ANTENNA GAIN MEASUREMENTS FROM RADIO STAR SOURCES

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INTRODUCTION

The accurate determination of antenna gain is one of the most difficult engineering measurements of radio system performance. While the theory is well established, the environmental variables are not easily controlled. This paper describes the technique used by the K3NSS Moonbounce Group to determine the performance of the 84 ft. (25.6 meter) diameter parabolic dish antenna which the Group recently restored for 432 MHz moonbounce operation.

The dish restoration included installation of the complete RF communication chain as shown in Figure 1. The construction of the coaxial antenna feed tower, the most critical component, was described last year by W3PJM.[1] The original feed dipole was replaced later by a two element array. The technique described in this paper was used to measure the system performance of both configurations.

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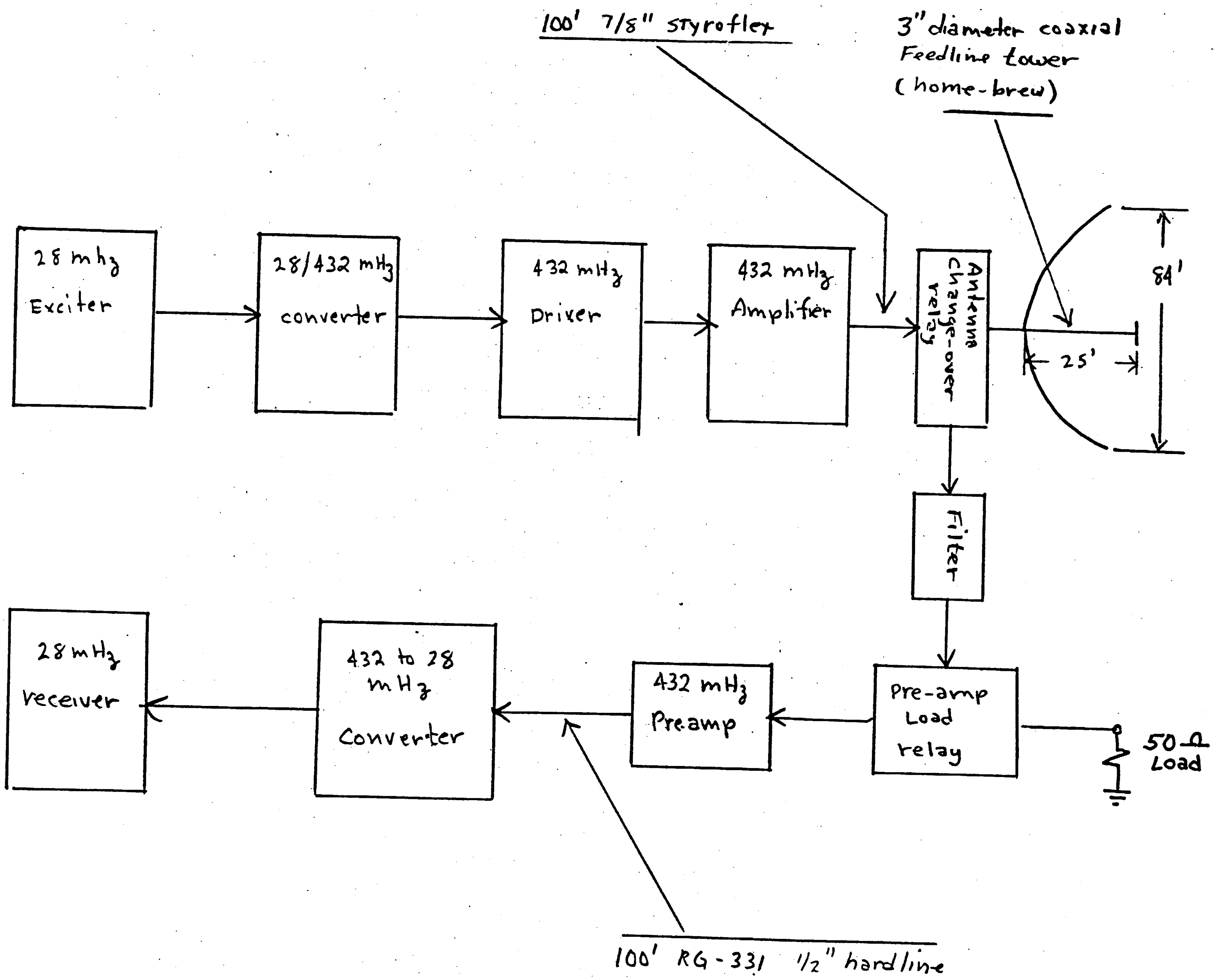

