IMPLEMENTATION OF A TWO-TEMPERATURE CALIBRATION LOAD UNIT FOR THE SUBMILLIMETER ARRAY

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***Abstract*—A calibration load unit has been constructed and implemented for the Submillimeter Array (SMA). This unit incorporates an ambient load and a heated load, in addition to a waveplate assembly. The unit is installed inside the SMA antenna cabin near the compact image plane along the SMA beam waveguide. The loads are constructed from a matrix of 9 RAM tiles with a clear aperture diameter of 75 mm. The heated load is heated through the copper plate on which the RAM tiles are mounted, and the temperature of the plate is servo controlled. A 3 µm thick mylar window is used to reduce the effects of convection cooling. Both loads can slide in and out of the signal beam under computer control. The target temperatures of the ambient and heated loads are 15 and 55 degrees C respectively. An *in-situ* calibration procedure has been developed to calibrate the radiation temperature of the heated load. The procedure includes a modulated noise injection technique to remove any non-linearity of the receivers.**

***Index Terms*—Submillimeter wave receivers, superconductor-insulator-superconductor mixer, calibration**

I. INTRODUCTION

RECEIVER calibration in the laboratory is usually carried out using an ambient and a liquid nitrogen-cooled load in a Y-factor measurement. However, for routine operation in a radio telescope, a cryogenic temperature load is not always available. For a radio interferometer, such as the Submillimeter Array (SMA), where operators are responsible for tuning and optimizing many receivers at the same time, a two-temperature calibration unit is very valuable. The SMA has, thus far, been operating with the use of a single ambient temperature calibration load. The receiver output in response to the ambient load and the sky provides an approximate measure of the double-side-band system noise temperature. Receiver noise temperature is estimated with knowledge of the atmospheric opacity at the observing frequency, provided by the 225 GHz tipping radiometer or by sky dips. The actual flux from astronomical objects is determined by observing calibrators (objects with known radio flux) either at the end of an observation track or interlaced in the track.

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A two-temperature calibration unit is desirable since it provides a direct measure of the receiver noise temperature, allowing direct receiver optimization, and it is also a useful tool in precise flux measurements. This is particularly important in the observation of bright objects, such as planets, for which there is relatively large swing of receiver output power when the antennas are switched from on source to off source. In addition, the use of a two-temperature calibration unit can diagnose spectral baseline issues. A flat baseline will be instrumental in the current effort at the SMA to use atmospheric ozone lines for atmospheric phase correction [1].

In this paper, we describe the construction of the two-temperature calibration loads recently installed in the SMA. A calibration procedure has been developed. We also discuss calibration uncertainties.

II. CONSTRUCTION OF THE CALIBRATION UNIT

The calibration unit is installed near an intermediate beam waist in the SMA beam waveguide [2]. The required load size is therefore very small; we have used a clear aperture of 75 mm diameter but only the central 25 mm part of the load is nominally illuminated by the receiver. The load position corresponds to a pupil plane of the telescope such that all the receivers see the same geometrical area of the load. The three fold size margin of the loads should eliminate any diffraction or truncation effects.

Fig. 1 is a photo of the entire calibration load assembly. It consists of 3 sub-assemblies. In order from the receiver towards the sky, there is a rotatable quarter-wave-plate unit for circular to linear polarization transformation, followed by the heated load assembly, and finally the ambient load assembly. Each of the sub-assemblies is mounted on a linear actuator and can slide into the receiver beam independently under computer control. Typical travel time into or out of the beam is about 0.5 second.

Both the ambient and heated loads are made from a square matrix of 3x3 Thomas Keating RAM tiles (25 mm x 25 mm each) [3, 4]. The interlocking tiles are set on a copper plate. In the case of the heated load, each tile is attached to the plate with a nut through its back stub. In addition, four springs provide further contact force pushing the 4 corner pieces against the copper plate. A flat heater is cemented to the back of the copper plate. An electronic and computer interface allows the temperature of the copper plate to be kept constant. Testing in an environmental chamber showed that the tiles could withstand prolonged days of heating to above 100^{o} C. In order to maintain a reasonable safety margin and because of gain compression issue, the maximum set point of the heated load is limited to below 65 ^{o} C. A small temperature sensor (Analog Device 590) is inserted into a small side hole in one of the tiles to more directly measure the tile temperature which is typically a few degrees below that of the copper plate. Finally, a thin mylar window is used in the heated load to reduce air convection.

