X-523-69-135
PREPRINT

NASA TM X- 63571

136 MHz GROUND STATION CALIBRATION USING CELESTIAL NOISE SOURCES

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APRIL 1969

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by

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ABSTRACT

A calibration technique, using radio stars, is developed that provides an absolute determination of the threshold sensitivity of a 136 MHz satellite ground station receiving system. Sensitivity is expressed in terms of the system constants, and radio star flux density. A station's day-to-day sensitivity can thus be monitored with high accuracy; preliminary field test results indicating 1 dB can be achieved.

The gain of a large steerable antenna, such as an 85 ft.-diameter parabolic dish, can also be determined within 1 db using radio stars; a calibrated, 136 MHz, injected-signal source being required.

The utilization of celestial "hot-spot" sources, including the galactic center, are suggested as standard noise sources for evaluating bit error probability performance in a 136 MHz PCM telemetry system.

136 MHz GROUND STATION CALIBRATION USING CELESTIAL NOISE SOURCES

INTRODUCTION

A calibration technique, using radio stars, is developed that provides an absolute determination of the threshold sensitivity, in a 136 MHz satellite ground station receiver, in terms of the system constants, and radio-star flux density. The utilization of a common, celestial-type, noise source makes possible an accurate station-to-station performance comparison in the Space Tracking and Data Acquisition Network (STADAN).

Radio stars, and other celestial noise sources, have been used to varying degrees to calibrate radio receiving systems. The flux densities of various radio stars, including Cassiopeia A and Centaurus A, are known to be constant within about 1 dB, at any given frequency; consequently providing a common far-field signal source, located at infinity, for calibrating large steerable antennas.

Hedeman[1] describes a technique for calibrating L-Band (1435-1535 MHz) and S-Band (2200-2300 MHz) telemetry receiving systems using the Sun. However, the Sun is a poor noise source for the 136 MHz space research band since the solar flux density is highly variable at VHF even over short intervals.[2] Therefore, it is concluded that the Sun is not a suitable source for calibrating 136 MHz systems.

This report discusses the following:

1. Use of radio stars to provide absolute calibration of 136 MHz receiving systems.

2. Suggests a 136 MHz STADAN receiver configuration for observing radio stars to determine:

   (a) Receiving system noise temperature.
   (b) Receiving system threshold sensitivity.

3. Suggests an alternate approach, using radio stars, for:

   (a) Determining receiving system noise temperature.
   (b) Measuring antenna radiation patterns, including low-level side lobes, with 50 dB of dynamic range.

(c) Providing antenna RF boresight axis vs. optical axis calibration.

4. Use of hot- and cold-sky celestial noise sources for determining PCM bit error probability.

5. Determination of antenna absolute gain using radio stars.

A method is described for determining the absolute threshold sensitivity, of a 136 MHz receiving system, by measuring the output steady-state voltage ratio from a square-law type detector. Two radio star readings are taken; a 3rd reading being taken for cold sky. A station's day-to-day 136 MHz threshold sensitivity can thus be monitored with high precision. This threshold measurement is more realistic, than currently used signal substitution methods, since the antenna is included.

A method is described for determining a PCM telemetry system's bit error probability using the galactic center as a hot-noise source, and cold-sky as the reference temperature. The resulting 7 dB noise spectral density change, between these two celestial sources, is sufficient to fix two data points on the PCM bit error probability characteristic curve for a system using a test-injected input signal. Additional intermediate points on the characteristic curve may be obtained by changing the test signal level.

A further method is described that determines the isotropic mainlobe gain, of a large steerable antenna, using a radio star at 136 MHz. The accuracy is on the order of 1 dB which compares favorably with aircraft calibration-type gain measurements on big dish antennas.

The radio star calibration technique can be extended above 136 MHz, for other frequencies, including the 400 MHz, 1.7 GHz and 2.2 GHz space bands. However, the galactic center is not suitable as a high-level noise source, for the upper frequency bands, since the noise temperature is too low above about 1 GHz (Reference 10). On the other hand, the highly variable flux density of the Sun becomes relatively constant above 1 GHz; thus making the solar disk an attractive high-level noise source for receiver calibration (Reference 1).

CALIBRATION OF STADAN 136 MHz RECEIVERS USING RADIO STARS

The flux densities of the strongest, nonthermal type, radio stars (Table 1) are known[3] within about 1 dB thus making them good far-field calibration signal sources. Table 1, taken from Starker,[4] defines radio star sources suitable for calibrating 136 MHz telemetry ground receiving systems. Radio stars are available for calibrating both Northern and Southern latitude STADAN stations; source

Table 1
136 MHz Radio Star Sources

Northern (N) or Southern (S) Latitude	Radio Star Source	Position (1950.0)				136 MHz Flux density, F w m^{-2} Hz^{-1}
		RA		Dec		
		h	m	Deg	Min	
N	Cassiopeia A	23	21	+58°	34	15.0×10^{-23}
N	Cygnus A	19	58	+40°	36	11.0×10^{-23}
N	Taurus A, Crab Nebula	05	32	+22°	0	1.8×10^{-23}
S	Centaurus A	13	22	-42°	46	1.5×10^{-23}
N	Virgo A	12	28	+12°	42	1.2×10^{-23}

locations in Table 1 being given in terms of 1950.0 position coordinates. These positions do not require correction since the coordinate correction factors for the current year are small ($\lesssim$ 0.1°) compared to the narrowest 6° half-power beamwidth for an 85' dish at 136 MHz.

This analysis neglects the effects of the atmosphere and the ionosphere at 136 MHz, and assumes that the antenna mainlobe boresight axis is 30°, or greater, above the horizon. The effects of antenna side lobes are neglected. It is also assumed that the noise temperature is constant over the receiver IF bandwidth, Δf.

There are certain restricted time zones, where celestial measurements should not be made, for the Taurus A radio star, and the Anticenter Region cold-sky reference. These restricted time zones, caused by the passage of the solar disk through that particular region of the sky during the year, are listed in Table 2 on the following page.

Receiver Configuration

A proposed STADAN receiver configuration, using a standard receiver channel, is shown in Figure 1; a General Dynamics/Electronics diversity telemetry receiver channel, or a Teledyne Model 105A autotrack receiver being used in a radio-astronomy type receiver configuration. The receiver's manual gain control is used throughout (no AGC).

Table 2
Restricted Time Zones, for Celestial Sources, Due to Passage of Solar Disk

Celestial Source	Source Position (1950.0)				Restricted Time Zone
	R.A.		Dec.		
	h	m	Deg.	Min.	
Taurus A, Crab Nebula radio star	05	32	+22°	0	May 30th to June 30th
Anticenter Region Cold-Sky Reference	03	00	+25°	0	April 30th to May 30th

A simple square-law type detector circuit has been added to convert the receiver IF output signals to appropriate d-c potentials for monitoring or recording. Because the detector output voltage change for the radio star is small, compared to the background voltage level, high amplification of this incremental voltage is needed in order to get an output indication on the d-c voltmeter or recorder. An RC-type post-detection integrator filter (RC time constant on order of seconds) considerably enhances the output signal-to-noise ratio (SNR), and reduces output noise fluctuation voltage to a low level compared to the steady-state d-c value.

The following analysis shows how the Figure 1 receiver configuration, and the resulting test data, can be utilized to:

1. Determine 136 MHz receiving system noise temperature, T_{sys}

2. Compute 136 MHz receiving system threshold sensitivity, P_{sen}

The square-law detector steady-state output voltage, V_{det}, for a fixed receiver manual gain setting and a fixed predetection bandwidth, is

