ALMA Front-End Verification Using a Dry Cold Load

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***Abstract*— Several techniques for measuring the radiometric temperature (brightness) of a refrigerated dry calibration load for ALMA front-end verification are presented. The brightness of the load including the effects of the cryostat window is estimated using different techniques and compared at frequencies up to 1 THz. The measured results are compared with those obtained by a conventional calibration technique using the ALMF front-end. The estimated brightness shows a good agreement at lower ALMA bands (below 400 GHz) with increased deviation at higher frequencies. Measured noise temperatures of the ALMF front-end using a wet LN_2 load and the dry cold load are also presented.**

I. Introduction

Noise temperature is one of the crucial parameters that describe the performance of a high sensitivity cooled receiver. The noise performance of a receiver can be characterised by performing a relative measurement using thermal calibration loads with the radiated noise power or radiometric temperature known *a priori*. For a reference radiometric temperature, thermal calibration loads commonly use high emissivity absorbing materials immersed in liquid cryogen (wet load), which provides stable radiometric temperatures at stationary state. However, owing to the difficulties in handling of the wet load, the measurement could be cumbersome when the receiver under test needs to be measured repeatedly at different orientations. Verification of the Atacama Large Millimetre/submillimetre Array (ALMA) front-end [1] requires such a task, for which use of a closed cycle refrigerator cooled load inside a vacuum container, *i.e.*, a dry cold load shown in Fig. 1 is proposed. This will reduce the need for a liquid Nitrogen (LN_2) load and will ensure stable load temperature during measurement. Key requirements of the dry cold load for the characterisation of the ALMA receivers include a constant stable brightness temperature over a wide bandwidth up to 1 THz, polarisation insensitiveness, high emissivity, mechanical stability, etc.

For an ideal blackbody load (emissivity = 1), the radiometric temperature (brightness) of the load is identical to its physical temperature. The reflection from the load will add the same fraction of radiation from the surrounding environment to its original brightness, hence results in a modified overall radiometric temperature. Owing to the presence of the window and metallic surroundings in the dry cold load, the accurate estimation of the load brightness is challenging. The most significant factor that affects the performance of the dry load is the window characteristics, which are described by absorption and reflection coefficients.

In this paper, several techniques for estimating the brightness of the dry cold load by using a network model, Fourier transform spectroscopy and receiver calibration are presented.

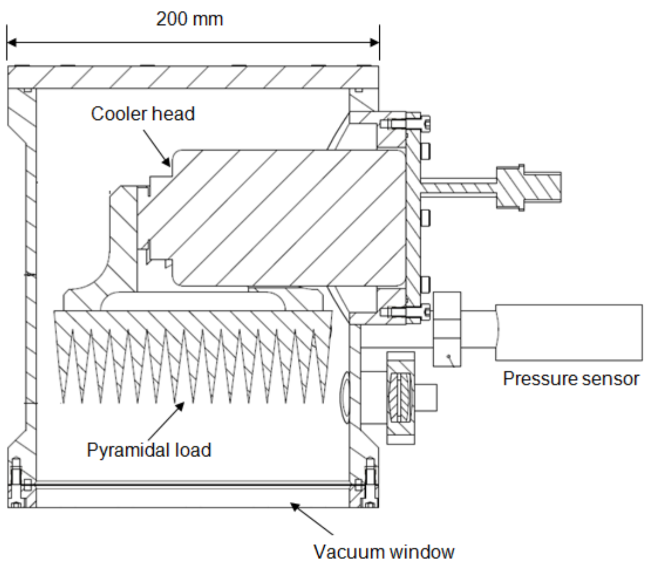

Fig. 1 Cross section of dry cold load

II. Load Design

The calibration target for the dry cold load shown in Fig. 3 is manufactured by the Rutherford Appleton Laboratory (RAL) and is based on a pyramidal absorber fabricated from cast epoxy that is loaded with ferrite to provide good absorption properties at microwave and millimetre-wave frequencies [2]. A corresponding pyramidal aluminium backing structure ensures that the surface of the absorber is no more than 2 mm from the aluminium, providing good thermal coupling between the absorber and the heat sink. The target load is mounted in a cryostat and cooled by a commercial cold head (Cryo Tiger T2114). The performance of the cooler is independent of orientation. To maintain a vacuum a 119 mm window of Mylar sheet with 23 µm thickness is used and this is backed (without using glue) by