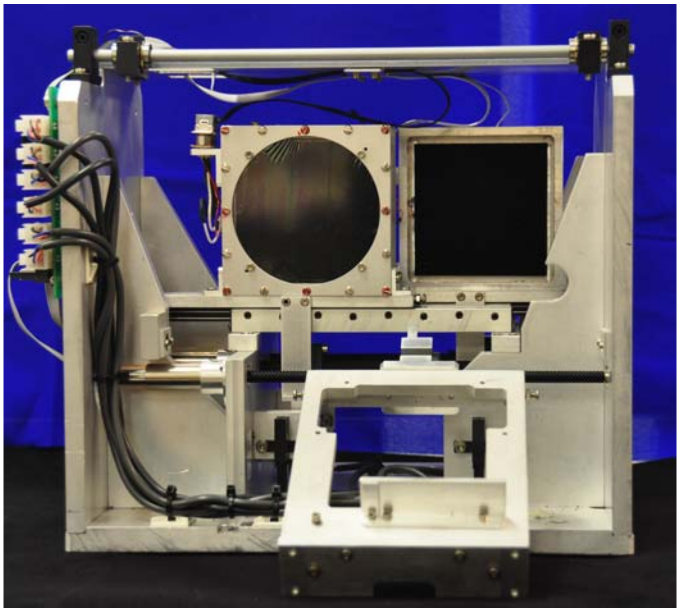

Fig. 1. Front view of the SMA calibration load assembly (taken from the receiver side). In this photo, the rotatable quarter-wave plate module has been removed and its carrier is flipped down to allow a better view of the heated and ambient loads. All 3 sub-assemblies are mounted on carriers that can be translated horizontally into or out of the signal beam. Note that the heated load is equipped with a 75 mm diameter window, which is absent in the ambient load.

III. Return Loss of the Heated Load

We have studied the input return loss of the loads by measuring the output power spectra of the receiver with an FFT spectrometer. Since the SIS receiver is generally not well matched, standing waves will be present if the return losses of the loads are not small enough. Standing waves in the beam waveguide lead to baseline ripples in the receiver IF output spectrum. Because the SMA operates in double-side-band (DSB) mode, the amplitude of the baseline ripples depends on whether the standing waves associated with the two sidebands are in constructive or destructive interference, which in turn depends on the Local Oscillator (LO) frequency. Since the optical path between the loads and the receiver is about 3.3 meters, a 45 MHz periodic ripple is observed in the output power spectra. The magnitude of the standing waves can be studied and accessed by tuning the LO frequency over a cycle of the baseline ripple pattern to find its maximum amplitude as observed in the DSB IF output spectrum.

By taking the ratio of the receiver power spectrum with the hot load in the signal beam to that of the ambient load, which is equivalent to taking spectral Y factor measurements, we can compare the return losses of different load configurations. It is found that the heated load is generally poorer in return loss, primarily due to its window. We have tried different window materials, and our final choice is a 3 µm thick mylar film, which is both electrically thin even for our highest operating frequency and is effective in reducing convection cooling of the front surface of the heated load.

In an effort to further improve the performance of the loads, we have determined empirically that a rotation of 3 degrees about a vertical axis can further reduce the baseline ripples.

IV. Load Calibration Procedure

Since the ambient load is in thermal equilibrium with the environment, we can assume that its radiation temperature is that of the ambient temperature. A commercial grade precision temperature sensor, with calibration traceable to NIST standard, is mounted on the ambient load to provide accurate temperature measurements.

For the heated load, its radiation temperature is determined from the receiver responses to a liquid nitrogen cooled load and an ambient load. Since the SIS receiver is unlikely to be perfectly linear, a two-step calibration procedure is employed. First, its approximate temperature is determined by assuming that the receiver is perfectly linear. Then any gain compression of the receiver is measured using an injected modulated signal method [5], from which the correct load temperature is derived.

A. Linear Calibration

For a linear receiver, the radiation temperature of the heated load is given by:

$$T_{hot} = T_{amb} + \frac{(P_{hot} - P_{amb})}{(P_{amb} - P_{cold})}(T_{amb} - T_{cold}) \qquad (1)$$

where P_{hot}, P_{amb} and P_{cold} are the receiver output power in response to heated, ambient and cold loads respectively, and T_{hot}, T_{amb} and T_{cold} are their physical temperatures respectively. The above equation gives accurate result if the receiver gain is stable. In the presence of gain fluctuations, the result T_{hot} would exhibit statistical variations.

The SMA cryostat currently operates without any temperature stabilization scheme. The 4 K stage exhibits temperature fluctuations of about 20 mK over a 60 – 80 second cycle, with more irregular temperature spikes occurring every 5 – 10 cycles. Thus, the measurement of P_{hot}, P_{amb} and P_{cold} should be performed as quickly as possible to minimize the effects of receiver gain fluctuations induced by cryogenic temperature changes. In our measurement setup, we are able to cycle through the three temperature loads in 7 seconds. A series of measurement cycles are performed and the derived value of T_{hot} exhibits a standard deviation of about 0.25 K.

B. Linearity Calibration

In the second phase of calibration, the linearity of the receiver is probed by injecting a modulated signal into the LO unit [5]. This method was adapted from an approach proposed by Kerr *et al* [6]. In the present procedure, instead of injecting a CW signal, a noise source is employed, which eliminates the effects of standing wave associated with any particular frequency. The band-limited injected noise is up-converted by the frequency multiplier in the LO unit, providing a very low level double-side-band AM modulation to the LO. This modulation is down-converted by the single-ended SIS mixer. The 1 kHz modulation can then be recovered using a power detector at the receiver output using a lock-in amplifier. The strength of the injected noise source is adjusted so that the detected modulation power represents ~1% of the total power at the receiver output when the receiver input is terminated by an ambient load. This same technique is used to study the linearity of THz Hot-Electron Bolometer mixer [7].