Figure 1. K3NSS Transmitting/Receiving Chain

THE MEASUREMENT PROCEDURES

The procedures employed were developed from those used for measuring the performance of astronomical radio telescopes and satellite communications earth stations[2]. The technique involves independent measure of the receiving sensitivity, expressed as the ratio of the antenna gain (G)* to receiving system equivalent noise temperature (T), and the receiving system equivalent noise temperature (T). Knowing the G/T ratio (pronounced "gee over tee"), and T, G is calculated from the relation:

$$G/T(dB/{}^{0}K) = G(dB) - T(dB) \qquad (1)$$

or

$$G(dB) = G/T(dB/{}^{0}K) + T(dB) \qquad (2)$$

Where all terms are expressed as decibels (i.e. algebraic ratios are converted to decibels by taking ten times the logarithm to the base ten of the algebraic ratio).

DETERMING G/T FROM OBSERVATIONS OF RADIO STARS

Three radio stars are of sufficient intensity for observation by the K3NSS 84 ft. antenna. They are listed in Table 1, with the sun and moon, along with the radiation intensity (watts per square meter per Hertz) for amateur moonbounce frequencies.

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*All antenna gains in this paper are referenced to an isotropic radiator.

G/T is measured by observing the ratio of the received "signal"* noise power to the noise power received from the "cold" sky. This ratio, called the "Y" factor, is compared to the known radiation flux density (S) of the source (Table 1) to determine the receiving system figure of merit, G/T {equation (3)}.

The advantages of this technique are simplicity and accuracy. The technique is elegant because it does not require knowledge of either the antenna gain (G) or the system noise temperature (T). The critical measurement (Y) is calculated as a ratio so that measurement units and biases cancel. Finally, no special equipment beyond that for normal station operation is necessary. All that is required is a suitable measure of receiver output power. This could be the receiver 'S' meter, although better accuracy will result if a simple noise integrator, as described in reference (9), is used in conjunction with a chart recorder.

The qualifying minimum performance necessary to employ this procedure is that the system must be able to detect sun noise, the strongest source. The measurement accuracy achievable depends on the following factors:

1. <u>The source used.</u> The flux density (S) of the sun

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*The "signal" of these celestial sources has noise characteristics.

varies randomly by a factor of two or more. Therefore, measurements from the sun may not be accurate within 3dB unless the actual sun radiation flux density (S) for the time of observation is used in equation (2). Readings of the sun 'S' are available by computer interface from the Space Environment Laboratory of the National Oceanic and Atmospheric Administration located in Boulder, Col.* Figure 2 is a sample of this print-out for July 5 to July 18. Note the large data variation. If the G/T is large enough to permit radio star measurements, accuracies to within 0.5dB are attainable under favorable conditions. In general, accuracies to ±1 decibel are consistently possible with reasonable care and high performance arrays.

2. <u>Atmospheric/ionospheric attenuation.</u> Source attenuation varies inversely with frequency and elevation angle. Observations at 144 MHz near the horizon may not be accurate within 3dB. Observations of Cassiopeia A or Cygnus A at

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*For information regarding access to solar flux density data write or call: Jacob D. Schroeder III, System Manager, NOAA/ERL/SEL/R43, 325 Broadway, Boulder, Co. 80302, (303) 499-1000 ext. 3780. No charge is made for the data.

