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TO: VLBA Electronics Group

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SUBJECT: Thermal Behavior of External Front Ends

One of the important goals in VLBA design is to minimize phase shifts in the signal over time, since these will add errors directly to the observational results. The most important factor which introduces these phase shifts is the effect on components of temperature change, which thus must be minimized.

One area of particular difficulty in keeping component temperatures constant is in the 330 and 610 MHz front ends. These will be mounted externally, thus exposing them to a wide range of temperatures similar to the VLA 330 MHz front end. For this reason, various tests and modeling of the VLA 330 MHz front end thermal behavior were made to gauge the magnitude of the problem.

A picture of the VLA 330 MHz front end appears in Figure 1.

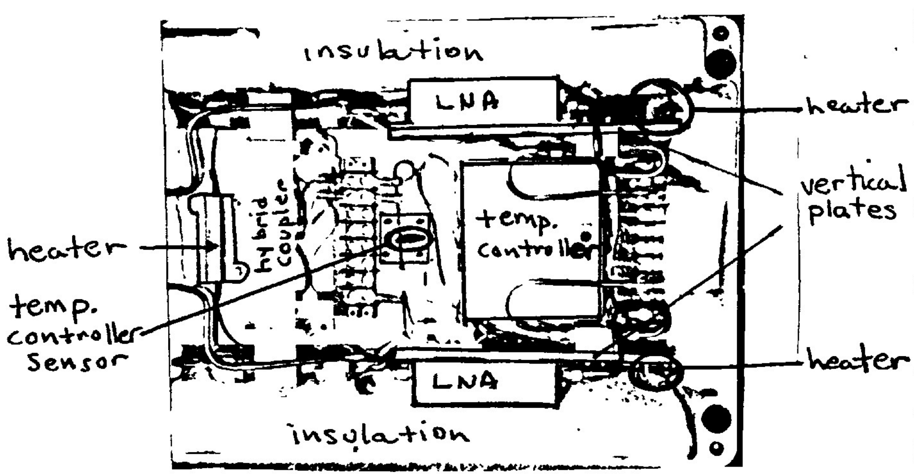

Fig. 1. Inside of 327 MHz front end, showing temperature controller, LNA's, temperature sensor, and heater resistors.

Its temperature control system consists of a proportional controller connected to a temperature sensor and some high power resistors used as heaters. All of these are bolted to a modified Aluminum channel which distributes the heat to the various amplifiers and couplers. The temperature controller works as depicted in Figure 2.

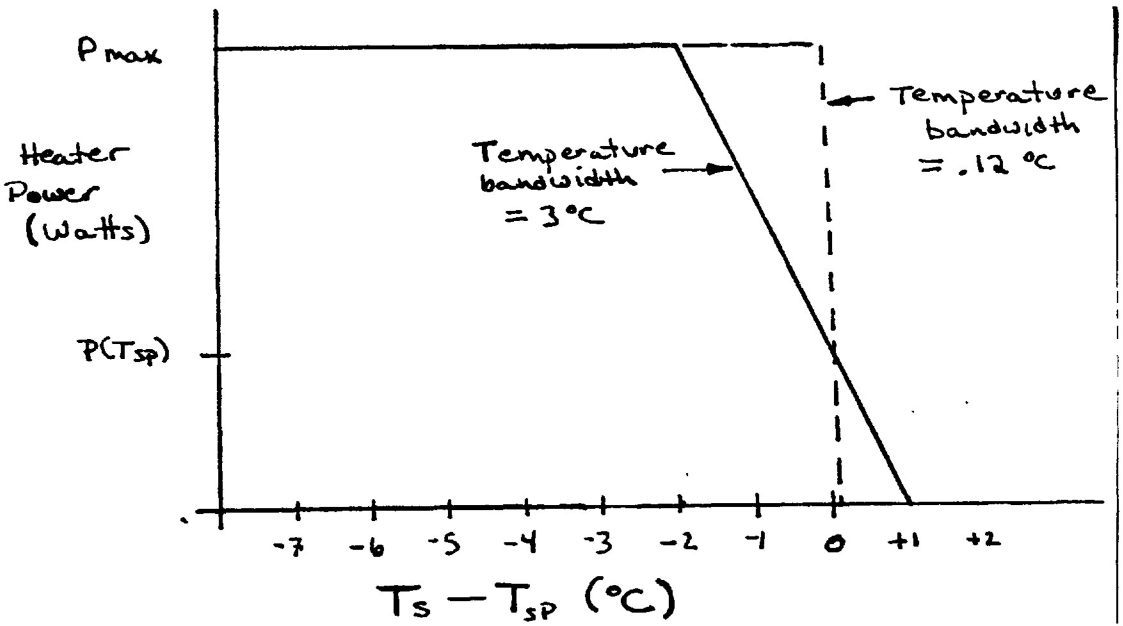

Fig. 2. Temperature controller heater power versus deviation of sensor temperature from set point temperature.

