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ON MEASURING LOW NOISE TEMPERATURES

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Introduction

The introduction of low noise masers into the repetoire of NRAO receivers challenges the long used methods of measuring noise temperatures. The uncertainty in the value of the liquid N_2 cold load makes the traditional hot/cold load Y-factor method suspect when noise temperatures less than 30 Kelvin are encountered. Measurements at short wavelengths serve to compound this problem. In this paper we offer an alternate method based on a quantity called the operating temperature and using the sky as a cold load. This method has been used for some time at the Jet Propulsion Laboratory, and we are in their debt for bringing it to our attention.

Discussion

If we attach a feed horn to the receiver input and point this toward the sky, we can define the operating temperature as:

$$T_{op} = T_{sky} + T_{horn} + T_{receiver} \quad [1]$$

We note that this differs from the system temperature in that the contributions from the antenna (other than the feed horn loss) are not included (i.e., spillover). If we now cover the feed horn with ambient temperature absorber material and define the resulting Y factor as Y_{sky}, then:

$$T_{op} = \frac{T_{absorb} + T_{horn} + T_{receiver}}{Y_{sky}} \qquad (1)$$

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[1] JPL prefers to define T_{op} without including the second stage contribution, but I don't propose to start that game at NRAO.

In order to assign a value to T_{op}, after measuring Y_{sky}, we must estimate the values of T_{horn} and $T_{receiver}$. Investigating the maximum error this estimation might produce, we note that the lowest value T_{op} can ever assume is for a perfect receiver, i.e., $T_{horn} + T_{receiver} = 0$. Thus,

$$T_{op\ (min)} = \frac{T_{absorb}}{Y_{sky}} \tag{2}$$

Similarly the maximum T_{op} would be for a perfect cold load ($T_{sky} = 0$), when $T_{op} = T_{horn} + T_{receiver}$. Thus,

$$T_{op\ (max)} = \frac{T_{absorb}}{Y_{sky} - 1} \tag{3}$$

We will see that the maximum and minimum values do not differ greatly for a typical maser receiver, since Y_{sky} is usually ≥ 10 dB.

The operating temperature is of most interest to the user, and defines the maser performance when used as the prime amplifier. However, for engineering purposes or in applications where the maser is to be used as an IF amplifier, we wish to determind the equivalent maser noise temperature. First, we note that:

$$T_{receiver} = T_{maser} + T_{2nd}$$

As pointed out in the introduction, the standard hot/cold load method results in substantial uncertainty in the value of $T_{receiver}$. (Typical masers will give a Y factor > 5 dB when using a liquid N_2 load.) An alternate measurement can be made in the case of the reflected wave maser currently in use at NRAO. By placing a hot load and a short on the maser input we obtain:

$$Y_{short} = \frac{T_{hot} + T_{maser} + T_{2nd}}{T_{load} + 2T_{line} + T_{structure} + T_{2nd}}$$

where:

T_{load} = temperature of input isolator load which radiates out input of maser and should be equal to the maser bath temperature of about 4.6 Kelvin.

T_{line} = noise contribution of maser input waveguide.

$T_{structure}$ = equivalent noise temperature of maser at circulator input flange.

For the NRAO K-band masers:

$$T_{load} \simeq T_{structure} \quad [2]$$

Thus:

$$Y_{short} \simeq \frac{T_{hot} + T_{maser} + T_{2nd}}{2T_{maser} + T_{2nd}}$$

and

$$T_{maser} \simeq \frac{T_{hot} - (Y_{short} - 1)\, T_{2nd}}{2Y_{short} - 1} \tag{4}$$

To find T_{2nd}, we place the hot load on the input, turn off the maser pump and define:

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[2] $T_{structure}$ is actually related to the bath temperature, the gain and unpumped loss, and the circulator losses; and equals 4 Kelvin (theoretically) for the K-band maser.

$$Y_{on/off} = \frac{(T_{hot} + T_{maser} + T_{2nd})\, G_{maser}}{L_{maser}\, T_{hot} + T_{maser(off)} + G_{maser}\, T_{2nd}}$$

$Y_{on/off}$ is the ratio of noise power referred to the maser output and:

L_{maser} = 1/2 maser electronic gain in dB, or $\approx$ 20 dB.