$$V_{det} = V_D + \Delta V_{star} \tag{1}$$

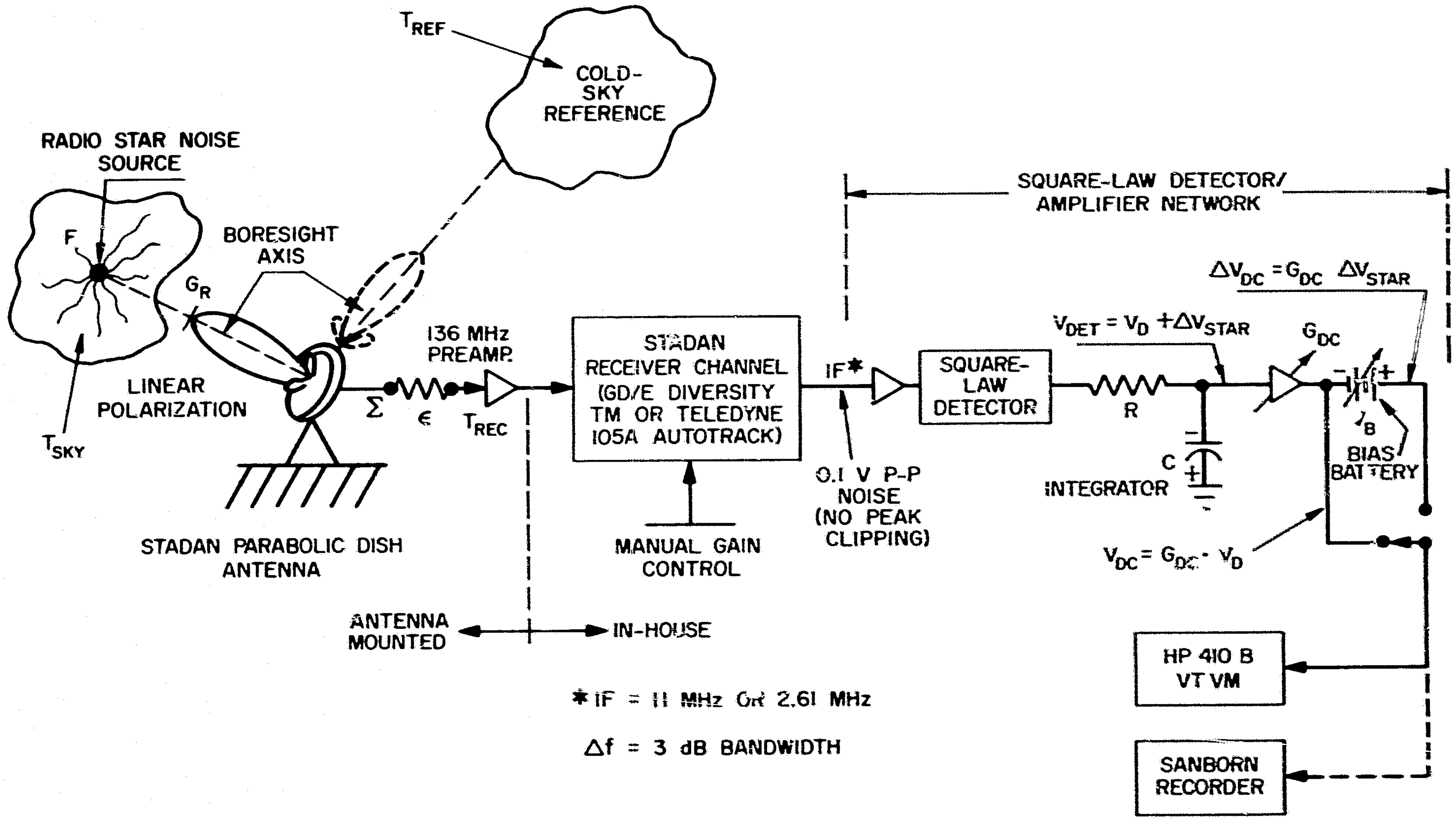


Figure 1—STADAN Receiver Configuration for 136 MHz Radio Star Calibration.

V_D = detector steady-state output voltage due to system noise temperature, T_{sys}

ΔV_{star} = detector steady-state output voltage change due to increased antenna noise temperature caused by radio star on boresight.

Kraus[5], p. 242, shows that the detector d-c output voltage is directly proportional to predetection input power where

$$V_D = \beta G_{RF} k \Delta f \ (T_{sky} + T_{rec}) \tag{2}$$

$$\Delta V_{star} = \beta G_{RF} k \Delta f \ T_{star} \tag{3}$$

Eq. (2) results directly from the square-law function, $V_D = \beta V_{in}^2 = \beta P_{in}$

where

P_{in} = input noise power to square-law detector,

β = circuit constant,

G_{RF} = receiver RF power gain,

k = Boltzmann's constant, 1.38×10^{-23} joules/°K

Δf = receiver predetection bandwidth, Hz

T_{sky} = antenna temperature due to background sky temperature surrounding radio star, °K

T_{rec} = receiving system noise temperature, °K

T_{star} = radio star noise temperature, or change in antenna temperature

Taking the following ratio from (2) and (3),

$$\frac{\Delta V_{star}}{V_D} = \frac{T_{star}}{T_{sky} + T_{rec}} \tag{4}$$

Note that the constants β, G_{RF}, k and Δf cancel in (4) by taking the voltage ratio, $\Delta V_{star}/V_D$. Furthermore, the ΔV_{star} change in the detector voltage, due to the radio star, is proportional to the radio star noise temperature, T_{star}. A further advantage is that ΔV_{star} is independent of the detector power level, for a square-law type detector, thereby simplifying calibration. The amplified steady-state potentials can be accurately measured with a VTVM or analog recorder as illustrated in Figure 1.

It can be shown that the antenna temperature rise, due to the star, is

$$T_{star} = \frac{G_R \lambda^2 F}{8\pi k} \text{ degrees Kelvin, } {}^{\circ}K \tag{5}$$

when

$$\epsilon \neq 1, \; T'_{star} = \frac{G \lambda^2 F}{8\pi k} \; {}^{\circ}K \tag{5a}$$

G_R = receiving antenna power gain above isotropic.

G = effective antenna power gain referenced to preamplifier input.

λ = wavelength = 2.2 meters(m) at 136 MHz.

F = radio star flux density, watts/meter^2/Hz (W m^{-2} Hz^{-1}).

ϵ = transmission line power loss, $0 \leq \epsilon \leq 1$.

All the quantities in (5) are known; therefore, the rise in antenna temperature, T_{star}, due to the radio star, can be determined. Substituting (5) into (4) gives

$$\frac{\Delta V_{star}}{V_D} = \frac{G_R \lambda^2 F}{8\pi k \, (T_{sky} + T_{rec})} \tag{6}$$

Letting

$$T_{sys} = T_{sky} + T_{rec}, \tag{6a}$$

$$T_{sys} = \frac{G_R \lambda^2 F}{8\pi k} \left(\frac{V_D}{\Delta V_{star}} \right) \tag{7}$$

where

$$\Delta V_{star} > 0$$

The 136 MHz receiving system noise temperature, T_{sys}, can be computed from (7) since the quantities on the right-hand side of the equation are known, or can be measured.

Determination of V_D :

Actually, the detector output voltage, V_D , is proportional to the sum of the receiver noi· temperature, T_{rec} , and the temperature of the background sky about the radio star. The required value of V_D assumes the radio star IS NOT PRESENT in that portion of the sky.

It is not possible to ELIMINATE the radio star, in order to measure V_D; however, this effect can be simulated as follows. Since the radio star is a localized or point source, the antenna main lobe boresight axis can be shifted, through an angle approximately equal to one-half the main lobe beamwidth between first nulls, until the radio star is positioned in a first null or on the lower-skirt edge of the main lobe (see Figure 2).

This angular shift corresponds approximately to the Rayleigh resolution[5] beamwidth. The contribution of the radio star to the antenna temperature is thus made small compared to the background sky. On the other hand, the background sky temperature, T_{sky} , remains essentially the same; providing the main lobe is shifted along constant-temperature contour lines. The main lobe should be shifted 10° to 15° off the boresight axis to obtain a measurement of V_D for a 40' dish; an 85' dish requiring only 5° to 10° off boresight. Care should be taken not to point the antenna main lobe to a celestial sphere "hot spot," otherwise, V_D will deviate more than 1 dB from the correct value.

Special Instructions:

Move antenna main lobe in following specific directions of Declination and Right Ascension (R.A.) angles to maintain constant background temperature, T_{sky} , for a given radio star:

1. Cassiopeia A – move main lobe either side of Cass. A, in degrees of R.A. only, with constant declination angle.

2. Cygnus A – move main lobe in direction of decreasing positive declination angle, and decreasing R.A., by a ratio of 1.7:1 Dec./R.A.

3. Taurus A, Crab Nebula – move main lobe in direction of increasing positive declination angle, and decreasing R.A., by a ratio of 2:1 Dec./R.A.

4. Centaurus A – move main lobe in direction of increasing negative declination, and decreasing R.A. angle, by the ratio 0.5:1 Dec./R.A.

