ABSOLUTE CALIBRATION OF ECE DIAGNOSTIC: A FULL REVIEW

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In this work we provide a full review of the absolute calibration of ECE quasi-optical diagnostics, such as Fourier transform spectrometers. The optimisation of the overall process of averaging the interferograms to extract a reliable calibration curve are discussed. The basic assumptions, for example the linearity of the detector and the achievability of a given signal to noise ratio, are pointed out. Finally the actual physical meaning and the "accuracy versus precision" characteristics of the calibration curve are analysed.

1. Basic Concepts

Calibrated ECE measurements [1–3] are one of the principal sources of electron temperature data in Fusion experiments. Local Electron Temperature T_e can be inferred from the intensity of the emission measured by a spectrometer calibrated by replacing the plasma with a reference blackbody, whose emission characteristics are well known. The absolute spectral response of the system, i.e. the Calibration Curve **C**, is obtained by comparing the measured signal with the source known spectrum. The temperature **T** of a plasma spectrum, under black body conditions [4], is given by:

$$T = C^{-1} \times \text{Plasma Spectrum} \quad .$$

In order to provide the calibration of the whole system, without the need to make corrections for the vacuum windows, antennae and couplers, the calibration sources must be taken into the Tokamak vacuum vessel.

Among all the available spectrometers, the Michelson Interferometer [5,6] is particularly amenable to calibrate, given its high Signal to Noise Ratio (SNR).

Since T_e plasma >> $T_{calibration}$ (10^5 times or more) the SNR is much lower in calibration than in plasma measurement and long averaging is required.

The output signal of a Michelson Interferometer contains two types of background, normally negligible during plasma experiment, which ought to be eliminated or compensated for. The thermal background due to the emission of waveguides and other objects in the detector view field can be minimised by evaluating the signal difference between two sources at different temperature. The instrumental background, because of the intrinsic differential nature of the Michelson, is usually minimised by using roof-top instruments [7] (Fig. 1) and ultimately cancelled by using two different sources.

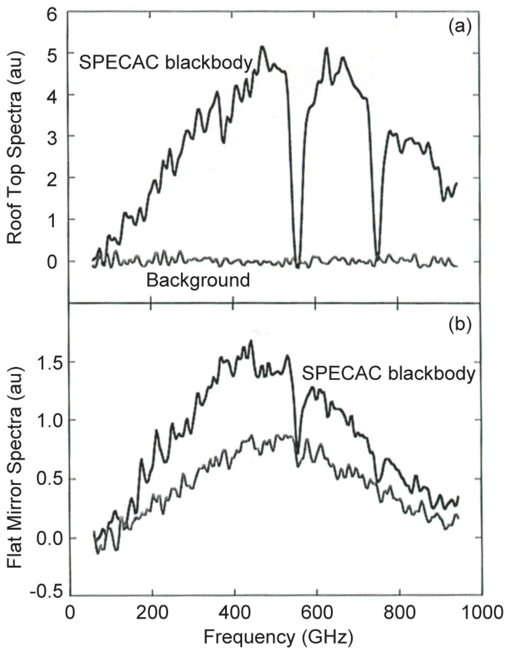

Figure 1. Comparison between hot source spectra (solid lines) and the corresponding instrumental background (shaded lines), (a) roof-top mirror, (b) flat mirror. ENEA Frascati [6].

A radiation attenuator is used during plasma measurements to prevent strong plasma emission to saturate detectors and pre-amplifiers. It consists of a wire grid placed between the Michelson and the detector with the angle between the ECE electric field and the wires adjusted to give the desired attenuation, usually ~3.

The attenuator is removed during calibration measurements from the torus to maximise the signal. A local calibration before and after re-installing the attenuator is used to determine the frequency (f) dependant multiplicative correction A(f) to be applied to plasma measurements.

It is often observed that this type calibration implies the extrapolation of the results over the million degrees temperature range from the calibration source to the plasma. This is a legitimate process, since the InSb detector linearity has been tested using microwave sources which have a high equivalent-temperature [8]. The wire grid attenuator response has also been proved to be linear in this range. It is worth underlining that the large extrapolation does not increase the measurement error since its relative value remains unchanged.

2. Physics of Calibration: the Rayleigh-Jeans Law

In the relevant frequency and temperature range for ECE measurements the classic approximation[*] hf << kT is valid, so the Rayleigh-Jeans (R-J) law can be used to calculate radiative emission[9]. In the well known traditional form it is:

$$I_{BB} = \frac{\omega^2 kT}{8\pi^2 c^2} \quad . \tag{1}$$

For single polarization black-body, the intensity (W/m^2) per unit solid angle and per unit radian frequency, can be written encompassing all the required constants in z [T (K)=1.16x10^4 T (keV), conversion radian to GHz etc.]:

$$I_{BB}(f,T) = z f^2\, \mathrm{T}(f) \quad . \tag{2}$$

The quantities involved in the spectral response measurement are:

$T_S(f)$ = frequency dependent radiation temperature of calibration source
T_R = frequency independent radiation temperature of reference source
$S_C(f)$ = measured calibration spectrum
G_C = amplifier gain for calibration experiment
$A(f)$ = frequency dependent attenuation of the wire grid polariser
$C(f)$ = measured spectral response
G_P = amplifier gain for plasma measurements
$S_U(f)$ = measured (uncalibrated) plasma spectrum

[*]h and K are Planck and Boltzmann constant

$S_P(f)$ = calibrated plasma spectrum

$T_e(f)$ = deduced frequency dependent radiation temperature of plasma

The signal measured by the Michelson is equal to the source spectrum multiplied by the spectral response and any gain/loss factors in the system. For the calibration measurement using Eq. (2):

$$S_c(f) = G_c\ C(f)\, I_{BB}(f,T) = G_c\ C(f)\, z f^2 \left[T_s(f) - T_R\right] \quad . \tag{3}$$

$S_C(f)$ is the output of the calibration measurement, the other parameters are known, so the absolute spectral response, i.e. the calibration $C(f)$ is:

$$C(f) = S_c \Big/ \left(G_c\ z f^2 \left[T_s(f) - T_R\right]\right) \quad . \tag{4}$$

To apply this calibration to plasma measurements (when the wire grid attenuator is installed) we need to multiply the measured plasma spectrum by A(f), and divide it by the amplifier gain G_P. The calibrated plasma spectrum is:

$$S_P(f) = S_U(f)\, A(f) \big/ \left[C(f)\ \mathrm{G_P}\right] \quad . \tag{5}$$

The opticallty thick plasma radiation temperature T_e is obtained from $S_P(f)$ by applying the R-J law. In this case T_R can be ignored, since $T_e >> T_R$.

$$T_e(f) = S_P(f) = S_P(f) \big/ \left(z f^2\right) \quad . \tag{6}$$

3. Accuracy vs Precision

The ***accuracy*** is a measure of how closely the experimental results agree with the true value. Determining the accuracy of a measurement requires calibration of the method against a known standard. The ***precision*** of the experiment is a measure of its reproducibility in multiple measurements (standard deviation or confidence interval). ECE measurements, given the good SNR, are usually ***precise***. Nevertheless the presence of systematic errors, due to mismatches between calibration and plasma configurations, can make them less ***accurate***.

The relative accuracy of calibrated ECE spectra can be improved with a technique using plasma pulses with magnetic field ramping [10]. If plasma conditions are kept reasonably constant during the ramp, the ECE spectrum remains unchanged and the calibration errors can smoothed out by averaging the spectra obtained at different fields. A relative correction curve for the calibration can be obtained as ratio between the spectrum at each field, and the average "true" one. This method improves ***relative accuracy*** of the measurement, but does not change the ***absolute accuracy***, nor it has any effect on the ***precision***.

4. Digital Averaging

The SNR in calibration is as low as 0.05, i.e. the noise amplitude is 20 times the signal. This situation can be improved by **coherent digital averaging**. The improvement results from the fact that the signal (buried in the noise) is the same for every sweep of the averager, and accumulates in each memory location in proportion to the number of sweeps. The noise is random and accumulates as the square root of the number of sweeps [11] proportional to the integration time T_i:

$$SNR(f) = \left[F(f)\,\Delta f / NEP\right] \times \sqrt{(T_i/4)} \quad , \qquad \text{where} \qquad (7)$$

$F(f)$ = Brightness Distribution (will assume the BlackBody at 600ºC)
Δf ~ 50 GHz (ECE 2nd Harmonic)
NEP = Noise Equivalent Power.

By assuming NEP ~ 3×10^{-12} $W\sqrt{Hz}$, the typical value of a InSb cryogenic detector, to obtain SNR ~ 10 an integration time T_i ~ 1500 s is required. This means 150 thousand interferograms for a 10 ms scan. An estimate coherent with common laboratory results.

5. Alternative Hardware Setup

In case of limited access to the vacuum vessel, a switching device can be used to direct the ECE waveguide to an exact antenna replica, located very close to the machine. This technique has been successfully used on FTU for many years (Fig. 2) and provides a regular calibration of the external ECE system [12].

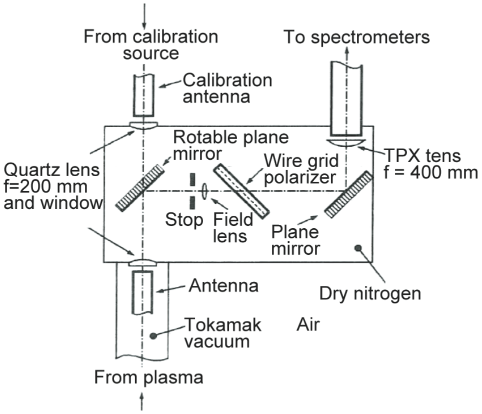

Figure 2. Optical box for external calibration with antenna replica (FTU).

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