GBT G/T Calculation for Satellite Engineers

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Abstract

This memo provides $\frac{G}{T_{sys}}$ values for the Green Bank Telescope (GBT). This memo does not address other various radio telescopes stationed within the Green Bank Observatory (GBO) property. Herein, we present the nominal values for receivers positioned at the primary or the secondary Gregorian focus with various referenced sources.

For the reader only interested in the nominal $^{G}/_{T_{sys}}$ values in dB/K units, refer to Table 1 of this document. Detailed references and definitions follow in various sections, supporting the stated values in the aforementioned table. In addition, Green Bank Observatory offers an online sensitivity calculator for public use for exact calculation of the telescope sensitivity.

Contents

1 Table of nominal ${}^{G}/_{T_{sys}}$ Values for the Green Bank Telescope (GBT)

Table 1 presents the nominal ${}^{G}/_{T_{sys}}$ values for the GBT. These values take into account atmospheric opacity at typical operational elevations and weather conditions. A cosmic microwave background (CMB) of 2.7 K is included in these values as well as a spill-over noise temperature value of 3 K. The spill-over is receiver and frequency-dependent. It does vary in an approximate range of 2.5 - 6 K. The Green Bank Telescope Sensitivity calculator utilizes the 3 K value. Exact values of T_{sys} under different operating parameters and conditions can be calculated by the Green Bank Telescope Sensitivity calculator. [1]

A detailed approach and derivation of these values can be found in the various appendices of Dr. Klahold's memo, [1] and discussed herein Section 2. It should be noted that just as with antenna gain, many of the contributing variables are dependent upon angle of arrival (AoA) and the relative attitude of the telescope. Such variations are addressed in the subsections of Section 2.

Table 1: Nominal ${}^{G}/_{T_{sys}}$ and selected characteristics for GBT Receivers at stated frequencies.

Receiver	**Frequency** *(GHz)*	$\boldsymbol{T_{Rcvr}}$ *(K)*	$\boldsymbol{T_{Sys}}$ *(K)*	**Gain** *(dBi)*	$\boldsymbol{{}^{G}/_{T_{sys}}}$ *(dB/K)*
L-Band	1.4	8	17.4	61.83	49.43
S-Band	2	6	14.9	64.93	53.20
C-Band	5	7.4	16.5	72.88	60.70
X-Band	9	11	21	77.94	64.72
Ku-Band	14	10.3	22.5	81.70	68.18
KFPA	25	24.3	46.7	86.44	69.75
Ka-Band	32	37	61	88.31	70.46
Q-Band	43	36.3	75.8	90.70	71.91
W-Band	77	40	108.1	93.82	73.48
Argus	86	55	104.5	94.08	73.89

The values given in Table 1 utilize various surface errors when accounting for surface irregularities or deviations, implementing the well-known Ruze equation. These Root Mean Square (RMS) surface deviation values are stated herein Table 2. Utilizing these values along with the design goal of 71% illumination efficiency provides the nominal efficiency values per receiver as stated therein. Further discussion of the calculation basis of η_{total} and T_{sys} can be found in their associated sections.

[1] For assistance with this calculator, see the NRAO help desk at URL https://help.nrao.edu/

Table 2: GBT Main Dish Surface RMS Deformation and associated efficiencies based upon the illumination taper efficiency of 71% and associated effect of the surface deformation as defined by the Ruze equation.

Receiver	**Frequency** *(GHz)*	**RMS Surface Deformation** (μm)	$\boldsymbol{\eta_{total}}^{a}$ (%)
L-Band	1.4	450	70.95
S-Band	2	450	70.90
C-Band	5	300	70.72
X-Band	9	300	70.10
Ku-Band	14	300	68.84
KFPA	25	300	64.33
Ka-Band	32	300	60.40
Q-Band	43	250^{b}	57.97
W-Band	77	250^{b}	37.06
Argus	86	250^{b}	31.55

^{a} $\eta_{total} = \eta_{aperture}$

^{b} Can be obtained at night with 'AutoOOF' surface corrections.

