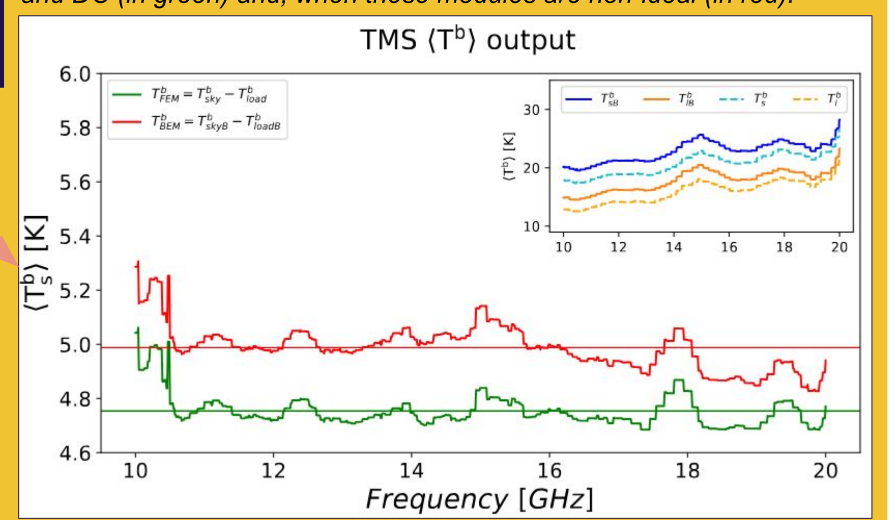
Characteristic values of insertion (L) and return (R) losses; LNA gains (g), and thermal noise (Tn) for TMS components.



Initial conditions:
- Sky temperature
- Load temperature
- Temp. stages of the cryostat

Software simulation Python

TMS output ΔT = Tb_{sky} − Tb_{load}, when the systems has a lossless BEM and DC (in green) and, when these modules are non-ideal (in red).

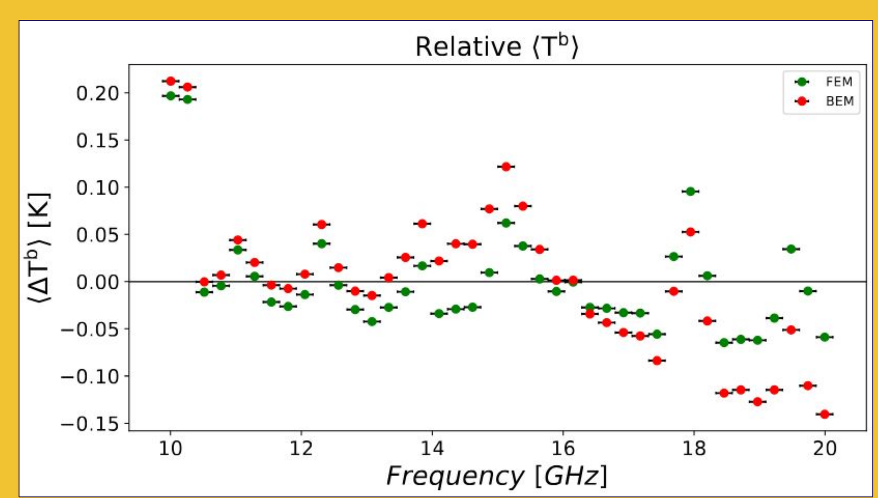


TMS Simulation: Absolute and Relative Measurement Results

Component	$\langle \delta T^b_c \rangle$ [K]
Sky chain	
δ_{Window}	$3.68 \pm (11\times10^{-3})$
δ_{IRF}	$0.54 \pm (1\times10^{-3})$
δ_{FHs}	$(60\pm1)\times10^{-3}$
δ_{OMTs}	$(110\pm2)\times10^{-3}$
$\delta_{Hyb\,(X)}$	$(120\pm2)\times10^{-3}$
Load chain	
δ_{FHl}	$(60\pm1)\times10^{-3}$
δ_{OMTl}	$(110\pm2)\times10^{-3}$
$\delta_{Hyb\,(Y)}$	$(110\pm2)\times10^{-3}$

Component	$\langle \Delta T^b_{1mK} \rangle$[K]
Window	1.98×10^{-6}
IRF	0.71×10^{-6}
FH_s	10.22×10^{-6}
Cold-structure	
OMT_s	41.59×10^{-6}
Hs_{180}	42.63×10^{-6}
FH_l	10.22×10^{-6}
OMT_l	41.59×10^{-6}
Hl_{180}	42.63×10^{-6}

Excess brightness temperature: mean and standard deviation per component (left), and **total average ΔTb increment** due to a 1 mK rise in component physical temperature (right).



The TMS consists of 40 sub-bands with a frequency width of approximately ±0.25 GHz. The figure shows the **ΔTb variation in each sub-band** after computing the average value over the sub-band, for the FEM (green), and the FEM+BEM (red).

Conclusions

1. Using Jones matrices, an analytic model for the Stokes parameters measured by TMS was derived. These equations are the starting point to design a calibration strategy. The gain (g_k) and phase difference (ψ) from the LNAs should be balanced with an accurate calibration strategy procedure. All instrumental contributions have to be calibrated in the laboratory or during the commissioning phase at the Teide Observatory.
2. The **ΔT** equation were obtained to calculate the absolute and relative temperature contributions into TMS system. Lossy parameters (R, L, SPO) contribute to the temperature variations measured by the system. Absolute and relative measurements results show that components such as Window, Feedhorns, Hybrids and OMTs need to be carefully characterized, and monitored in temperature.

1. Rubiño Martín et al. (2020), International Society for Optics and Photonics (SPIE), 114530T 2. Paz Alonso-Arias et al. (2023), Journal of Instrumentation (JINST), arXiv: 2309.07320 3. M. Bersanelli et al. (2010), A&A 520 A4, DOI: 10.1051/0004-6361/200912853 4. Fixsen, D. et al. (2021), The Astrophysical Journal, 734, 5 5. Bersanelli, M. et al. (1994), ApJ, 424, 517