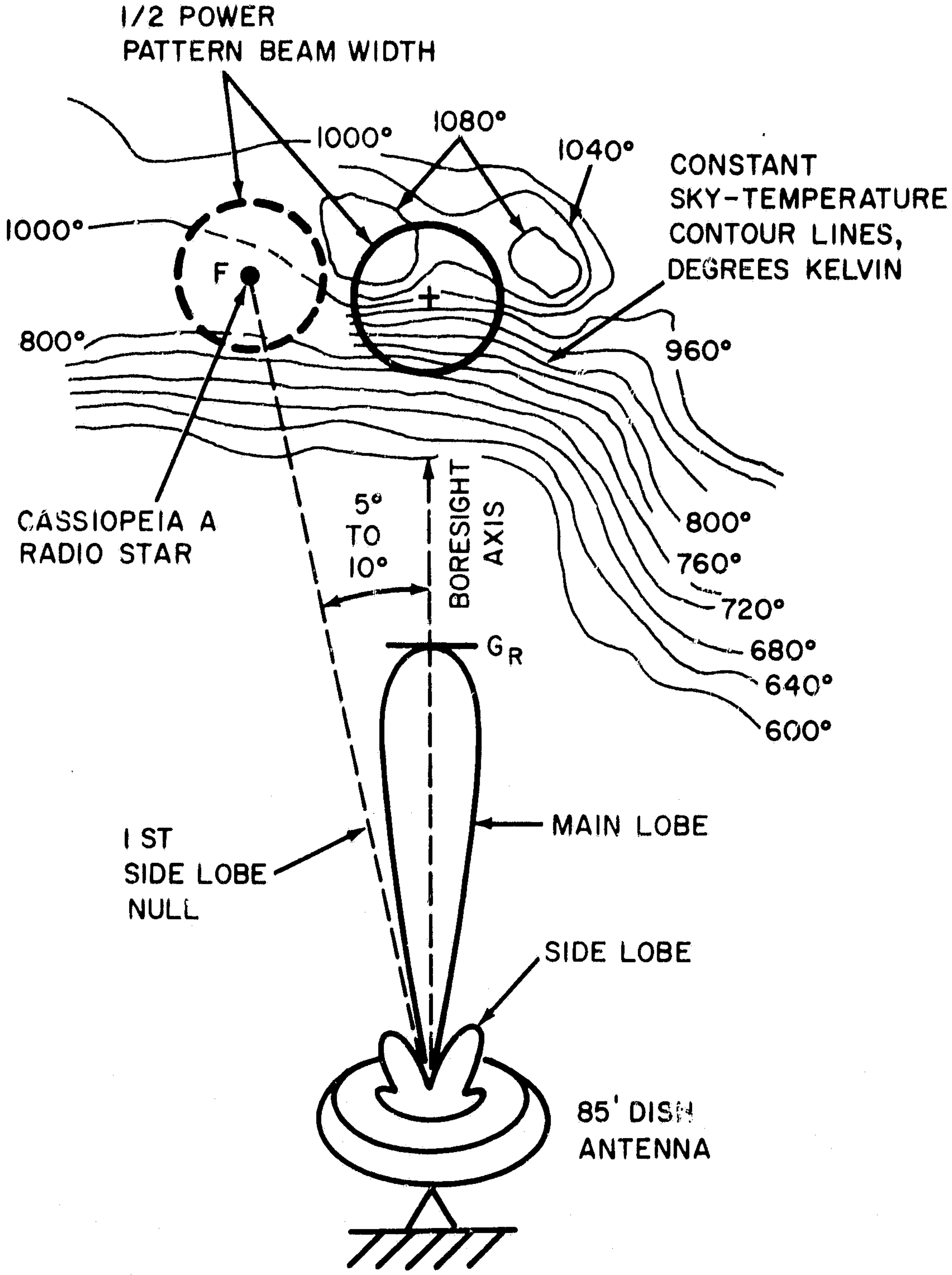


Figure 2—Measuring Cassiopeia A Radio Star Background Temperature at 136 MHz.

5. Virgo A – Move main lobe in direction of increasing positive declination, and increasing R.A., by an equal (1:1) ratio.

Measurement of $V_D / \Delta V_{star}$ Ratio:

Test Procedure (Ref. Figure 1):

1. Set antenna polarization to linear.

2. Tune receiver to 137.00 MHz, or a frequency setting clear of radio frequency interference (RFI).

3. Set receiver predetection IF bandwidth to 300 KHz or 1 MHz. When using Teledyne 105A receiver, put in Correlation (open loop) mode.

4. Adjust receiver manual gain control near maximum unsaturated setting. Square-law detector input level to be approximately 0.1 v p-p at IF amplifier output.

5. Point antenna boresight axis to suitable radio star (see Table 1 listing).

6. Readjust manual gain control for unsaturated level with boresight axis on radio star.

7. Shift boresight axis to position radio star near main lobe 1st null.

8. Measure V_{DC} at amplifier output with G_{DC} fixed over the range of +20 dB to +45 dB.

9. Adjust bias battery voltage, V_B, to EXACTLY CANCEL the term $G_{DC} V_D$ at bias battery output terminal.

10. Shift boresight axis back on radio star and measure ΔV_{DC} for same circuit conditions as for V_{DC}.

The RC integrator time constant (Figure 1) is arbitrarily set to RC = 0.33 sec. This value, used throughout this analysis, is obtained with R = 100 Kohms and C = 3.3 microfarads (tantalum type capacitor rated at 10 vdc).

Referring to Figure 1, the amplified detector output voltage, V_{DC}, due to the sum of background sky temperature and receiver temperature, is

$$V_{DC} = G_{DC} V_D \text{ for linear d-c amplification} \tag{8}$$

This steady-state value of V_D in (8) is to be measured at the d-c amplifier output terminal without the radio star. When the radio star is present, the detected voltage change is

$$\Delta V_{DC} = G_{DC} (V_D + \Delta V_{star}) - V_B . \tag{8a}$$

Setting the adjustable bias voltage* to be

$$V_B = G_{DC} V_D , \tag{8b}$$

and substituting (8b) in (8a), the radio star voltage change at the bias battery (adjustable from 0 to -10 vdc) output terminal is

$$\Delta V_{DC} = G_{DC} \Delta V_{star} . \tag{8c}$$

Taking the ratio, $V_{DC}/\Delta V_{DC}$, from (8) and (8c),

$$\frac{V_D}{\Delta V_{star}} = \frac{V_{DC}}{\Delta V_{DC}} \tag{9}$$

for fixed V_B bias, predetection gain, and bandwidth settings. V_{DC} and ΔV_{DC} are conveniently measured at separate output points shown in Figure 1.

Determination of 136 MHz System Noise Temperature

Having measured the d-c voltage ratio, $V_{DC}/\Delta V_{DC}$, the receiving system noise temperature, T_{sys}, can be determined after substituting (9) in (7) from

$$T_{sys} = \frac{G_R \lambda^2 F}{8 \pi k} \cdot \frac{V_{DC}}{\Delta V_{DC}} \tag{10}$$

where $\Delta V_{DC} > 0$.

*Actually, V_B is continuously adjustable, whereas the value of G_{DC} is preset to a fixed "low" or "high" setting for strong or weak radio stars.

Eq. (10) assumes zero dB transmission loss between the antenna terminal and the preamplifier input. When the attenuation is not negligible (i.e. $\geq$ 0.5 dB), the effective system noise temperature in (6a) becomes

$$T'_{sys} = \epsilon\,(T_{sky} - T_0) + T_0 + T_{rec}\,. \tag{10a}$$

where

ϵ = transmission line power loss, $0 \leq \epsilon \leq 1$

T_0 = transmission line ambient temperature, °K

Furthermore, (10) becomes

$$T'_{sys} = \frac{G\,\lambda^2\,F}{8\pi k}\left[\frac{V_{DC}}{\Delta V_{DC}}\right]' \tag{10b}$$

where

$G = \epsilon\, G_R$ = effective antenna gain, above isotropic, referenced to preamplifier input (i.e. after cable loss).

The primes indicate modified values.

<u>Determination of Threshold Sensitivity</u>

The receiving system threshold sensitivity is determined by making three detector d-c output voltage readings. One reading is made with the antenna boresight axis on the radio star. A 2nd reading being made with the main lobe close to the radio star (Figure 2); a 3rd reading being made with the main lobe pointing to a cold-sky reference. All 3 readings are made with the same receiver settings.

The available radio stars have already been defined (Table 1). It remains only to define suitable cold-sky reference positions and noise temperatures. The reference temperatures can be taken from available literature, as was done in Table 3, or they may be measured with a Dicke Radiometer.

There are several possible cold-sky reference choices, depending upon station location, as given below in Table 3. However, there is a time restricted zone, for the Anticenter Region cold-sky reference position, from about April 30th to May 30th, each year, when the solar disk passes through that region of the sky (see Table 2).

Table 3
Reference Regions of Sky at 136 MHz

Northern (N) or Southern (S) Latitude	Celestial Source	Position (1950.0)				Cold-Sky Reference Noise Temperature, T_{Ref} (°K)
		R.A.		Dec.		
		h	m	Deg.	Min.	
N	North Celestial Pole (NCP)	–	–	+90°	–	600°K (Ref. 4, p.39)
S	South Celestial Pole (SCP)	–	–	-90°	–	390°K (Ref. 7, p. 13)
N	Anticenter Region*	03	00	+25°	00	460°K (Ref. 8, p. 474)
N	North Galactic Pole (NGP)	12	49	+27°	24	280°K (Ref. 8, p. 471)
S	South Galactic Pole (SGP)	0	49	-27°	24	300°K (Ref. 9, p. 27)

*Anticenter at 5^h 30^m R. A. and +21° 00^m Dec.

The North and South Celestial Poles (NCP and SCP) have the advantage of being visible all the time from a given station; however, the NCP and SCP sky temperatures are somewhat higher than temperatures at the North and South Galactic Poles (NGP and SGP). Nevertheless, the NCP and SCP temperatures are quite constant making them good reference points. It is assumed that the antenna temperature is the same as the cold-sky reference temperature (e.g. cold-sky completely fills the main lobe).

Using similar reasoning as was used for developing (4), it can be shown that

$$\frac{V_{ref}}{V_D + \Delta V_{star}} = \frac{T_{ref} + T_{rec}}{T_{sky} + T_{rec} + T_{star}} \tag{11}$$

V_{ref} = detector output d-c voltage with antenna main lobe pointed to cold-sky reference temperature, T_{ref} .

Also,

$$\frac{V_{ref}}{V_D + \Delta V_{star}} = \frac{V_{ref\ DC}}{V_{DC} + \Delta V_{DC}} \tag{12}$$

ΔV_{DC} = voltage change at d-c amplifier output terminal, due to radio star, above background voltage V_{DC}.

$V_{ref\ DC}$ = post-detection amplifier output terminal d-c voltage, for reference sky, at the same point V_{DC} is measured (Figure 1) for the same receiver settings. From (5), (6a), (10), (11) and (12),

$$T_{sen} = \frac{G_R \lambda^2 F}{8 \pi k} \cdot \frac{V_{ref\ DC}}{\Delta V_{DC}} \tag{13}$$

where $\Delta V_{DC} > 0$.