2 Definitions of Terms and Factors

2.1 Definition of T_{sys}

Simply written, the sytem noise temperature is as given in Equation (1).

$$T_{system} = T_{antenna} + T_{losses} + T_{receiver} \tag{1}$$

Where the term T_{losses} refers to transmission line loss and can be of any type, such as coaxial, microstrip, hollow waveguide structures, or variations thereof. T_{losses} for a given transmission line can be calculated as shown in Equation (2)

$$T_{losses} = \left(\frac{1}{e^{-2\alpha L}} - 1\right) T_{Line\,Temp} \tag{2}$$

Where:

$$\begin{aligned} e^{-2\alpha L} &\triangleq transmission\ line\ thermal\ efficiency^2 \\ \alpha &\triangleq transmission\ line\ attenuation\ constant \\ T_{Line\,Temperature} &\triangleq physical\ temperature\ of\ the\ transmission\ line. \\ L &\triangleq physical\ tranmission\ line\ length \end{aligned} \tag{3}$$

If we consider the T_{losses} terms as negligible due to direct attachment or limited line length to the receiver in a cryogenic environment, we can state $T_{antenna}$ as given in Table 3.

Table 3: GBT Antenna Temperatures Calculated by the Difference of the nominal T_{sys} and T_{Rcvr} as given in Table 1.

Receiver	**Frequency** *(GHz)*	T_{ant} *(K)*
L-Band	1.4	9.4
S-Band	2	8.9
C-Band	5	9.1
X-Band	9	10
Ku-Band	14	12.2
KFPA	25	22.4
Ka-Band	32	24
Q-Band	43	39.5
W-Band	77	68.1
Argus	86	49.5

By the definition stated in Equation (6), $T_{antenna}$ includes all sources within the view of the antenna weighted by the normalized power pattern of said antenna. For a formal introduction to normalized power patterns, see [2]

[2] It is of note that this equation is meant for in transmission line calculations. Thus, as it typical, most calculations are completed with easily measurable terms, such as voltage within the T_{losses} equation.

Thus, $T_{antenna}$ can be written as follows:

$$\begin{aligned} T_{antenna} = & T_{Spill\,over} + T_{Sidelobes} + T_{ohmic\,losses\,of\,antenna\,structure} + \\ & T_{Cosmic\,Microwave\,Background} + T_{Galactic\,background\,Noise} + \\ & T_{Radio\,Frequency\,Interference} + T_{Solar\,and\,Lunar\,Noise} + T_{atmospheric} + T_{local\,weather\,effects} \end{aligned} \tag{4}$$

To abbreviate these terms, Equation (4) can rewritten as:

$$\begin{aligned} T_{ant} = & T_{Spill} + T_{Sl} + T_{ohmic\,losses} + \\ & T_{CMB} + T_{gal} + \\ & T_{RFI} + T_{Sol} + T_{atm} + T_{weather} \end{aligned} \tag{5}$$

Equation (1) and furthermore, Equation (4) detail the various noise temperatures that can be included in the calculation of either T_{system} or $T_{antenna}$. For the purposes of the nominal figures given in Table 1, some of the stated terms are excluded, while others are considered constant values. For detailed derivation and calculation of many of these values, see [3] and [4].

- T_{Spill} is approximately 3 K.
- T_{SL} is minimal, but not always negligible, dependent upon source distribution. Radio Frequency Experience (RFI), or as it is more commonly known in non-Astronomy fields, Electromagnetic Interference (EMI) may also enter through the sidelobes but this temperature is accounted for herein T_{RFI}. Generally, the first GBT sidelobes are -27 dB relative to peak of beam with various other lobes being much less [5].
- $T_{ohmic\,losses}$ is not the same T_{losses} as stated in Equation (1) and Equation (2), rather it is the loss of the antenna structures, including the reflector surface as well as the feed structure. This extends to any surface where current is induced to a non-negligible level.
- T_{CMB} is set to 2.7 K.
- If one is not observing in or pointed towards the galactic plane, T_{gal} is approximately equal to 0.
- T_{RFI} is not included in the stated nominal values as it varies per frequency and it is not known a priori.
- T_{Sol} is negligible when the sun is not within the main beam of the GBT. This is limited in the side lobes due to the design and standard illumination of the GBT. Generally, the magnitude of the first side-lobes of the GBT are -27 dB from the beam peak.
- T_{atm} varies with AoA and time. Nominal figures include minimum elevations of 40 degrees. For a complete review of this term, see chapter 14 in [6]. Essientially this presents a method to calculated the complex permititivy of the atmosphere, and thus propagation affects.
- $T_{weather}$ utilizes typical operational conditions per receiver band. A detailed review of the weather prediction utilized for the GBT, and hence this value is presented in [7]