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BEGIN MONTH, DAY? 77,,55
END MONTH, DAY? 77,,1188




   RADIO FLUX LOG

      OTT  SAG  SAG  SAG  SAG  SAG  SAG  SAG  SAG  PAL  PAL
DATE 2800  210  415  606 1415 2695 4995 8800  15K 1415 8800

7/ 5  115                                           83  316
7/ 6  117   12   29   61   85  120  153  315  582   83  311
7/ 7  125   12   28   64   88  126  160  314  560   88  294
7/ 8  132   19   34   68   92  134  169  332  576
7/ 9  146   14   33   70  101  147  184  355  594   93  370
7/10  153   74   45   68  107  156  203  379  610  100  391
7/11  162   32   31   71  108  165  213  381  621  106  394
7/12  175   21   33   74  112  175  225  399  608
7/13        14   33   72  109  161  213  376  600  106  382
7/14  154   14   28   70  112  163  208  370  595  108  383
7/15  164                                          112  367
7/16  158   12   29   70  118  165  196  351  557  109  352
7/17  156   13   29   71  120  154  177  332  520  111  355
7/18  152   15   33   71  113  156  188  355  599
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– STATION

– FREQUENCY (MHz)

READINGS ($W/m^2/Hz \times 10^{-22}$)

Figure 2. Solar Flux Density by Frequency and Date

1296 MHz at elevation angles greater than 45° can be accurate to ±0.5dB (provided G/T is high enough to support a consistent 'Y' factor measure). References 2, 3, 4 and 5 contain additional information for those interested in corrections to obtain the greatest possible accuracy.

3. <u>Number of measurements.</u> Averaging a large number of observations, or applying linear regression analysis will smooth measurement anomalies and improve accuracy.

4. <u>The system noise floor.</u> The more sensitive the system, the larger the difference between the "signal" noise power and the "cold" sky noise power, i.e., the larger the Y factor. The larger the Y factor, the more accurate the results. Reference (7) is an excellent chart of sky noise. It illustrates the relatively high noise characteristic of the galactic equator and the relative low sky noise at the galactic poles. The more sensitive the system, the more attention must be paid to "cold" sky temperature. As an extreme example, to take accurate readings from the moon, (requiring a very high G/T) which has a very weak 'S', care would have to be taken to insure the "cold" sky reading was from a low noise area.

Obviously, this is not so important for sun measurements. The object is to get large Y factor measurements whatever celestial source is used. Reference 14 contains a succinct discussion of attainable accuracies. For precise measurements (i.e., within .25dB), 'Y' factors of greater than 175 must be observed. Such ratios are beyond the capability of most amateur antennas, even for sun observations.

CALCULATING G/T

The algebraic relationship of G/T to the Y factor and source intensity {I(s)} is given by:

$$G/T = \frac{Y-1}{I(s)} \tag{3}$$

where:

$$Y = \frac{\text{"signal" noise power (source)}}{\text{"cold" sky noise power}}$$

$$I(s) = \frac{\lambda^2 S}{8\pi K} \tag{4}$$

λ = wavelength (meters)

S = source flux density from Table 1 (watts per square meter per Hertz)

K = Boltzmann's constant

= 1.38×10^{-23} (Joules per degree Kelvin)

Equation (4) translates the source flux density (S) to units of equivalent temperature (T). It includes a factor (½) to account for the unavoidable loss resulting from the interception of a randomly polarized signal by an antenna sensitive to a single polarization. The factor $\lambda^2/4\pi$ accounts for the antenna gain relationship to wavelength (area factor). Table 3 lists values of I(s) for the amateur bands commonly used for moonbounce.

Equation (3) is an algebraic ratio. The G/T value is more useful in logarithmic (decibel) units. Therefore the following conversion applies:

$$G/T(dB/^{0}K) = 10 \log_{10} \{G/T \text{ ratio from equation (1)}\} \quad (5)$$

or alternatively:

$$G/T(dB/^{0}K) = 10 \log_{10} \{Y-1\} - 10 \log_{10} \{I(s)\} \quad (6)$$

RECEIVE SYSTEM NOISE MEASUREMENTS

The receiving noise factor (NF), also called noise figure (F) when expressed in dB, is part of the total system noise performance (T). The noise factor is a measure of the noise added by the receiving chain starting at the preamp (see Figure 1). A perfect receiving chain will add no noise and will have a noise factor (NF) of 1.0, and a corresponding noise figure (F) (10 log 1.0) of 0dB. In this perfect system, the output noise power will be the input noise power increased by the gain of the receiving chain.