For small deviation from linearity, we model the receiver output power as:

$$P_{out}(T_{load}) = P_0 + mT_{load} - \alpha T_{load}^2 \qquad (2)$$

The voltage measured by the lock-in amplifier, U, is proportional to the slope of the above equation. Note that for a linear receiver, the lock-in amplifier should register the same voltage irrespective of the load temperature. In the presence of gain compression, it is clear that the lcok-in voltage corresponding to the cold load, U_{cold} , should be bigger than that corresponding to the ambient load, U_{amb}. Let R_{amb} be the ratio U_{amb} / U_{cold} .

$$R_{amb} = \frac{U_{amb}}{U_{cold}} = \frac{m - 2\alpha T_{amb}}{m - 2\alpha T_{cold}} \approx 1 - 2\frac{\alpha}{m}(T_{amb} - T_{cold}) \qquad (3)$$

Using the data from the first and second step of the measurement procedure, the coefficients in equation (2) can be solved, and P_{hot} can be mapped to T_{hot}. Since the lock-in amplifier has a very high dynamic range, the value of R_{amb} can, in principle, be determined fairly accurately. Accuracy is limited by receiver gain fluctuations. In our measurements, the standard deviation for R_{amb} is between 0.4 – 0.8 %. The receiver gain compression is expected to increase with temperature. We have, therefore measured the value of the ratio $R_{hot} = U_{hot}/U_{cold}$.

V. Results and Discussion

As of April 2009, three complete calibration units have been installed in the SMA. The SMA antenna cabin is maintained at a temperature of about 15° C. Initially, we have set the copper plate in the heated loads to 65 ° C. We found that such an arrangement caused the ambient load to be heated above the ambient temperature of the cabin because of its proximity to the heated load. Subsequently, we have reduced the copper plate servo temperature to 55 ° C. This reduces the heating effect of the heated load on the ambient load. At this set point, the temperature sensor buried inside the RAM of the heated load registers temperatures of between 50 ° and 52 ° C, indicating a few degrees drop between the copper plate and the RAM material.

The equivalent radiation temperature of the heated load, calibrated by the above procedure, is a few degrees below that indicated by the temperature sensor inside the heated load RAM. Clearly, the radiation temperature is related to the surface temperature of the RAM which is an insulating material. Table 1 gives the calibration data for one of the heated load measured with the SMA 200 GHz receiver [8]. For this data set, the copper plate of the heated load was 65 ° C.

It is noted from Table 1 that the SMA 200 GHz receivers have non-negligible gain compression for an ambient input load, which increases with decreasing frequency (or decreasing width of photon step) [9]. The calibration procedure appears to be successful in removing this effect because the final calibrated temperature shows little frequency dependence. Clearly, the successful application of the calibration load depends on a knowledge of the amount of gain compression of the receiver in normal operation. The measured values of R_{hot} is only slightly smaller than that of R_{amb} showing that gain compression is not significantly different between the ambient and heated loads.

The same procedure has been used in the 300 GHz receiver. For this frequency range, the values of R_{amb} and R_{hot} are somewhat higher: between 0.92 and 0.97, corresponding to gain compression below 5% with the ambient load. Therefore, the temperature correction needed to account for deviation from linearity is smaller. However, the calibrated temperature shows some weak frequency dependence. It is believed that this is a result of the poorer match of the receiver, especially near the band edges. Further investigation is being pursued.

VI. Conclusion

A two-temperature calibration load unit has been designed and is being installed in the Submillimeter Array. The assembly consists of an ambient (15 ° C) and a heated load with low return loss in the submillimeter band. The heated load offers a radiation temperature ~50 ° C. Both loads can be moved into the intermediate beam waist of the SMA beam waveguide in ~0.5 seconds. An *in-situ* calibration procedure has been developed to determine accurately the equivalent radiation temperature of the heated load. Using the modulated injection noise technique, the calibration procedure takes the gain compression of the SIS receiver into account. This calibration unit will be used in receiver optimization and calibration, allowing a more accurate measurement of sub-millimeter flux.

TABLE I Calibration Data of Heated Load Installed in SMA using SMA-200 GHz Receiver

LO Freq. (GHz)	Calibrated Ambient Temp (C)	Heated Load sensor Temp (C)	T_{hot} assuming linear receiver (from eq. (1))	Ratio of Lock-in voltages		Final Calibrated Temperature T_{cal} (C)	Percentage of gain compression @ T_{amb}
				R_{amb}	R_{hot}		
215	14.01	59.0	52.45 ± 0.25	0.881 ± 0.004	0.877 ± 0.009	55.4 ± 0.3	8%
225	14.54	59.1	53.10 ± 0.13	0.911 ± 0.005	0.907 ± 0.008	55.2 ± 0.2	6%
235	14.34	59.0	53.83 ± 0.34	0.940 ± 0.008	0.937 ± 0.011	55.2 ± 0.4	4%

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