2.1.1 Definition of T_{Ant} and Spatially Dependent Noise Temperatures

Antenna temperature or T_{Ant} is the product of the normalized power pattern and brightness distribution about the antenna as shown in Equation (6).

$$T_{ant} = \frac{1}{\Omega_a} \oiint_{4\pi} F\left(\theta,\phi\right) \cdot T_{B(\theta,\phi)}\, d\Omega \tag{6}$$

Given the following:

$$\begin{aligned} \Omega_A &= antenna\ beam\ solid\ angle \Rightarrow d\Omega \equiv \sin(\theta)\, d\theta\, d\phi \\ F(\theta, \phi) &= normalized\ power\ pattern\ of\ the\ antenna^3 \\ T_{B(\theta,\phi)} &= brightness\ temperature\ of\ the\ sphere\ ecompassing\ the\ entire\ antenna\ structure \end{aligned} \tag{7}$$

Various terms differ between the professional fields of Radio Astronomy and Antenna Engineering. Concerning the intersection of Antenna Engineering and Radio Astronomy, one should note that T_{ant} encompasses the astronomy recognized temperature of T_{sky}; both main beam and sidelobes as shown below in Equation (9) and Equation (10). For more concerning the intersection of Radio Astronomy and Antenna Engineering, see the presentation by Clegg as given in [8].

$$T_{ant} = T_{sky_{main\ beam}} + T_{spillover} + T_{sidelobes} + T_{ohmic\ losses} \tag{8}$$

$$T_{sky_{main\ beam}} = T_{ant} - (T_{spillover} + T_{sidelobes} + T_{ohmic\ losses}) \tag{9}$$

$$T_{sky_{sidelobes}} = T_{ant} - (T_{spillover} + T_{sky\, main\, beam} + T_{ohmic\ losses}) \tag{10}$$

Ohmic losses herein include dielectric losses as well as general conductive losses of the GBT feeds (generally corrugated horns) and illuminated surfaces. The conductive losses due solely to the conductivity of the physical antenna structure and surfaces can be written as show in Equation (11). Some may include this physically based antenna temperature as part of $T_{ohmic\ losses}$. Whether it is folded into $T_{ohmic\ losses}$ as alluded to by Equation (8) or in T_{sky} is a decision of the practicing engineer in terms of the combined temperature value. While this is an informative term for the reader, it is rarely utilized in isolation and is generally encompassed in the T_{ant} term.

$$T_{antenna\, noise\, temperature\, due\, to\, material\, and\, physical\, properties\, thereof} = \tag{11}$$

$$\left(\frac{1}{\eta_{antenna\, thermal\, efficiency}} - 1\right) T_{antenna\, physical\, temperature}$$

2.1.1.1 Spatially Dependent Noise Temperatures Multiple terms in the full system temperature (T_{sys}) are spatially dependent. These terms are: T_{Spill}, T_{SL}, T_{RFI}, T_{Sol}, T_{atm}, and $T_{weather}$. Refer to the statements concerning these values given in Section 2.1. For quick interactive calculation of these terms or ranges thereof, one can utilize the GBT sensitivity calculator. This calculator can be found at the URL: `https://dss.gb.nrao.edu/calculator-ui/war/Calculator_ui.html`.

It is of note, that the term T_{RFI} varies both spatially and temporally. The GBO Interference Protection Group (IPG) closely monitors all site interference, but a priori prediction of such is not available at this time.

2.1.2 Definition of T_{Rcvr}

The receiver noise temperature or T_{rcvr} as shown in Equation (1) denotes the noise temperature contribution of the receiver itself. The front-end cryogenic Low Noise Amplifier (LNA) generally dominates this figure in the system noise cascade calculation. The nominal T_{Rcvr} figures are given herein Table 1.