$T_{sen} = T_{ref} + T_{rec}$ = system reference noise temperature for main lobe pointing to a cold-sky reference.

when $\epsilon \neq 1$, the effective system reference noise temperature becomes

$$T'_{sen} = \epsilon (T_{ref} - T_0) + T_0 + T_{rec} \tag{13a}$$

Eq. (13) then becomes

$$T'_{sen} = \frac{G \lambda^2 F}{8\pi k} \left[\frac{V_{ref\ DC}}{\Delta V_{DC}}\right]' \tag{13b}$$

where

G = effective antenna power gain, above isotropic, referenced to preamplifier input.

The primes indicate modified values.

The receiving system absolute threshold sensitivity, for an equivalent pre-detection SNR = 1, can be computed from

$$P_{sen} = k\, T_{sen}\, \Delta f \quad \text{watt} \tag{14}$$

Substituting (13) in (14) gives

$$P_{sen} = \frac{G_R\, \lambda^2\, F\, \Delta f}{8\pi} \cdot \frac{V_{ref\ DC}}{\Delta V_{DC}} \tag{14a}$$

when $\epsilon \neq 1$,

$$P'_{sen} = \frac{G\, \lambda^2\, F \Delta f}{8\pi} \left[\frac{V_{ref\ DC}}{\Delta V_{DC}}\right]' . \tag{14b}$$

The threshold sensitivity can be determined for various receiver bandwidths including Δf = 1 MHz, 300 kHz and 100 kHz. The 136 MHz receiving system front-end noise temperature can be determined from

$$T_{rec} = T_{sen} - T_{ref} = \frac{G_R\, \lambda^2\, F}{8\pi k} \left[\frac{V_{ref\ DC}}{\Delta V_{DC}}\right] - T_{ref} . \tag{14c}$$

If $\epsilon \neq 1$,

$$T_{rec} = T'_{sen} - T'_{ref} = \frac{G\, \lambda^2\, F}{8\pi k} \left[\frac{V_{ref\ DC}}{\Delta V_{DC}}\right]' - \epsilon (T_{ref} - T_0) - T_0 . \tag{14d}$$

The primes again indicating modified values. Also, if $T_{ref} \simeq T_0$, (14d) further reduces to

$$T_{rec} = \frac{G\, \lambda^2\, F}{8\pi k} \left[\frac{V_{ref\ DC}}{\Delta V_{DC}}\right]' - T_0 . \tag{14e}$$

An alternate approach uses the galactic center, and a cold-sky reference source, to determine the receiving system noise temperature, T_{rec}. It can be shown that

$$T_{rec} \cong \frac{T_A - \left[\frac{V_g}{V_{ref}}\right] T_{ref}}{\left[\frac{V_g}{V_{ref}}\right] - 1} \text{ degrees Kelvin} \tag{15}$$

where $V_g/V_{ref} > 1$ for $\epsilon = 1$ (no loss)

T_A = antenna temperature with boresight axis on galactic center as determined in Appendix B, °K

V_g = Square-law detector output for antenna boresight axis on galactic center, vdc

V_{ref} = Square-law detector output for antenna boresight axis on cold-sky reference source (Table 3 listing), vdc.

V_g and V_{ref} are measured for the same receiver conditions; furthermore, at the d-c amplifier output terminal (Figure 1):

$$\frac{V_{gDC}}{V_{refDC}} = \frac{G_{DC} V_g}{G_{DC} V_{ref}} = \frac{V_g}{V_{ref}} \tag{15a}$$

However, it is ascertained that the accuracy of (15) will not be as good as (14c), (14d) or (14e) since the galactic center is an extended celestial source.

Antenna Radio Star Resolution:

The minimum resolvable radio star temperature rise, T_{star}, is assumed to be 75°K for the Figure 1 136 MHz receiver-detector configuration. This corresponds approximately to a 5% change in the square-law detector output d-c voltage (e.g. - 0.05 vdc change out of -1.0 vdc). The minimum detectable d-c signal is on the order of 1% change assuming no external radio frequency interference (RFI). Using the 5% criterion, all 5 radio stars in Table 1 can be resolved with an 85' dish. Cassiopeia A and Cygnus A can be resolved with the

SATAN and 40' dish antennas; however, these antennas will not resolve the weaker radio stars. Table 4 lists the effective radio star antenna temperatures with the equivalent pre- and post-detection signal level increases for 3 STADAN antenna types.

Alternate Approach for Determining System Noise Temperature

It can be shown that the receiving system noise temperature, for the antenna boresight axis pointing directly on a given radio star, can be obtained from

$$T_{sys} = \frac{G_R \lambda^2 F}{35.5k} \left(\frac{e_{rms}}{E_{sig}}\right) \left(\frac{\Delta f}{B_{RC}}\right)^{1/2} \text{°K}. \qquad (16)$$

G_R = receiving antenna power gain, above isotropic

λ = wavelength, m

ϵ = 1 (no loss)

F = radio star flux density, w m^{-2} Hz^{-1}

k = Boltzmann's constant = [illegible] $\times 10^{-23}$ joule/°K

Δf = predetection bandwidth, Hz

B_{RC} = post detection, RC filter, 3dB cutoff bandwidth, Hz

E_{sig} = maximum steady-state d-c signal output, from a square-law detector, for a radio star

e_{rms} = background fluctuation noise voltage output from post detection RC filter, vrms.

The receiving system noise temperature, T_{sys}, can be obtained from (16) by measuring the RC filter output voltage ratio, E_{sig}/e_{rms}; the constants in (16) being known for a given receiving system and radio star. Ko[6] has demonstrated (Figure 3) that it is possible to obtain a high output SNR, on the order of +50 dB, taking the ratio of the E_{sig} level to the background noise fluctuation level for the Cygnus A radio star at 242 MHz.

Table 4
STADAN Antenna Radio Star Resolution Capability (Computed Values)

Radio Star	"N" or "S" Latitude Station	Flux Density, F $w\ m^{-2}\ Hz^{-1}$	85' Dish			40' Dish			SATAN		
			T^*_{star}	Pre-det.** Rise	ΔV^{***}_{star}	T^*_{star}	Pre-det.** Rise	ΔV^{***}_{star}	T^*_{star}	Pre-det.** Rise	ΔV^{***}_{star}
1. Cassiopeia A	N	15.0×10^{-23}	1,050°K	+2.3 dB	−0.71 vdc	132°K	+0.37 dB	−0.09 vdc	332°K	+0.88 dB	−0.23 vdc
2. Cygnus A	N	11×10^{-23}	770°K	+1.8 dB	−0.52 vdc	97°K	+0.28 dB	−0.07 vdc	243°K	+0.66 dB	−0.17 vdc
3. Taurus A Crab Nebula	N	1.8×10^{-23}	126°K	+0.40 dB	−0.09 vdc	15.8°K	+0.05 dB	−0.01 vdc	39.8°K	+0.12 dB	−0.03 vdc
4. Centaurus A	S	1.5×10^{-23}	105°K	+0.30 dB	−0.07 vdc	13.2°K	+0.04 dB	−0.01 vdc	33.2°K	+0.10 dB	−0.02 vdc
5. Virgo A	N	1.2×10^{-23}	84°K	+0.20 dB	−0.06 vdc	10.6°K	+0.03 dB	−0.007 vdc	26.5°K	+0.08 dB	−0.02 vdc

$$*T_{star} = \frac{G_R \lambda^2 F}{8\pi k}\ °K.$$

$\lambda = 2.2m$

G_R = +27 dB (85' dish), +18 dB (40' dish), +22 dB (SATAN), above isotropic.

**From (4), (5) and (10), radio star predetection signal power rise above background, $dB = 10 \log \left[\frac{T_{star}}{T_{sys}} + 1\right]$ for $T_{sys} = T_{sky} + T_{rec} = 1470°K$.

***Equivalent detector output d-c voltage change when $V_D = -1.0$ vdc (Fig. 1).

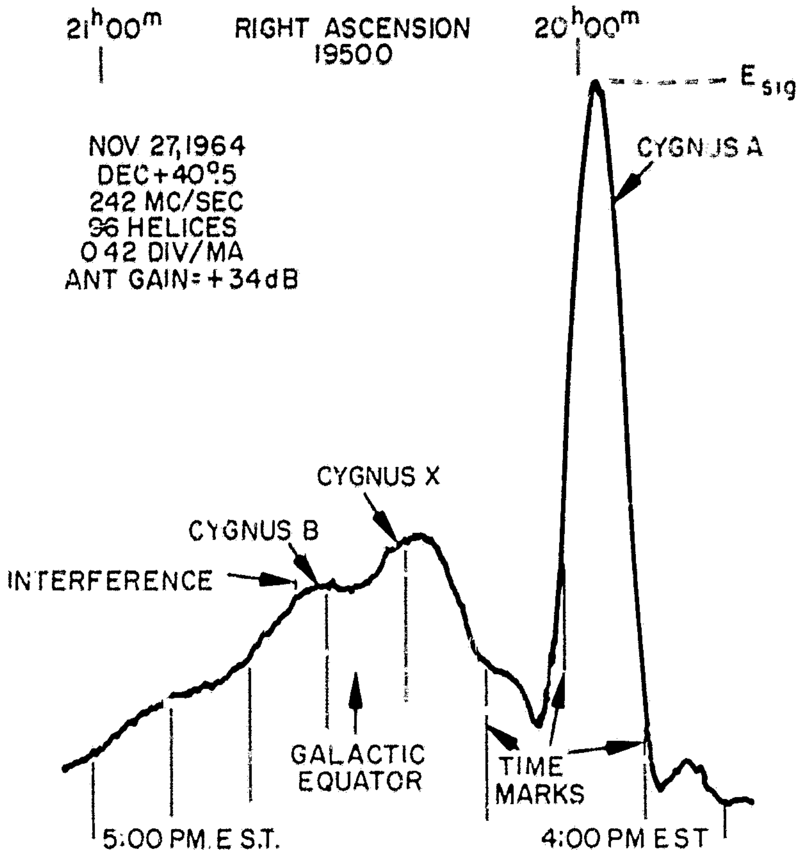


Figure 3–KO Observation of Cygnus A Radio Star at 242 MHz.