50 mm of expanded polystyrene foam (FLOORMATE 700-A, Dow Chemical Co.) fitted in an aluminium frame attached to the cryostat for mechanical support. The geometry and photo of the dry cold is shown in Figs. 1 and 2, respectively.

The backscatter of the calibration target has been measured using a millimetrewave VNA. The maximum reflectance of the target was searched and recorded for the angle of incidence varied between -10° and +10°. The overall reflectance of the target was measured around -40dB at most frequencies within the band (75 - 360 GHz) as shown in Fig. 4. The polarisation sensitivity of the calibration target is also tested by rotating the target with a fixed incident polarisation (vertical electric field). The measured results showed that the target does not show significant variation in the maximum reflectance for different polarisations at normal incidence.

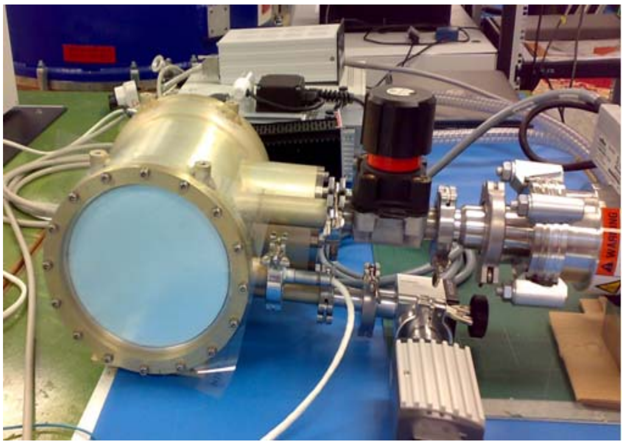

Fig. 2 Dry cold load connected to a vacuum pump and cooler

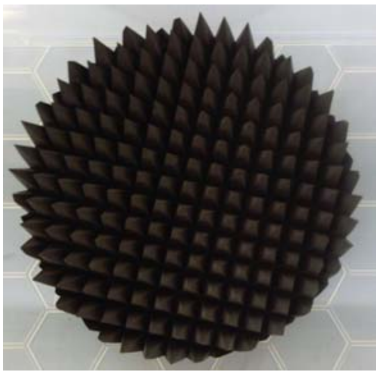

Fig. 3 Calibration target manufactured by RAL

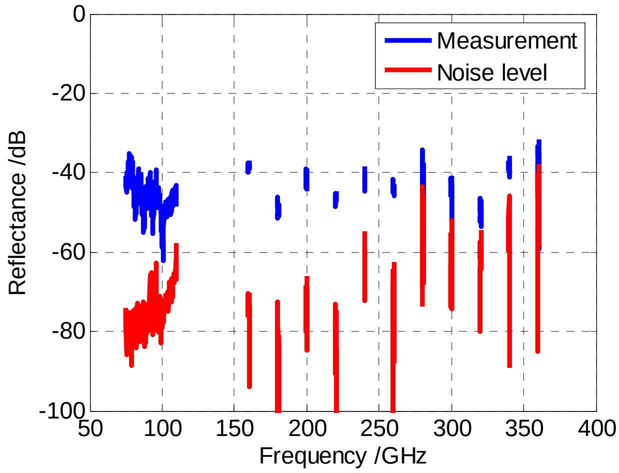

Fig. 4 Measured reflectance of the calibration target

III. Window Properties

Effects of the vacuum window on load performance must be minimal and provide transparent radiometric characteristics to the calibration target. Several low-loss materials have been investigated and it was found that combination of insulating foam commonly used for construction material and a Mylar sheet showed desirable performance. The window material introduces reflective and absorptive properties, which alter the effective brightness of the calibration load. Fig. 5a shows the simulated reflectance of commercially available Mylar sheets with different thicknesses. The insertion loss of the Mylar sheet is primarily due to reflection from the material. Fig. 5b shows the transmittance of the foam material measured using a Fourier transform spectrometer (FTS) [3].