The values per receiver per frequency can be found in the GBT Sensitivity Calculator.

[3] This is the *Pattern-Propagation Factor* as defined by [2] in the famous MIT Radiation Laboratory or Rad Lab Series. It is of note that due to type setting limitations of the time, $\int_{4\pi}$ is utilized in place of $\oiint_{4\pi}$.

2.1.3 Definition of System Equivalent Flux Density (SEFD)

A commonly used figure of merit within radio astronomy is the System Equivalent Flux Density or SEFD of the T_{sys} term. SEFD is calculated as shown in Equation (12). This can be derived from the Rayleigh-Jeans expression for specific field intensity as shown in [9]. For a more detailed approach in a classical text, see [6].

$$SEFD = \frac{2\,k\,T_{sys}}{A_{equivalent\ crosssectional\ area\ of\ the\ aperture}} = \frac{2\,k\,T_{sys}}{A_e} \tag{12}$$

T_{sys} can be expressed as a SEFD. It is of use to the reader to understand how the field of radio astronomy presents this figure. The constant *k* is the Boltzmann constant is $1.380649 \times 10^{-23}\ \frac{J}{s}$. The reason for the use of SEFD is to equate the system temperature with the observable field, the flux density, S_ν, over the antenna solid angle of the antenna main beam.

This is shown in [9] as well as [6] but recreated here for the reader.

$$S_{\nu,\,rms} = \frac{SEFD}{\sqrt{\Delta\nu\tau}} \quad [Jy] \tag{13}$$

Where $\Delta\nu$ is the bandwidth in Hz and τ is the integration time in seconds. This leads to a final unit of Jansky, or Jy.

If one defines a variable K_a, not to be confused with the units of Kelvin, as is shown in Equation (14); SEFD can be simply stated as given in Equation (15). Thus, a factor of two typically seen in the denominator of Equation (14) is not present herein.

$$K_a = \frac{\eta_a \cdot A_p}{2 \cdot k} = \frac{A_e}{2 \cdot k} \quad \left[\frac{K}{Jy}\right] \tag{14}$$

$$SEFD = \frac{T_{sys}}{K_a} \tag{15}$$

One of the shining examples of the difference in the fields of Radio Astronomy and Antenna Engineering is how the term *Gain* is defined. Herein, the typical engineering definition of gain is given in Section 2.2. Yet to discuss SEFD, we must approach it from an Astronomy viewpoint. While we delve into this area, we must also state that in Astronomy, the noise generated by the physical temperature of the antenna is not included in the T_{ant} term. As expressed in Equation (16), the definition of antenna temperature utilizing the low frequency Nyquist approximation of a matched resistor across a single polarization generating thermal energy is dependent upon the received spectral power and the Boltzmann constant, and thus the effective Aperture A_e.

$$T_a \triangleq \frac{P_\nu}{k} = \frac{A_e \cdot S}{2 \cdot k} \tag{16}$$

Where S is the unpolarized flux density of the source. This description, derived in [3] on page 79, relates the increase in antenna temperature due to a point source flux density, S.

$$K_a = \frac{T_a}{S} = \frac{A_e}{2 \cdot k} \quad \left[\frac{K}{Jy}\right] \tag{17}$$

In astronomy, one tends to think of antenna gain as temperature increase per Jansky, or $^K/_{Jy}$. Thus, rather than unit-less gain as defined in Section 2.2, we utilize a gain with the units of $^K/_{Jy}$. If one sets K_a equal to 1, we can then describe what the A_e must be to provide an astronomer's gain of 1 $^K/_{Jy}$ as defined in Equation (17).

$$\eta_a \cdot A_p = A_e = 2 \cdot k \cdot K_a = 2 \cdot k = \frac{2 \cdot 1.380649 \times 10^{-23}}{1 \times 10^{-26}} = 2761.298 \quad \left[m^2\right] \tag{18}$$

One may ask where the term 1×10^{-26} originates. This can be seen through unit analysis as shown below in Equation (19) and Equation (20).