The set-point temperature, T_{sp}, is the temperature that the controller will maintain at the sensor. The sensor temperature, T_s, is supposed to be within ± 0.03 deg C of T_{sp}.

For temperatures below a certain value, the power into the resistors is a maximum (in this case 99.3 watts nominal) determined by the values of the resistors. The difference between this temperature, and that at which the power goes to zero is the proportioning "bandwidth", adjustable between 0.12 and 3.0 deg C in the Oven Industries 5C1-213P used here. This bandwidth is set to most quickly compensate temperature deviations without oscillation in temperature. If the item being controlled is of low heat capacity and the bandwidth is too narrow, the high value of dP/dT will cause the controller to deliver too much power when the temperature deviates, and the temperature will over shoot. If the BW is too wide, the controller will not return the object to the right temperature as fast as possible.

The VLA 330 MHz front end as a whole can be modelled as a simple bulk thermal system consisting of a thermal mass with heat capacity (C) connected to a heat source of power (P). The thermal mass represents the Aluminum plate and amplifiers, and the heat source models the heater resistors attached to it. The thermal mass is also connected through a thermal resistance of heat conduction K_T to an isothermal region of temperature T_a which represents the air around the enclosure.

The equation describing this model is:

$$P - K_T(T-T_a) = CdT/dt = Q \qquad (1)$$

where T is the temperature of the mass, t is time and Q is the total heat flow to the system per unit time.

The heating represented by P comes from three sources,

Waste heat from amplifiers: 1.74 watt
Temperature controller circuitry: 2.40 watt
Temperature controller heaters: 0 to 99.3 watt

The two quantities K_T and C are not known a priori, and must be measured. Several methods were used to measure them. The first was to heat up the system, while observing the heating rate with constant heat applied. Following this, the temperature controller was disconnected, and the system allowed to cool down. Since $K_T(T-T_a) << P$ for the warm-up, T increases linearly in time. The cool-down is exponential. This follows from solving the above equation for T(t) assuming constant $P=P_o$:

$$T' = T_s' e^{-t/\tau} \qquad (2)$$

where

$$T' = T - (T_a + P_o/K_T)$$

$$T_s' = T_s - (T_a + P_o/K_T)$$

T_s = sensor temperature at start

$\tau = C/K_T$ is the system time constant

For the cool-down, P_o is just the waste heat produced by the amplifiers, about 1.74 watts.