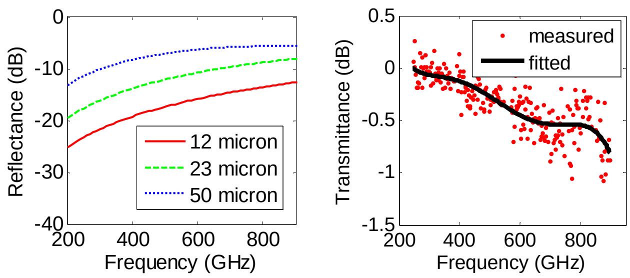

Fig. 5 Characteristics of the window material: (a) simulated reflectance of Mylar, (b) measured (FTS) transmittance of expanded polystyrene foam

IV. Effective Radiometric Temperature

If the radiometric temperature of the load is known, the overall effective brightness of the load, including the window effects, can be calculated using a microwave network model [4]. The window material is characterised by absorption and reflection coefficients and represented using the S-parameters. The overall brightness of the load is calculated using the model shown in Fig. 6. The S-parameters used for the investigation were extracted from reflectance and transmittance of the window materials shown in Fig. 5.

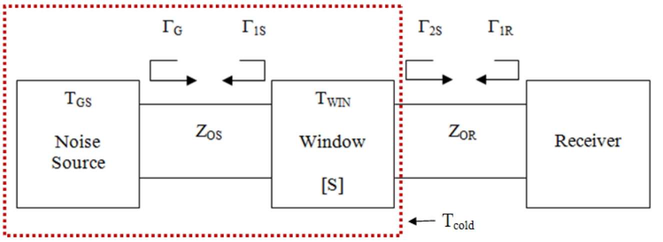

Fig. 6 Microwave network model of cold load problem (T_{GS}: radiometric temperature of the target, T_{WIN}: radiometric temperature of the window, T_{cold}: radiometric temperature of the cold load, Z_{OS}: characteristic impedance of the medium between the target and the window, Z_{OR}: characteristic impedance of the medium between the window and the receiver, Γ_G: reflection coefficients of the target, Γ_{1S}: reflection coefficients of the window, Γ_{2S}: reflection coefficient of the window, Γ_{1R}: reflection coefficients of the receiver, [S]: S-parameter of the window)

Owing to a low thermal conductivity of the window material, the temperature gradient within the window is ignored in the model and a uniform ambient temperature is used; however, in reality, the contribution of the reflection and absorption of the window to the overall radiometric temperature must be weighted by the temperature gradient within the window.