$$\begin{aligned} W &\triangleq \frac{J}{s} = \frac{kg \cdot m^2}{s^3} \\ J &\triangleq \frac{kg \cdot m^2}{s^2} \\ Jy &\triangleq 1 \times 10^{-26} \frac{W}{m^2 \cdot Hz} = 1 \times 10^{-26} \cdot \frac{kg \cdot m^2}{s^3} \cdot \frac{s}{m^2} = 1 \times 10^{-26} \cdot \frac{kg}{s^2} \\ Hz &\triangleq \frac{1}{s} \end{aligned} \tag{19}$$

Where Boltzmann's constant (k) is in the units of $^J/_K$, one can see by simple unit analysis where the value 1×10^{-26} originates in Equation (18).

$$k \cdot K_a \Rightarrow \frac{J}{K} \cdot \frac{K}{Jy} = \frac{J}{Jy} = \frac{kg \cdot m^2}{s^2} \cdot \frac{s^2}{1 \times 10^{-26} \cdot kg} = \frac{m^2}{1 \times 10^{-26}} \tag{20}$$

With this understanding and referring to Equation (15) we can then proceed to show its utilization in scaling the SEFD per telescope (or required A_e) by setting a reference $K_a = 1$ and multiplying by the K factor, think of this as the Astronomer's gain, for the given telescope as shown in Equation (21) and Equation (22).

$$SEFD \cdot K_{GBT} = T_{sys} \tag{21}$$

or more clearly as

$$\frac{SEFD \cdot K_{GBT}}{K_a} = \frac{T_{sys}}{K_a} \tag{22}$$

Wherein $K_a = 1$ and SEFD is scaled by the K_{GBT} factor, referred to herein as *Astronomer's Gain*. An example of a gain in these terms is the typical L-band gain in $^K/_{Jy}$ is 2. The SEFD term is included in this memo to introduce the reader to the meaningful differences in terms utilized by Antenna Engineers and Radio Astronomers. It is useful to classify radio telescopes by the K factor or Astronomer's gain, and indeed the SEFD per source to assist in performance and data comparison.

2.2 Definition of Antenna Gain (G)

The reader should recall that the antenna Gain is the antenna directivity multiplied by the antenna efficiency:

$$G = \eta \cdot D \tag{23}$$

Where D is defined as:

$$D = \frac{4\pi}{\oiint_{4\pi} F(\theta, \phi)\, d\Omega} = A_p \cdot \frac{4\pi}{\lambda^2} = \frac{4\pi}{\Omega_A} \tag{24}$$

Herein A_p is the physical cross-section of the antenna aperture. Refer to Equation (7) for an alternative form of $d\Omega$ and variable definitions.

The Gain at characteristic frequencies per receiver is given in Table 1. For clarity, as stated within Section 2.2.1, we shall notate the total system efficiency as η_a, thus:

$$G = \eta_a \cdot D = \eta_a \cdot A_p \cdot \frac{4\pi}{\lambda^2} = A_e \cdot \frac{4\pi}{\lambda^2} \tag{25}$$

For general purposes, it is worthwhile to mention that the term often seen as $\frac{\lambda^2}{4\pi}$ is the A_e of an isotropic radiator, as stated in Equation (26). This can be easily derived by setting Gain (G) to 1. Therefore, when such a term is seen, or the inverse thereof, the gain is stated relative to an isotropic radiator or in units dBi if so stated in logarithmic scale.

$$A_{effective\ isotropic\ radiator} = \frac{\lambda^2}{4\pi} \tag{26}$$

In addition, we should always keep in mind that gain is a spatially dependent function. The GBT is a fully steerable telescope; hence, the beam peak is typically on target for tracked sources. While this may alleviate the need for spatial dependence in Gain in terms of the static pattern, there other efficiency terms that are spatially dependent.

To alleviate gain variation with respect to elevation, induced by the gravitational deformation, GBO utilizes an Out Of Focus holography or OOF methodology to derive a Zernike-gravity model. OOF has been available for the GBT since 2009. The implementation of OOF measurement-based Zernike coefficients has essentially alleviated gain dependency upon elevation angle when tracking a target. The history of this technique and the various aperture efficiency improvements of the GBT over the years can be found in [10]. This memo presents effectively flat gain curves with respect to elevation at given frequencies below 80 GHz on the GBT.