However, equipment low frequency gain variations, manifested as a residual fluctuation level at the radio receiver square-law detector output, must not mask e_{rms} in order to observe an output SNR $\simeq$ + 50 dB. External RFI signals can also mask e_{rms}. The potential operational applications of such a system include:

1. Antenna radiation pattern measurements, both main lobe and side lobes, with about 50 dB of dynamic range.

2. Accurate antenna RF boresight axis vs. optical axis alignment calibration using radio stars.

PCM SYSTEM CALIBRATION

Two celestial noise sources, such as the galactic center and a cold-sky reference point, can be used by mid- and Southern-latitude stations to determine the bit error probability of a pulse code modulation (PCM) telemetry link at 136 MHz.

A clean PCM-modulated test signal should be injected into the antenna output transmission line, whereas the noise, to establish a given SNR, would come from a celestial source. About a 7 dB change in noise power level exists between the galactic center, used as a hot source, and a cold-sky reference point for an 85' or 40' dish at 136 MHz. This noise level change is sufficient to establish two data evaluation points on the bit error probability vs. SNR characteristic curve.

The Northern latitude stations, unable to view the galactic center, could use the radio star, Cassiopeia A, as a hot noise source for the same function. The following analysis defines the antenna noise temperature, and corresponding noise power, for the available celestial sources. The radio brightness of the galactic center is relatively constant at 136 MHz; making it a desirable noise source for this type measurement.

The equatorial coordinate position of the galactic center is at R.A. = $17^h 40^m$ and Dec. = $-29° 6^m$ expressed in 1950.0 coordinates. However, there is a time restriction zone from about December 1st to January 10th, each year, when the solar disk goes into conjunction with the galactic center.

The galactic center is not a point source, as for the radio stars, since its angular width is not small compared to the antenna half-power beamwidth. Therefore, it becomes necessary to compute the antenna noise temperature, for variable brightness temperatures over the beamwidth, for the various STADAN antennas that may view the galactic center. The noise temperature of the galactic center is assumed to be T_{gc} = 3,300°K at 136 MHz (Reference 7).

Neglecting antenna sidelobes, Blake's[10] simplified approximation gives antenna noise temperature, T_A, for an antenna main beam as

$$T_A = \sum_{i}^{n} \alpha_i T_i \tag{17}$$

where

$$\sum_{i}^{n} \alpha_i = 1 .$$

also

$$T_A \cong \alpha_g T_g + \alpha_{gc} T_{gc} \tag{18}$$

for $\epsilon = 1$ (no loss).

α_i is the ratio of the ith noise source cross-sectional area, A_i , to the main beam cross-sectional area, A_b.

T_g = adjoining galactic ridge temperature = 2,000°K.

T_{gc} = galactic center noise temperature = 3,300°K.

<u>85' Dish Viewing Galactic Center:</u>

From (18), for an 85' dish main lobe pointing to the galactic center (see Figure 4):

$$T_A = 0.27\ (2000^\circ) + 0.73\ (3{,}300^\circ)$$

$$T_A \simeq 2{,}950^\circ K$$

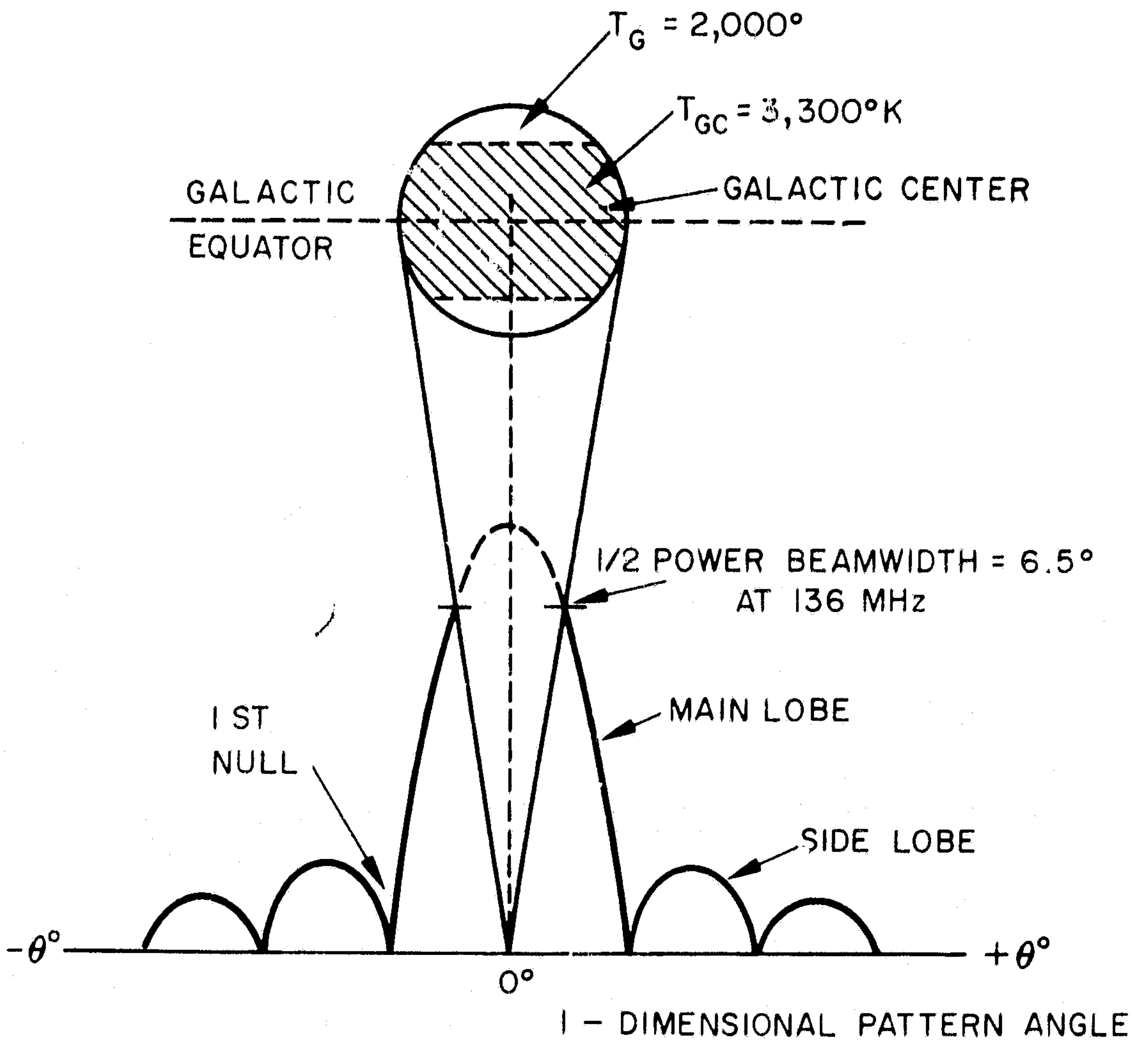


Figure 4–85 Ft. Dish Antenna Beam Pointed to Galactic Center.

The total receiving system noise temperature,

$$T_{RS} = T_A + T_{rec} \tag{18a}$$

T_{rec} = 136 MHz receiver front-end noise temperature $\simeq$ 290°K (3 dB noise figure).

$T_{RS} = T_A + T_{rec} = 2{,}950° + 290°K.$

$T_{RS} \simeq 3{,}240°K$ for 85' dish.

The radio receiver predetection noise power, N_{gc}, for the 85' dish boresight axis on the galactic center, is

$$N_{gc} = kT_{RS}\,\Delta f\,. \tag{19}$$

k = Boltzmann's constant - 1.38×10^{-23} joules/°K.

Δf = receiver predetection bandwidth, Hz.

When the main lobe is directed towards a cold-sky reference temperature, T_{ref}, the noise power is

$$N_{sen} = k\,T_{sen}\,\Delta f \tag{19a}$$

where

$$T_{sen} = T_{ref} + T_{rec} \tag{19b}$$

T_{sen} = system noise temperature, °K

T_{ref} = temperature of reference (SCP) cold-sky = 390°K.

T_{rec} = receiver front-end noise temperature = 290°K.