$T_{maser(off)}$ = Temperature of L_{maser} pad at T_{bath}, or $\approx$ T_{bath}.

Then:

$$Y_{on/off} = \frac{T_{hot} + T_{receiver}}{\dfrac{L_{maser}\, T_{hot} + T_{bath}}{G_{maser}} + T_{2nd}} \simeq \frac{T_{hot} + T_{receiver}}{T_{2nd}}$$

Rearranging:

$$T_{2nd} = \frac{T_{hot} + T_{receiver}}{Y_{on/off}} = \frac{T_{hot} + T_{maser}}{Y_{on/off}} \; \frac{Y_{on/off}}{Y_{on/off} - 1}$$

Since $Y_{on/off}$ is usually > 20 dB,

$$T_{2nd} \simeq \frac{T_{hot} + T_{maser}}{Y_{on/off}} \qquad (5)$$

With the use of equations (1), (4), and (5) and measurements of Y_{sky}, Y_{short} and $Y_{on/off}$ one can, in a few iterations, assign values to T_{maser}, T_{2nd} and T_{op} to a high degree of certainty.

Example:

To demonstrate the previous discussion, consider the K-band maser recently developed at JPL. At 22 GHz the measured Y factors are:

$$Y_{sky} = 9.6 \text{ dB}; \quad T_{absorb} = 298 \text{ Kelvin.}$$

$$Y_{short} = 10.5 \text{ dB}; \quad T_{hot} = 298 \text{ Kelvin.}$$

$$Y_{on/off} = 24.2 \text{ dB}; \quad T_{hot} = 298 \text{ Kelvin.}$$

From equation (4):

$$T_{maser} \simeq \frac{298 - 10\, T_{2nd}}{21} = 14.2 - \frac{10}{21} T_{2nd}.$$

From equation (5) and estimating $T_{maser} = 13.5$ K from above:

$$T_{2nd} \simeq \frac{298 + 13.5}{263} = 1.2 \text{ Kelvin.}$$

Then using equation (4):

$$T_{maser} = 13.6 \text{ Kelvin.}$$

From equations (2) and (3):

$$T_{op(min)} = \frac{298}{9.1} = 33 \text{ Kelvin}$$

$$T_{op(max)} = \frac{298}{8.1} = 37 \text{ Kelvin.}$$

Thus:

$$T_{sky} + T_{horn} + T_{maser} + T_{2nd} \simeq 35 \text{ Kelvin}$$

and

$$T_{sky} + T_{horn} \simeq 20.2 \text{ Kelvin.}$$

Estimating T_{horn} = 3 Kelvin and T_{sky} = 17 Kelvin, then from equation (1):

$$T_{op} = \frac{298 + 3 + 13.5 + 1.2}{9.1} = 34.7 \text{ Kelvin.}$$

Using this value for T_{op} we can determine the following noise temperature budget:

T_{sky}	17	Kelvin — 3 K black body, 2 K O_2, 12 K H_2O.
T_{horn}	3	Kelvin
T_{maser}	13.5	Kelvin
T_{2nd}	1.2	Kelvin
T_{op}	34.7	Kelvin

Summary

In summary, the useful equations for determining low noise temperatures of maser receivers are:

$$T_{op} = \frac{T_{absorb} + T_{horn} + T_{maser} + T_{2nd}}{Y_{sky}} \tag{1}$$

$$T_{maser} \approx \frac{T_{hot} - (Y_{short} - 1)\, T_{2nd}}{2Y_{short} - 1} \tag{4}$$

$$T_{2nd} \approx \frac{T_{hot} + T_{maser}}{Y_{on/off}} \tag{5}$$

It should be remembered, however, that equation (4) is an approximation valid only for a reflected wave maser when the equivalent structure noise temperature is approximately equal to the temperature of the input isolator load.