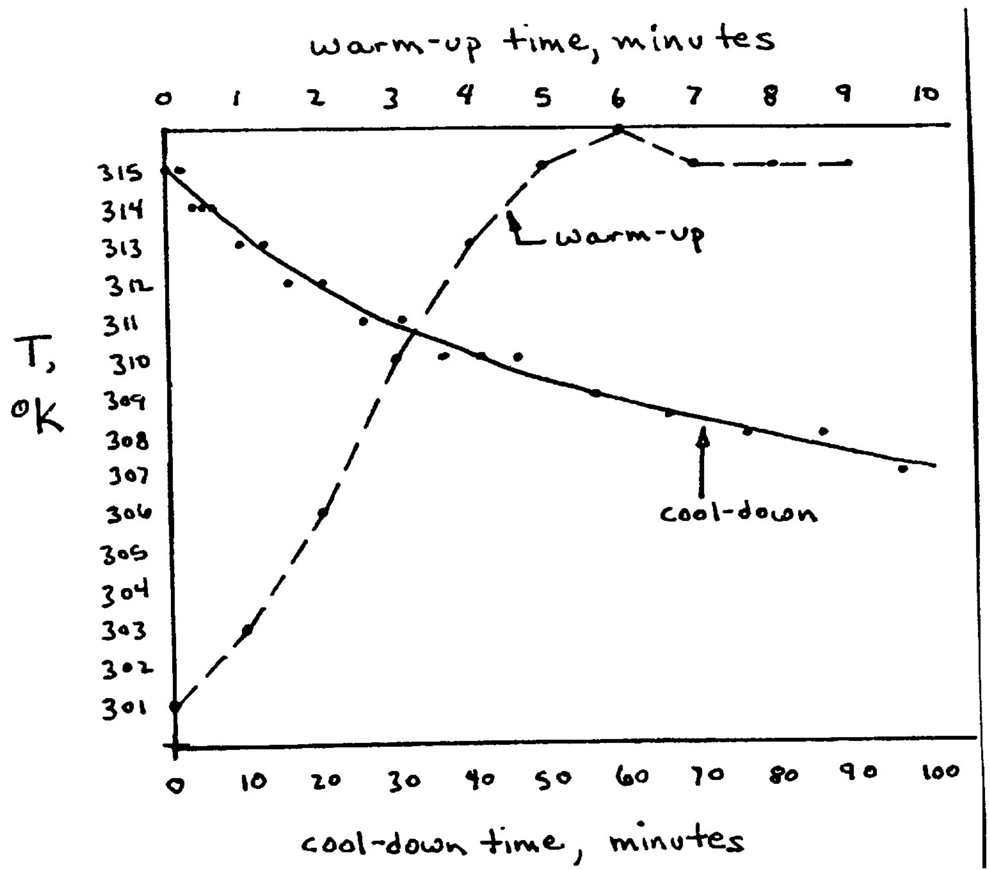

Fig. 3. 327 MHz front end temperature versus time for heat-up and cool-down.

The values derived from this analysis:

$C = 1839\ J/^oK$

$K_T = 0.456\ W/^oK$

Since these tests were taken over a $T-T_a$ range of about 15 deg K, $K_T(T-T_a)$ is indeed much less than P for warm-up (6-8 watts vs. 103 watts). However, the values for C and K_T have been corrected for warm-up by subtracting $K_T(T_s-T_a)/2$ from P.

A couple alternative methods were used to measure K_T. They both involved keeping the internal temperature constant and measuring the power supplied to the resistors. This gives a value for K_T only, since $CdT/dt = 0$.

The first measurement method consisted of measuring the power input to the front end box with two different ambient temperatures. The second method was to raise the ambient temperature just until the temperature controller shut off the heaters. The results of these measurements are presented below:

Method	T_s (deg C)	T_a (deg C)	P(W)	K_T (W/deg K)
1	45	7.5	17.69	0.47
1	45	24.5	9.22	0.45
2	45	33.7	4.14	0.37

The first two K_T values agree pretty well with the first measurement shown earlier. The last is not so close, but this is probably due to the difficulty of accurately determining the temperature at which the controller shuts off the heater resistors.

The important operating parameters which can be deduced from the measurement of K_T are the minimum and maximum ambient temperatures at which the temperature controller will work. From equation (1), if $dT/dt = 0$,

$$T_a = T_s - P/K_T \tag{3}$$

The minimum value of P is 4.14, the total waste heat, the maximum value is 103.4 so, taking $K_T = 0.456$,

$$T_a(\text{min}) = T_s - 227 \text{ deg C}$$
$$T_a(\text{max}) = T_s - 9.1 \text{ deg C}$$

Evidently there is no difficulty with the minimum temperature. The maximum external temperature, however, must be at least 9 deg below the internal temperature.

Within the limits of the temperature extrema above, the most troublesome aspect of the external front ends for VLBA use are temperature variations inside the enclosure. The variation in phase shift of the 330 MHz signal in the front end was found to be, approximately:

$$d\phi/dT = -0.135 \text{ deg/deg K}$$

Of this, about -0.110 deg/deg K is due to the low noise FET amplifiers. Thus, keeping them constant in temperature is quite critical. The external front ends for the VLBA will have two bands in one enclosure, hence four LNA's for only one sensor.

One possible solution is to make the unit symmetrical, front to back and side to side in distribution of thermal mass and heater resistors. Thus, the temperature of the LNA's will be nearly equal, and the sensor can be placed under one of them. This idea will be investigated experimentally when a prototype VLBA 330/610 MHz front end assembly is built.

To determine what the expected temperature variation might be, a quick check of the variation in temperature of the LNA enclosure in the 330 MHz front end shows that when $T_s - T_a$ is 38 degrees, the amplifier temperature is about 2.5 degrees less than the set point temperature.