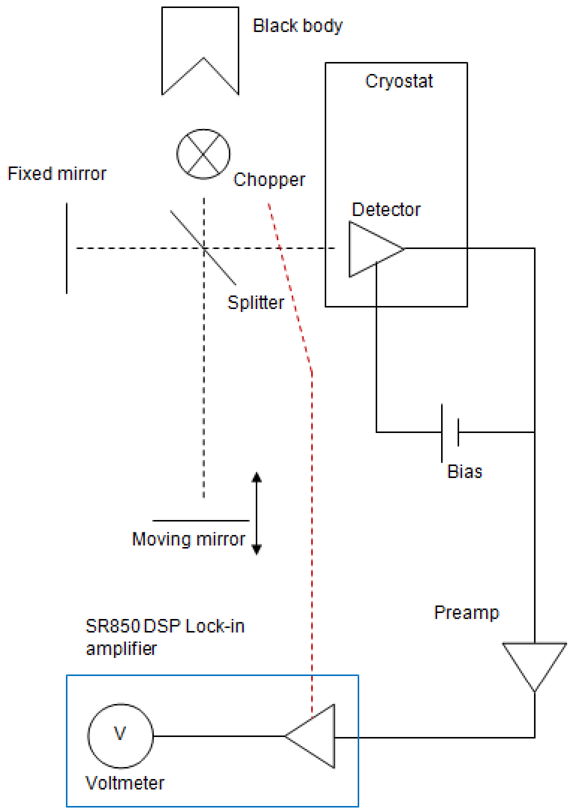

Fig. 7 Fourier Transform Spectrometer set-up

Direct observation of the radiated noise power from the load at upper ALMA bands (200 GHz – 1 THz) was performed using a Fourier transform spectrometer (FTS) and the detected power from the dry cold load was compared with those from an ambient and an LN_2 load. A cooled InSb hot electron bolometer detector system (QFI/2BI, QMC Instruments, Ltd.) was used for the measurement. For the reference load, microwave absorbing materials (Eccosorb® AN-72) [5] at ambient temperature and immersed in LN_2 were prepared. The radiometric temperature used for the LN_2 load is 77.35 K over the observed frequency. The reflection from the LN_2 load was ignored, but the true radiometric temperature of the LN_2 load is slightly higher than 77.35 K. The input of the detector was chopped at 680 Hz against the ambient load and the detector output was measured using a lock-in amplifier (SR-850, Standard Research Systems). The overall diagram of the set-up is shown in Fig. 7. The detected spectra for different loads are plotted in Fig. 8. The results were accumulated over eight times of measurements in order to reduce measurement noise. The radiometric temperature of the load is calculated by comparing the detector output of two reference loads (ambient and LN_2 loads). Effects of the optics (lens) at the load side are subtracted from the results. The performance of the dry cold load was found to be almost identical up to 250 GHz showing very similar radiometric temperature compared with the physical temperature of the target and beyond 250 GHz, the brightness gradually increases. There were several atmospheric absorption lines observed in the measured spectrum, and the measurements at those frequencies were ignored. The calculated brightness of the load based on the FTS measurements was fitted by a polynomial and compared later with results obtained by other techniques.