The noise power considered is:

$$Pn = \text{Noise power} = KTB \quad (7)$$

where:

TABLE 1 SOURCE FLUX DENSITY (S) [derived from references (2), (3), and (4)]
(watts per square meter per Hertz x 10^{-23})

FREQUENCY (mhz)	SUN ($X\ 10^{-23}$) NOTE 1	MOON ($X\ 10^{-23}$) NOTE 2	23h-22m N 59° CASSIOPEIA A ($X\ 10^{-23}$) NOTE 3	19h-59m N41° CYGNUS A ($X\ 10^{-23}$)	5h-33m N22° TAURUS A ($X\ 10^{-23}$)
144 NOTE 4	52	0.01	15.0	10.0	1.80
432	280	0.08	5.55	4.00	1.25
1296	525	0.80	2.05	1.40	0.92

NOTES:

1. The value for sun 'S' varies randomly by a factor of 2 or more. The value listed is typical for a 'quiet' sun. (See figure 2.)
2. Calculated by the author from the relation: $S = (2KTm/\lambda^2)\ \Omega m$; where: Ωm = solid angle subtended by the moon viewed from earth. See reference (4).
3. 'S' decreases approx. 1% per year. Value corrected by the author to 1978. See references (2) and (3).
4. 144mhz values extrapolated by the author. Expect large measurement variations due atmospheric/ionospheric effects.

TABLE 2 SOURCE INTENSITY $\left[I(s)\right]$
calculated from:

$$Is = \frac{\lambda^2 S}{8\pi K} \quad \left[\text{equation (2)}\right]$$

Freq. (mhz)	SUN	MOON	Cas. A	Cyg. A	Tau. A
144 λ = 2.08m	6.5	1.25×10^{-3}	1.89	1.25	0.225
432 λ = .69m	3.89	1.11×10^{-3}	77.0×10^{-3}	55.5×10^{-3}	17.4×10^{-3}
1296 λ = .23m	0.81	1.23×10^{-3}	3.16×10^{-3}	2.16×10^{-3}	1.42×10^{-3}

K = Boltzmann's constant = 1.38046×10^{-23} Joules per degree Kelvin

K = Boltzmann's constant = 1.38×10^{-23} Joules/Hz-^{0}K

T = Temperature of the source, ^{0}K

B = System bandwidth, Hz

Boltzmann's constant is a fundamental physical property of matter. It is the electron energy per degree Kelvin per unit bandwidth.

T is defined as the effective temperature of the source being measured. It can either be the actual physical temperature (such as the temperature of a load resistor) or it may be an artificial equivalent temperature of a source generating RF noise power. For example, the output of a radio star source is sometimes expressed as the temperature the source would have to be to thermally generate the observed RF power flux density.

B is the system bandwidth, determined by the narrowest filter in the receiving chain. This is normally the IF amplifier bandwidth. Since the object is to measure noise power, the widest available IF bandwidth setting should be used.

Figure 3 shows the test arrangement used at K3NSS to measure the receiving chain noise figure. The liquid nitrogen cooled 50 ohm load was alternated with a room temperature (hot) 50 ohm load at the preamp input. The detected noise power resulting from each load was integrated and displayed by a chart recorder. Care was exercised to keep all amplifiers in the receiving chain operating linearly. Using the ratio of the two readings (Pr), the noise figure (F) is calculated from the relation:

$$\frac{\text{Measured noise power (hot)}}{\text{Measured noise power (cold)}} = \frac{\text{temperature (hot)} + Tr}{\text{temperature (cold)} + Tr} \quad (8)$$

where:

$$\frac{\text{Measured noise power (hot)}}{\text{Measured noise power (cold)}} = Pr \quad (9)$$

$$\text{temperature (hot)} = T_h = 300^\circ K$$

$$\text{temperature (cold)} = T_c = 77.3^\circ K$$

Solving for Tr, the receiving chain equivalent temperature:

$$Tr = \frac{T_h - PrTc}{Pr - 1} \quad (10)$$

Given the measurement results (Pr = 2.3):

$$Tr \simeq \frac{300 - 2.3(77.3)}{1.3} = 94^\circ K$$

Using the definition of noise factor (NF) as:

$$NF = \frac{To + Tr}{To} = 1 + Tr/To \quad (11)$$

where: $To = 290^\circ K$

Then for the K3NSS receiving chain:

$$NF = 1 + 94/290 = 1.32$$

From the definition of noise figure (F):

$$F = 10 \log (NF) \quad (12)$$

For the receiving chain measured:

$$F = 10 \log (1.32) = 1.22 dB$$

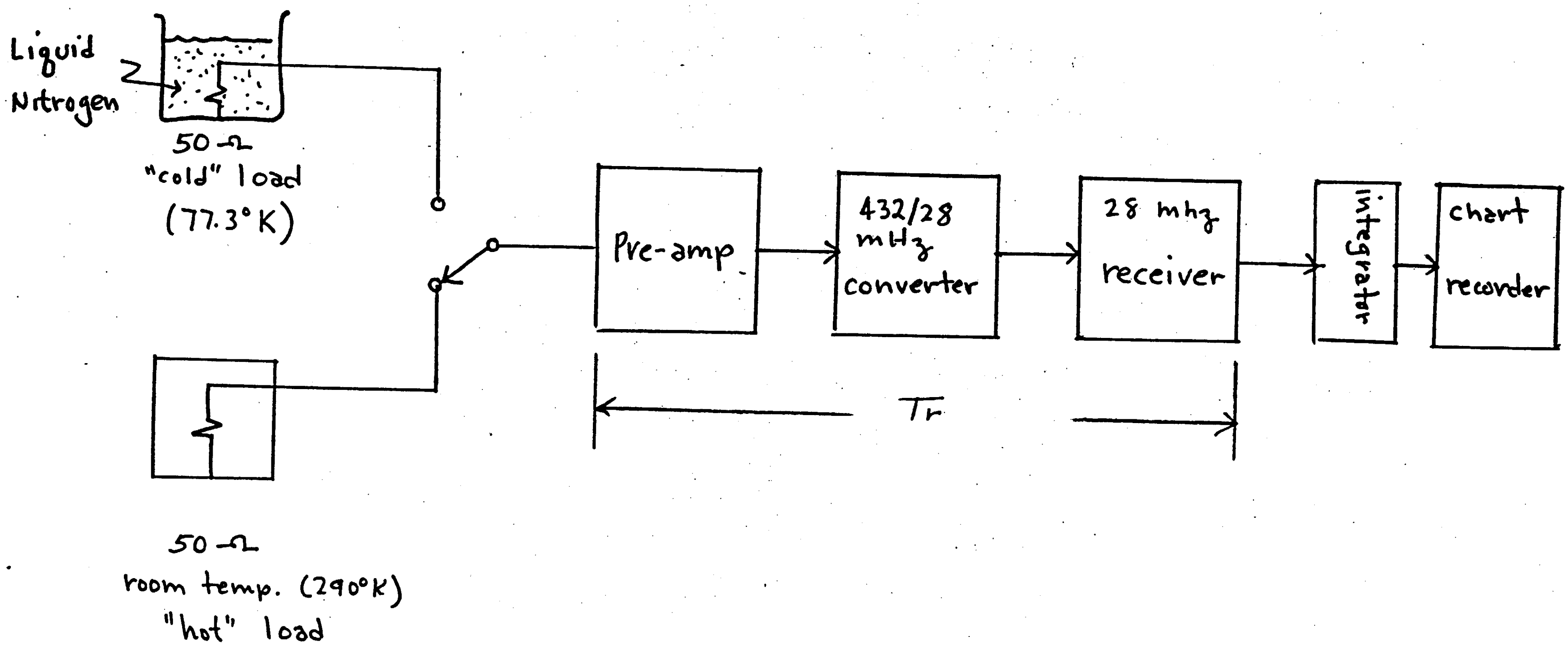

Figure 3. K3NSS Receive System Noise Temperature (Tr) Measurement

To determine the total receiving system equivalent noise temperature (T), the antenna temperature (including ambient earth temperature received in the side lobes) and feedline losses to the preamp must be added. Thus we have:

$$T = \frac{Ta}{L_1} + \frac{(L_1 - 1)To + Tr}{L_1} \qquad (13)$$

where:

Ta = Antenna effective temperature viewing "cold" sky (varies with elevation angle)

L_1 = Antenna to preamp feedline loss (expressed as a power ratio, <u>not</u> dB)

To = Ambient temperature = 290°K

Tr = Receiving chain equivalent temperature

For the K3NSS receiving system:

$L_1 \simeq 1.2$ (0.8dB) (Feed tower, relay and coupler losses)

Ta ≃ 70°K (typical)

Then:

$$T \simeq \frac{70}{1.2} + \frac{0.2}{1.2}(290) + 94 = 200.7 \text{ degrees Kelvin}$$

CALCULATING ANTENNA GAIN

Applying the results of measuring G/T {equation (3)} and system temperature {equation (13)} to equation (2), we can derive the antenna gain (G):

$$G(dB) = G/T(dB/{}^{0}K) + T(dB) \qquad (2)$$

$$G = 12.5 + 23.0 = 35.4dB$$

MEASUREMENT TECHNIQUES

The ease and accuracy of measurements depends greatly on individual ingenuity. The following are ideas for those interested in making these measurements.

1. Receiver linearity. The receiver chain must be operated linearly over the dynamic range of the measurements. As a starter, the receiver AGC must be defeated.
2. Receiver bandwidth. The IF should be operated at the widest possible bandwidth since noise power measurements are involved.
3. Measuring the Y factor. An accurate measurement technique is to alternate the antenna pointing from the source to the "cold" sky. By use of a precision variable attenuator, the source "signal" is reduced to equal the previous "cold" sky reading. The required attenuation is the Y factor. CAUTION: remember to convert decibel readings to algebraic ratios and vice versa as applicable. A large number of these readings should be used to show

G/T variation with elevation angle. (G/T will be reduced at low elevation angles.)

4. Power vs. voltage measurements. Be sure to measure the Y factor as a "power" ratio. Most meters and chart recorders respond to voltage or current, not power. Squaring a voltage or current ratio yields the corresponding power ratio.

5. Acquiring the source. Locating a source in the sky is a matter of determining its Greenwich Hour Angle (GHA) and declination (dec) for the time of observation. Table 1 lists celestial coordinates (right ascension and declination) for stellar sources. Reference (12) gives GHA and declination directly by hour for the sun and moon and procedures for finding stellar GHA from Sideral Hour Angle (SHA). SHA can be derived from right ascension. Polar antenna mounts can be calibrated directly in GHA, LHA or right ascension and declination, since these are the mount axes. To use azimuth/elevation antenna mounts, there are conversion formulas, calculator and computer programs published in reference (9) and other sources. The K3NSS group has several different programs for this purpose running in Basic and on the HP-97/67.

6. More information. The EIMAC compendium, reference (11), is a wealth of information for anyone with a serious interest in large VHF/UHF arrays. It is free from EIMAC for the asking. Members of the K3NSS group are available for discussions on any aspects of high performance VHF/UHF antenna performance measurement and operation.

MEASUREMENT REFINEMENTS

In describing the technique for G/T measurements, mention has been made of the errors introduced by propagation anomalies which are aggrevated at low elevation angles. These anomalies are inversely proportional to frequency at the amateur moonbounce bands and thus are much more pronounced at 144 than at 1296 MHz. Their effect is to reduce the 'Y' factor observed thereby reducing the observed G/T. The error can be as great as 3dB at 144 MHz. One possibility for measuring propagation attenuation is to use OSCAR (Orbiting Satellite Carrying Amateur Radio) or other satellites with signals in the frequency bands of interest.

Solar flux density variations can be adjusted by use of the NOAA data, shown in figure 2. The readings must be extrapolated to the amateur moonbounce frequencies. Regularly reported readings include 210, 415, and 1415 MHz.

System noise measurements using a liquid nitrogen require a 50 ohm non-inductive load which is stable under the thermal stress of periodic cooling to 77°K. An alternative procedure would be to use dry ice to cool the "cold" load and place the "hot" load in an oven. The object, of course, is to get as large a temperature spread as possible.

ACKNOWLEDGEMENTS

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