A simple model of the system was investigated, consisting of a 30 x 15 cm slab of 1/4 inch Aluminum with a constant amount of heat flowing into each end (see Figure 4):

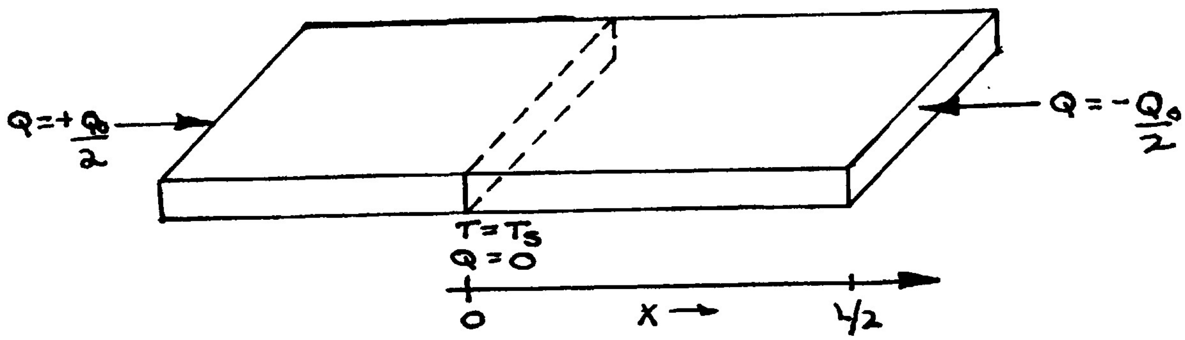

Fig. 4. Sketch of slab used to model 327 MHz front end internal chassis.

The heat flow and temperature profiles are taken to be approximately one-dimensional so that,

$$Q(x) = -K_1(dT(x)/dx) \qquad (4a)$$

where Q is the heat flow rate and K_1 is the thermal conductivity of Aluminum times the 15 cm x 1/4 " cross-sectional area of the slab. A second equation is derived from the crude and approximate assumption that the heat loss per unit area from any given location on the slab is proportional to the temperature difference between it and the ambient temperature, T_a. Hence

$$dQ/dx = -K_2(T-T_a) \qquad (4b)$$

where K_2 is the effective heat loss per unit area times the width of the slab. K_1 is known a priori but K_2 must be determined. These can be combined into an equation:

$$\frac{d^2T'}{dx^2} = a^2T' \qquad (5a)$$

with

$$T' \triangleq T - T_a$$

$$a^2 \triangleq K_2/K_1$$

The boundary conditions at X=0 are:

$$T' = T_s - T_a \qquad (5b)$$

$$dT'/dx = 0 \qquad (5c)$$

Symmetry indicates that T is an even function of x, so that solution over $0 < x < L/2$ is sufficient. Symmetry also dictates condition (5c).

The solution is:

$$T = \left(\frac{T_s - T_a}{2}\right)[e^{ax} + e^{-ax}] + T_a \qquad (6)$$

Also a transcendental equation for $a \triangleq \sqrt{K_2/K_1}$ in terms of Q_o is derived

$$Q_o = K_1(T_s - T_a)a(e^{ax} - e^{-ax}) \qquad x = \frac{L}{2} \qquad (7)$$

The maximum temperature will occur at $x = L/2$. For a case with values near those in the 327 MHz front end:

$$Q_o = 18 \text{ W}$$

$$K_1 = 22.6 \text{ W·cm/K}$$

$$T_s - T_a = 37.5 \text{ K}$$

$$L = 30 \text{ cm}$$

$$a = 0.0263 \text{ cm}^{-1}$$

$$K_2 = 0.0156 \text{ W/cm·K}$$

then:

$$T_{max} - T_s = 2.96 \text{ deg K}$$

Note that this is of the same order as the 2.5 deg K difference in the temperature of the LNA measured in the front end. Of course, the LNA temperature was 2.5 deg K less than T_S due to the more complex geometry. The temperature variation could be reduced by reducing K_2, which could be accomplished by putting more insulation into the box. However, as seen from equation (3), if the thermal conduction (K_T) is lowered, the temperature difference required to dissipate the waste heat is increased, resulting in a higher internal temperature for a given maximum external temperature.

From these investigations, the thermal design of the 330 MHz VLA front end appears to be a good model for design of the 330 and 610 MHz VLBA front end unit, perhaps with some modifications to be determined in prototype testing.