2.2.1 Definition of Antenna System Efficiency or η_a

The terms utilized in the calculation of efficiency of the antenna system (herein the Green Bank Telescope or GBT) are as follows, with summarized nominal η_{total} or η_a as given in Table 2:

$$\begin{aligned} \eta_{total} = &\eta_{illumination} \cdot \eta_{spillover} \cdot \\ &\eta_{ohmic\,losses\,of\,reflector} \cdot \\ &\eta_{polarization\,efficiency\,of\,feed\,and\,reflector\,combination} \cdot \\ &\eta_{Ruze} \cdot \eta_{focal\,error} \cdot \eta_{blocking\,efficiency} \cdot \\ &\eta_{structural\,gravitational\,distortion} \end{aligned} \tag{27}$$

To simplify the equation for ease of writing, we let the following be true:

$$\eta_{total} = \eta_a \tag{28}$$
$$\eta_{illumination} = \eta_i \tag{29}$$
$$\eta_{spillover} = \eta_s \tag{30}$$
$$\eta_{ohmic\,losses\,of\,reflector} = \eta_r \tag{31}$$
$$\eta_{polarization\,efficiency\,of\,feed\,and\,reflector\,combination} = \eta_p \tag{32}$$
$$\eta_{Ruze} = \eta_e \tag{33}$$
$$\eta_{focal\,error} = \eta_f \tag{34}$$
$$\eta_{blocking\,efficiency} = \eta_b \tag{35}$$
$$\eta_{structural\,gravitational\,distortion} = \eta_g \tag{36}$$
$$\tag{37}$$

Thus, an abbreviated form, similar to [11], is created herein Equation (38).

$$\eta_a = \eta_i \cdot \eta_s \cdot \eta_r \cdot \eta_p \cdot \eta_e \cdot \eta_f \cdot \eta_b \cdot \eta_g \tag{38}$$

Given that the GBT is an offset parabolic reflector, the following applies.

- η_i is a design constraint for feeds on the GBT. This is empirically, by various validation measurements, set as 71%. It should be noted, this is not constant across all receivers. As one decreases frequency, this illumination efficiency does decrease. Yet for nominal figures for frequencies greater than or equal to X-band 71% is an applicable value with surface deviation and thus the η_e increasing with frequency as shown in Table 2.
- $\eta_r \cdot \eta_s$ is considered to be 99 % for the main reflector
- η_p complexities associated with relative polarization efficiencies are not addressed here. This value is set to 1.
- η_e is utilized and applicable when active surface control is enabled or disabled for the various receivers. This utilization can be seen by the decreasing values of RMS surface deviation given in Table 2.
- η_f is the ability to ensure operation at optimal focal points of the GBT. Prior to general observations, a focus calibration is completed. While not 100% in terms of efficiency, it is considered negligible within the GBT Sensitivity Calculator.
- η_b is negligible due to offset parabolic design of the GBT and shall be defined with the value of 1 or 100%.
- η_g is corrected by a Zernike-gravity model and below 80 GHz can be considered non-variant with respect to elevation. See [10] for gain curves with respect to elevation for frequencies equal to or greater than 80 GHz

2.3 Definition of ${}^{G}/_{T_{sys}}$

Given the previous sections, the calculation of ${}^{G}/_{T_{sys}}$ where **G** is as given in Equation (25) can be re-written as:

$$\frac{G}{T_{sys}} = \frac{\eta_a \times D}{T_{sys}} \tag{39}$$

Hence, referring to Section 2.2.1 with its description of the various efficiencies and the discussion of the contributing noise temperatures in Section 2.1, one can appreciate the frequency, spatial, and temporal dependencies of the various contributing factors to the calculation of ${}^{G}/_{T_{sys}}$. For general calculations, the data presented in Table 1 will suffice. For mission planning or more accurate link budgets, we direct the reader to the GBT Sensitivity Calculator for the *Typical Effective* T_{sys} value. Utilizing the calculator *Typical Effective* T_{sys} and the gains presented in Table 1, one could generate a large table with respect to AoA and frequency. The reader is advised to recall the term $T_{weather}$ and plan their mission or observation accordingly.

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