The galactic center-to-cold sky reference noise power ratio is obtained from (19) and (19a) as

$$\frac{N_{gc}}{N_{sen}} = \frac{T_{RS}}{T_{sen}} \tag{19c}$$

From (18a), (19b) and (19c)

$$\frac{N_{gc}}{N_{sen}} = \frac{T_A + T_{rec}}{T_{ref} + T_{rec}} \tag{19d}$$

Expressing (19d) in dB for an 85' dish

$$\left[\frac{N_{gc}}{N_{sen}}\right]_{85'} = 10 \log_{10} \left[\frac{T_A + T_{rec}}{T_{ref} + T_{rec}}\right] \tag{19e}$$

$$\left[\frac{N_{gc}}{N_{sen}}\right]_{85'} = 10 \log_{10} \left[\frac{3,240^\circ}{390^\circ + 290^\circ}\right]$$

$$\left[\frac{N_{gc}}{N_{sen}}\right]_{85'} = +6.8 \text{ dB} \simeq 7 \text{ dB.} \tag{19f}$$

Equation (19f) states that for an 85' dish, at 136 MHz, the receiver IF noise power will increase about 7 dB when centering the main lobe on the galactic center; compared to a cold-sky reference point where the sky temperature is 390°K. The IF noise spectral density is also increased by 7 dB which is sufficient to establish two operational evaluation checkpoints on the bit error rate vs. SNR curve for a PCM telemetry system. It is assumed that an injected-type PCM test signal will be used with appropriate post detection signal conditioning equipment.

40' Dish Viewing Galactic Center:

From (17), and a noise temperature model of the galactic center at 136 MHz,

$$T_A \cong \alpha_{gc} T_{gc} + \alpha_1 T_1 + \alpha_2 T_2 \tag{20}$$

where, $\alpha_{gc} + \alpha_1 + \alpha_2 = 1$ from Fig. 5.

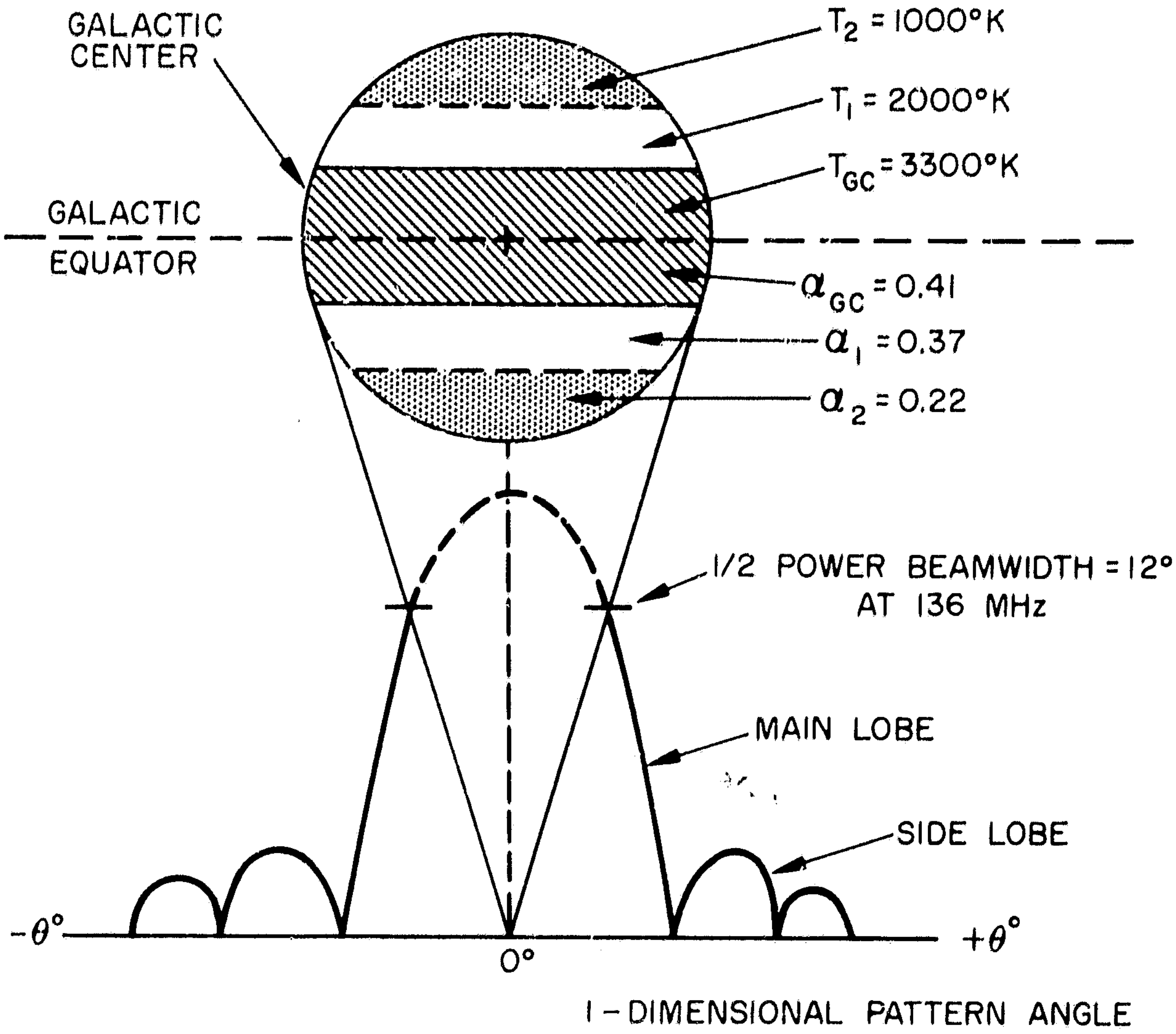


Figure 5–40 Ft. Dish Antenna Beam Pointed to Galactic Center.

From (19d),

$$\left[\frac{N_{gc}}{N_{sen}}\right]_{40'} = 10 \log_{10} \left[\frac{T_A + T_{rec}}{T_{ref} + T_{rec}}\right] \tag{21}$$

T_A = 40' dish effective noise temperature, °K

$T_A \simeq 0.41\ (3300°) + 0.37\ (2000°) + 0.22\ (1000°).$

$T_A \simeq 2{,}312°K$ for 40'dish.

T_{rec} = 290°K, 136 MHz receiver front-end noise temperature.

T_{ref} = 390°K, cold sky reference temperature.

Substituting the above values in (21),

$$\left[\frac{N_{gc}}{N_{sen}}\right]_{40'} \simeq 10 \log_{10} \left[\frac{2312^\circ + 290^\circ}{390^\circ + 290^\circ}\right]$$

$$\left[\frac{N_{gc}}{N_{sen}}\right]_{40'} \simeq +5.8 \text{ dB.}$$

Radio Star Noise Source:

The northern latitude stations seldom view the galactic center; therefore, the Cassiopeia A and Cygnus A radio stars can serve as hot-spot noise sources for 136 MHz PCM equipment using an 85' dish antenna. The radio star noise temperatures correspond to T_{star} = 1,050°K and 770°K, respectively (see Table 4 listing). The sky background temperature, around the radio star, increases the effective antenna noise temperature as follows:

Cassiopeia A:

$$T_{sky} + T_{star} + T_{rec} = 900^\circ K + 1{,}050^\circ K + 290^\circ K = 2{,}240^\circ K.$$

For cold-sky reference (NGP, Table 3),

$$T_{ref} + T_{rec} = 280^\circ + 290^\circ = 570^\circ K$$

$$\left[\frac{N_{star}}{N_{ref}}\right]_{85'} \simeq 10 \log_{10} \left[\frac{2240^\circ}{570^\circ}\right] \simeq +5.9 \text{ dB.}$$

Cygnus A:

$$T_{sky} + T_{star} + T_{rec} = 1{,}000^\circ + 770^\circ + 290^\circ = 2{,}060^\circ K.$$

For cold-sky reference (NGP, Table 3),

$$T_{ref} + T_{rec} = 280^\circ + 290^\circ K = 570^\circ K.$$

$$\left[\frac{N_{star}}{N_{ref}}\right]_{85'} \simeq 10 \log_{10} \left[\frac{2,060^\circ}{570^\circ}\right] \simeq +5.6 \text{ dB.}$$

Effective Noise Temperatures of Celestial Sources:

Table 5 compares the effective noise temperatures, both antenna and system temperatures, for various celestial sources and STADAN-type antennas.

There can be as much as a 15 dB variation, between antenna noise temperature extremes, as an 85' dish main lobe sweeps over the celestial sphere.

$$\left[\frac{N_{worst}}{N_{best}}\right]_{85'} \simeq 10 \log_{10} \left[\frac{8,580^\circ}{280^\circ}\right] \simeq 15 \text{ dB}$$

However, these temperature extremes represent a 12 dB variation, in terms of total 136 MHz receiver output noise power, for a receiver front-end noise temperature, $T_{rec} = 290^\circ K$. Correspondingly, there is an approximate 10 dB variation for the 40' dish and SATAN antennas.