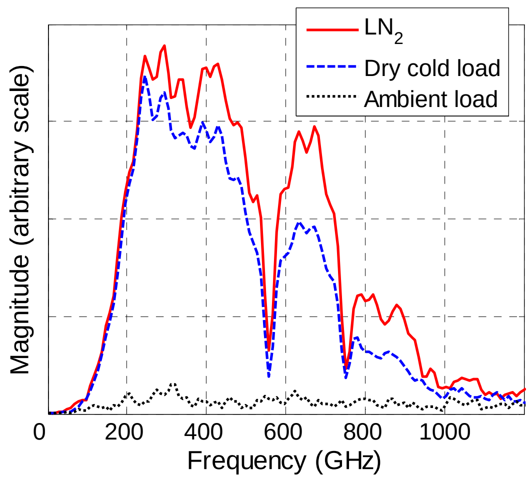

Fig. 8 Radiation spectra measured using FTS

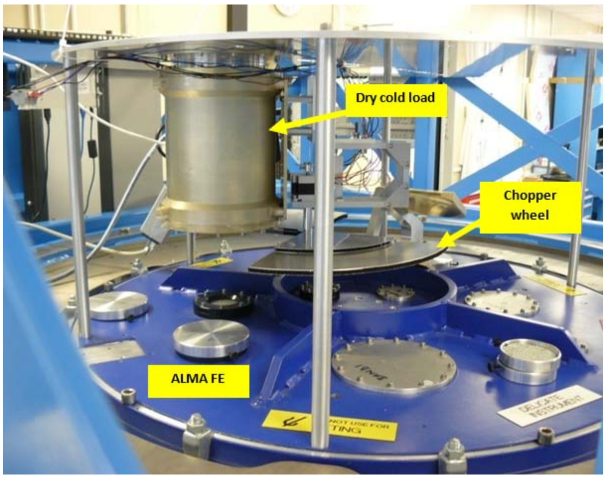

Fig. 9 Dry cold load installed at ALMA Front-End for receiver noise measurement

Finally, the brightness of the cold load was measured using the ALMA front-end receiver at Band 6 (221-265 GHz) and Band 9 (614-710 GHz). Fig. 9 shows the dry cold load installed on the ALMA front-end cryostat with chopper assembly. The standard Y-factor method was used to calculate the radiometric temperature of the load. For the calibration load, a cone of AN-72 absorbing material soaked in LN_2 and a sheet of AN-72 at ambient temperature were used. The radiometric temperatures estimated and measured by three different methods were plotted together in Fig. 10 for comparison. Good agreement was observed among three methods at lower frequencies, whereas some discrepancies, but with reasonable agreement in the trend, were noted at higher frequencies. These discrepancies are attributed to increased errors in the measured material properties used in the model and the assumptions made for the window, *e.g.*, temperature profile.

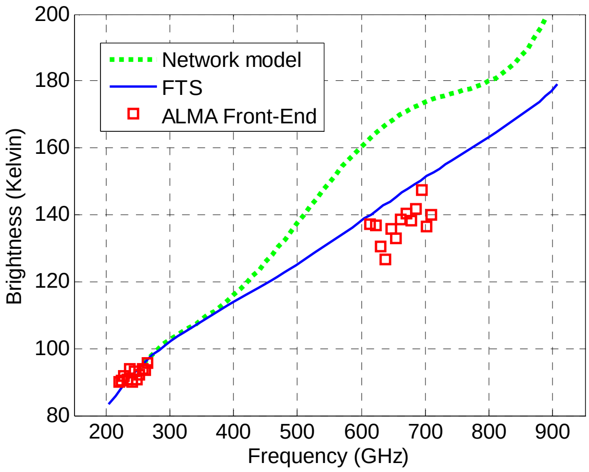

Fig. 10 Comparison of estimated and measured brightness

The receiver noise temperature of ALMA front-end at Band 9 was measured again using both the dry cold load and compared with the cartridge group data in Fig. 11.

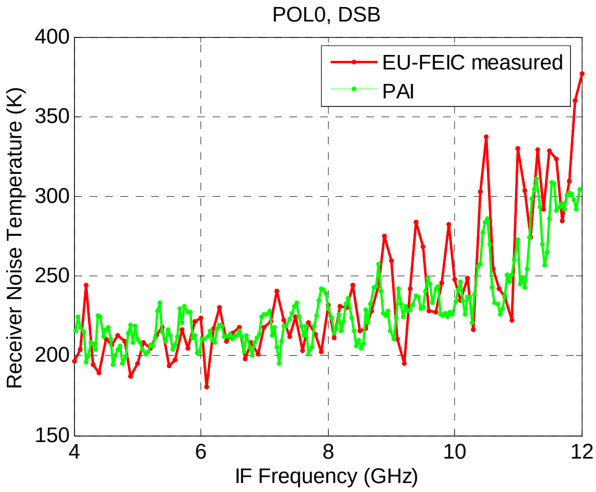

Fig. 11 Comparison of receiver noise temperatures (Band 9 LO = 614 GHz) measured at ALMA European Front-End Integration Centre (EU-FEIC) and reported in Preliminary Acceptance In-house (PAI) test results at cartridge group

V. CONCLUSIONS

The radiometric temperature of the dry cold load with a vacuum window has been measured using several techniques. A microwave network model based on the transmission and reflection characteristics of the window material is used to estimate the effective brightness of the dry cold load. The radiation spectrum of the dry cold load was directly compared with the liquid Nitrogen cooled and the ambient loads using the Fourier transform spectroscopy technique, and the effective brightness was calculated. Finally, the dry cold load was calibrated using the ALMA front-end. The performance of the dry cold load investigated by different techniques showed a good agreement in the estimated brightness. The FTS technique can be very effective for characterising calibration targets over a broad frequency range.

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