DETERMINATION OF ANTENNA GAIN USING RADIO STARS

Equation (10) can be rearranged to express receiving antenna gain, G_R, as

$$G_R = \frac{8\pi k}{\lambda^2 F} \cdot \frac{\Delta V_{DC}}{V_{DC}} (T_{sky} + T_{rec}). \tag{22}$$

where $T_{sys} = T_{sky} + T_{rec}$

If $\epsilon \neq 1$, the effective system noise temperature from (10a) is

$$T'_{sys} = \epsilon(T_{sky} - T_0) + T_0 + T_{rec}.$$

Table 5
Effective Noise Temperature of Various Celestial Sources at 136 MHz

Celestial Noise Source	85' Dish (θ_t = 6.5° beam)		40' Dish (θ_t = 12° beam)		SATAN ARRAY (θ_t = 10° beam)	
	†T_A	T^{**}_{sys}	†T_A	T^{**}_{sys}	†T_A	T^{**}_{sys}
1. Quiet Sun in Conjunction with Galactic Center*	8,680°	8,970°	4,700°	4,990°	5,500°	5,790°
2. Galactic Center	2,950°	3,240°	2,310°	2,600°	2,500°	2,790°
3. Quiet Sun***	5,730°	6,020°	2,390°	2,680°	3,000°	3,290°
4. Cassiopeia A, strongest radio star, and background sky.	2,050°	2,340°	1,130°	1,420°	1,330°	1,620°
5. Cygnus A radio star and background sky	1,770°	2,060°	1,100°	1,390°	1,240°	1,530°
6. North Galactic Pole (NGP) cold-sky reference (Table 3)	280°	570°	280°	570°	280°	570°

*Occurs once each year, around Christmas time, from December 15th to December 25th.
**$T_{sys} \cong T_A + T_{rec} \cong T_A + 290°K$ = receiving system noise temperature, degrees Kelvin.
***Assumes T_{sky} = 1,000°K background sky temperature.

$$\dagger T_A \cong \left(\frac{\theta_s}{\theta_t}\right)^2 T_{sun} + T_{sky}.$$

$$\theta_t >> \theta_s$$

$\theta_s = 0.5°$, $T_{sun} = 8 \times 10^5$ degs. Kelvin for quiet sun ideal model.

Eq. (22) then becomes

$$G = \frac{8\pi k}{\lambda^2 F} \left[\frac{\Delta V_{DC}}{V_{DC}}\right]' \left[\epsilon(T_{sky} - T_0) + T_0 + T_{rec}\right]. \tag{22a}$$

where

$G = \epsilon G_R$ = effective antenna power gain, above isotropic, referenced to preamplifier input.

The primes indicate modified values.

An independent measurement of T_{sys} will give G_R, from (22), as a function of physical constants and the amplified detector output voltage ratio. T_{sys} can be determined by injecting, through a directional coupler, a calibrated signal generator input just ahead of the front-end preamplifier (see Figure 6). The signal generator input power level, S, is adjusted to equal the system noise power, N, with the radio star positioned in the antenna's 1st sidelobe null. Setting S = N is equivalent to increasing the receiver predetection noise power level by 3 dB. For these conditions,

$$S = N = k T_{sys} \Delta f \text{ watt} \tag{23}$$

rearranging

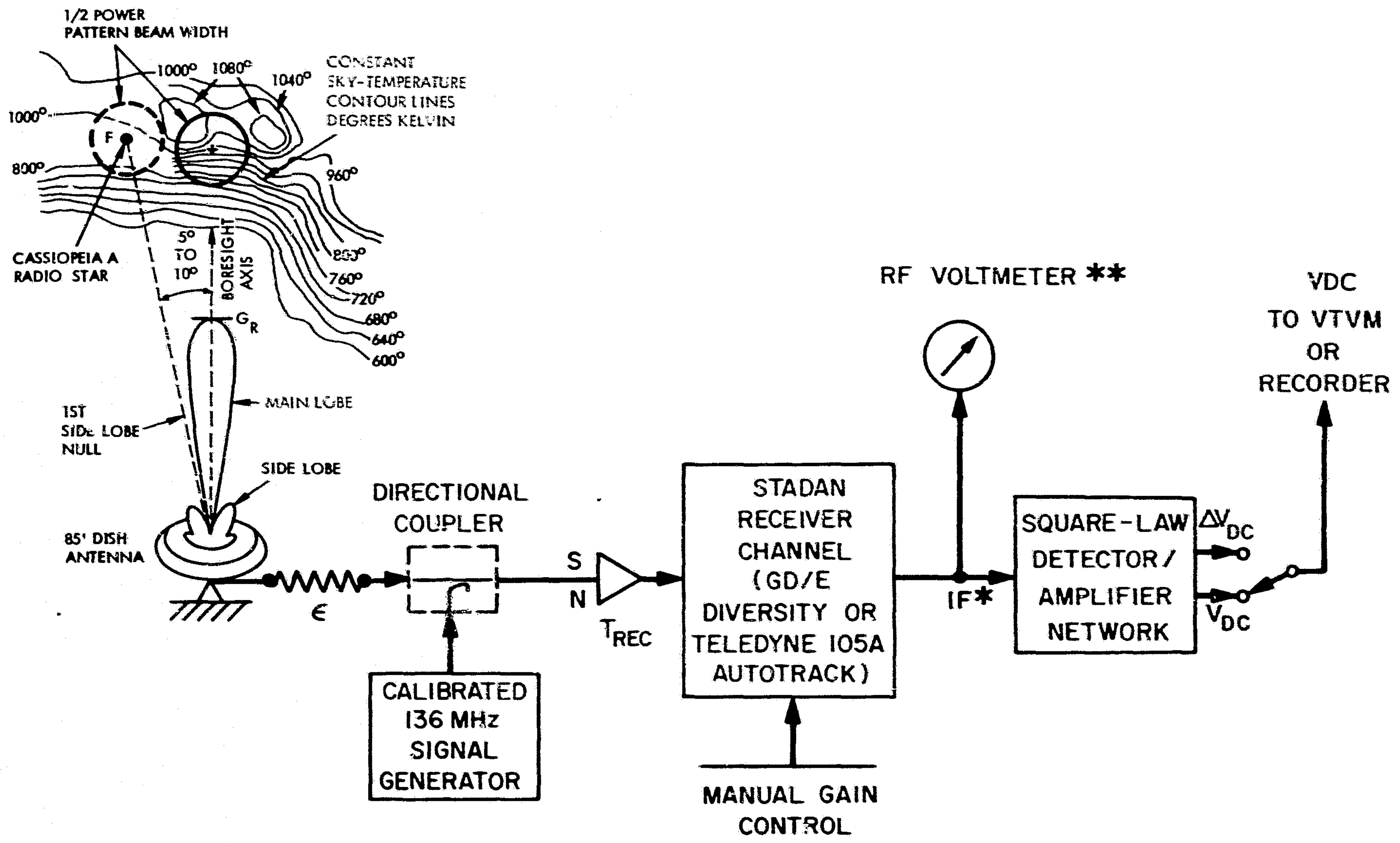
$$T_{sys} = \frac{S}{k \Delta f} \tag{23a}$$

Substituting (23a) in (22) gives

$$G_R = \frac{8\pi}{\lambda^2 F} \cdot \frac{\Delta V_{DC}}{V_{DC}} \cdot \frac{S}{\Delta f} \tag{24}$$

If $\epsilon \neq 1$, the effective antenna power gain becomes

$$G = \frac{8\pi}{\lambda^2 F} \left[\frac{\Delta V_{DC}}{V_{DC}}\right]' \left[\frac{S'}{\Delta f}\right]. \tag{24a}$$



* IF = 11 MHz OR 2.61 MHz

** BOONTON ELECTRONICS CORP. MODEL 91H-S5, OR EQUIVALENT

Figure 6–Block Diagram, Antenna Gain Calibration.

where

$$S' = N' = k\,T'_{sys}\,\Delta f \text{ watt.}$$

The primes indicate modified values.

The variables determining antenna gain includes the radio star flux density, F, the amplified detector output voltage ratio, and the signal generator input power level, S. The most significant uncertainty comes from measuring the detector output voltage ratio. The preliminary results of measurements taken at several South American STADAN stations indicate that $[\Delta V_{DC}/V_{DC}]'$ can be measured with a precision on the order of 1 dB for Cassiopeia A and Cygnus A using a 12° antenna beamwidth.

An alternate approach uses a Dicke Radiometer to measure the sky temperature, T_{sky}, at the antenna output terminals, and a noise figure meter to measure the receiver front-end noise temperature, T_{rec}. These temperature values would be substituted in (22) for determining antenna gain.

Equation (24) takes into account the overall effects of the various antenna design parameters including aperture efficiency, beam efficiency, transmission line cable losses, etc. It should be possible to determine actual antenna gain, with an accuracy on the order of 1 dB, assuming no uncertainities in F or S.

PRELIMINARY RADIO STAR TEST DATA

The Operations Evaluation Branch's (Code 514) aircraft calibration team began evaluating, in February, 1969, at several South American stations, the radio star calibration technique described in this report. A typical test result, for the Santiago, Chile 40 ft. dish antenna, is shown in Table 6. These test results are encouraging; showing that the voltage ratio, $[V_{DC}/\Delta V_{DC}]'$, is repeatable within 1 decibel, at 136 MHz, for the Cygnus A radio star observed from Santiago. Similar results were obtained with the Quito 40 ft. dish, using Cassiopeia A, and with the Satellite Automatic Tracking Antenna (SATAN), located at Greenbelt, Maryland, using Cassiopeia A.

The Santiago station's 136 MHz system noise temperature can be determined from (10b), Table 1, and the Table 6 average result, as

$$T'_{sys} = \frac{G\,\lambda^2\,F}{8\pi k}\left[\frac{V_{DC}}{\Delta V_{DC}}\right]' \tag{25}$$

Table 6
Santiago Celestial Source 136 MHz Test Data

Celestial Source	Background Sky Voltage, V_{DC}	Radio Star Voltage, ΔV_{DC}	Voltage Ratio, $[V_{DC}/\Delta V_{DC}]'$
Cygnus A	-2.40 vdc	-0.18 vdc	13.3
"	-2.55 vdc	-0.20 vdc	12.8
"	-2.70 vdc	-0.20 vdc	13.5
"	-2.40 vdc	-0.20 vdc	12.0
"	-2.35 vdc	-0.20 vdc	11.7
"	-2.30 vdc	-0.22 vdc	10.5
"	-2.32 vdc	-0.18 vdc	12.9
Cygnus A Averages:	-2.43 ± 0.133 vdc	-0.197 ± 0.013 vdc	12.4 ± 1.1
	Cold-Sky Voltage, $V_{ref\ DC}$		
SGP	-1.85 vdc	–	–
SGP	-1.80 vdc	–	–
Average $V_{ref\ DC}$ = -1.83 vdc			

Test Date: March 12, 1969

STADAN Station: Santiago, Chile.

Antenna: 40 ft. parabolic dish, 1/2 power beamwidth = 12°.
Linear polarization – Mode A

Bandwidth, Δf = 300 kHz

Wavelength, λ = 2.2 meters (m)

The effective antenna gain, G, is an extremely important parameter in (25) since the system noise temperature is directly proportional to antenna gain. It is difficult to obtain a precise value of G, using conventional methods; Eq. (22a) being used as follows to obtain an implied value from the Santiago celestial source data in Table 6. Restating (22a) as

$$G = \frac{8\pi k}{\lambda^2 F}\left[\frac{\Delta V_{DC}}{V_{DC}}\right]'\left[\epsilon(T_{sky} - T_0) + T_0 + T_{rec}\right]. \tag{25a}$$

where

$\epsilon = 0.63$ (2.0 dB total measured loss to preamplifier input).

$T_{sky} = 900° \pm 100°K$ Cygnus A background sky temperature for 12° beamwidth (Ref. 8).

$T_{rec} = 440°K$ (4.0 dB measured front-end noise figure).

$T_0 = 290°K$ ambient temperature of elements causing ϵ.

$F = 11.0 \pm 1.0 \times 10^{-23}$ w m^{-2} Hz^{-1} (Cygnus A flux density).

Computing the standard deviation (1σ value) from the propagation of precision indexes (Reference 11),

$$G = \frac{8 \times 3.14 \times 1.38 \times 10^{-23}\ J/°K}{(2.2m)^2 \times 11.0 \pm 1.0 \times 10^{-23} wm^{-2}Hz^{-1}}\left[\frac{1}{12.4 \pm 1.1}\right]\left[0.63\,(900° \pm 100° - 290°) + 290° + 440°\right]$$

$G = 58.5 \pm 8.1$ power ratio, expressed in terms of the 1σ value $= 17.7 \pm 0.6$ dB linear gain, above isotropic.

Substituting the value $G = 58.5 \pm 8.1$ in (25) gives

$$T'_{sys} = \frac{(58.5 \pm 8.1)(2.2m)^2 \times 11.0 \pm 1.0 \times 10^{-23}\ w\,m^{-2}\,Hz^{-1}}{8 \times 3.14 \times 1.38 \times 10^{-23}\ J/°K}\left[12.4 \pm 1.1\right]$$

$T'_{sys} = 1120° \pm 210°K$, as the overall effective 136 MHz system noise temperature, for the Santiago 40 ft. dish pointing about 10° away from Cygnus A.

The receiving system front-end noise temperature, referenced at the pre-amplifier input, can be determined directly from (14e). For the Santiago station data where $T_{ref} = 300°K$ (SGP),

$$T_{rec} = \frac{G \lambda^2 F}{8 \pi k} \left[\frac{V_{ref\ DC}}{\Delta V_{DC}}\right]' - T_0 . \tag{26}$$

From Table 6,

$$\left[\frac{V_{ref\ DC}}{\Delta V_{DC}}\right]' = \frac{-1.83 \text{ vdc}}{-0.197 \pm 0.013 \text{ vdc}}$$

$$T_{rec} = \frac{(58.5 \pm 8.1)\,(2.2\text{m})^2 \times 11.0 \pm 1.0 \times 10^{-23}\,\text{wm}^{-2}\text{Hz}^{-1}}{8 \times 3.14 \times 1.38 \times 10^{-23}\,\text{J}/°\text{K}} \left[\frac{-1.83\,\text{vdc}}{-0.197 \pm 0.013\,\text{vdc}}\right]$$

$T_{rec} = 545° \pm 150°K$ expressed in terms of the 1σ value.

The above value of $545° \pm 150°K$ agrees extremely well with the 440°K value (equivalent to 4.0 dB front-end noise figure) measured at Santiago using a conventional technique. The receiver noise temperature, $T_{rec} = 545° \pm 150°K$, is equivalent to a front-end noise figure,

$$(\text{N.F.})_{dB} = 10 \log_{10} \left[\frac{T_{rec}}{290°} + 1\right] . \tag{26a}$$

For Santiago, the front-end noise figure, measured using the radio star method, is $(\text{N.F.})_{dB} = 4.6 \pm 0.8$ dB; a value in close agreement with the 4.0 dB value measured by station personnel using a noise figure meter. This significant result also implies that the above calculated value of effective antenna gain, $G = 17.7 \pm 0.6$ dB, for the Santiago 40 ft. dish, at 136 MHz, is also correct.

From (14b), the Santiago absolute threshold sensitivity is

$$P'_{sen} = \frac{G\lambda^2 F \Delta f}{8\pi} \left[\frac{V_{ref\ DC}}{\Delta V_{DC}}\right]' . \tag{27}$$

$$P'_{sen} = \frac{(58.5\pm8.1)\ (2.2\mathrm{m})^2\ (11.0\pm1.0)\times10^{-23}\,\mathrm{wm}^{-2}\,\mathrm{Hz}^{-1})\ (3\times10^5\,\mathrm{Hz})}{8\times3.14} \left[\frac{-1.83\,\mathrm{vdc}}{-0.197\pm0.013\,\mathrm{vdc}}\right]$$

P'_{sen} = $(3.46 \pm 0.62) \times 10^{-15}$ watt, expressed as a 1σ value, that is equivalent to

P'_{sen} = - 114.6 dBm ± 0.8 dB, for Δ f = 300 kHz bandwidth, as the system threshold sensitivity with the Santiago 40 ft. dish pointing at the SGP.

The above result indicates a precision of ± 0.8 dB, in terms of the absolute system threshold sensitivity, that can be obtained from (27) for a given, constant, receiver bandwidth, Δf. The day-to-day repeatability of the threshold sensitivity determination, made by a given station, should be excellent; a sensitivity degradation of several decibels being easily ascertained.

CONCLUSIONS

A calibration technique is described, using various radio stars including Cassiopeia A and Cygnus A, that provides an absolute threshold sensitivity calibration of 136 MHz ground station receivers. Operationally, receiver calibration with a radio star is simple to implement, requiring only several minutes to obtain threshold sensitivity. A station's day-to-day sensitivity can thus be monitored with high accuracy, preliminary field test results indicating 1 dB can be achieved. Additional field evaluation tests are planned.

Care must be exercised to ensure that the celestial source being observed is far enough above the horizon to prevent multipath-type signal fluctuations. Allen and Gum[12] have suggested an elevation angle of 30°, minimum, for viewing celestial sources, although sources can be viewed down to 20° with somewhat greater signal fluctuation.

The directive gain of a parabolic dish antenna can be determined using radio stars, requiring only a calibrated 136 MHz signal source injected at the front-end preamplifier input terminal. Antenna gain can be thus determined within 1 dB; assuming the radio star's flux density is known precisely. It is believed that the method of computing effective antenna gain, using the system and celestial parameters in Eq. (25a), is a valid approach that results in a good determination of antenna gain also accurate within 1 dB.

The galactic center, and the strongest radio stars, Cassiopeia A and Cygnus A, can be used as standard noise sources to evaluate bit error probability (BEP) performance in a pulse code modulation (PCM) telemetry system. Relationships were developed for determining the approximate antenna temperatures for "hot-spot" celestial noise sources such as the galactic center. The input noise power, at 136 MHz, varys approximately 7 dB by shifting an 85-ft. dish mainlobe from the galactic center to cold sky, this change being sufficient to evaluate BEP performance in a PCM system.

An IBM 360/91 computer program is being written to determine received signal-to-noise ratio (SNR), at 136 MHz, for any type STADAN-station antenna. The computer radio map includes the galactic center, the Sun, and the significant radio stars; emissions from earth-orbiting satellites being also considered. Celestial noise, entering the main lobe, causes an 85 ft. dish antenna output SNR to vary as much as 12 dB, between extremes, over the celestial sphere. Such a large SNR variation should be taken into account both during the data acquisition and data processing phases.

ACKNOWLEDGMENT

The helpful suggestions of Mr. Larry W. Brown, Radio Astronomy Section, Code 615.5, are acknowledged. The use of equation (6), for determining antenna gain, was suggested by Dr. Robert J. Coates as he reviewed this manuscript. The stimulating discussions with Messrs. C. A. Scaffidi (514), F. J. Stocklin (514), R. F. Reich (RCA), V. R. Simas,(523), R. T. Fitzgerald (570.2), W. Poland (563), and Dr. W. R. Hedeman, of the Aerospace Corporation, are appreciated.

The invaluable field-evaluation tests, conducted by the Operations Evaluation Branch's (Code 514) aircraft calibration team, in South America, are gratefully acknowledged. Mr. W. Hillstrom, of the RF Support Office, designed the solid-state type detector/amplifier network used in the field tests.

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