MEANINGFUL G/T MEASUREMENTS – MADE AT NIGHT

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ABSTRACT

The ratio of receive antenna gain to receive system noise temperature (G/T) is widely used throughout the satellite and telemetry communities, always appearing in the link budget in some manner. The conventional method of measuring G/T for directional antennas seems simple: measure received power while pointing the antenna at the sun, repeat the measurement while pointed at "cold sky", and do a few simple calculations. This paper briefly summarizes the many sources of error in this technique and then presents an alternative approach using a calibrated signal source instead of the sun. Both theoretical and empirical results are presented. The proposed approach can be applied to any type of receiving system (including active antennas and multi-beam phased arrays) and yields G/T results that apply meaningfully to the link budget.

INTRODUCTION

Every wireless communication system is built around the link budget, and somewhere in that link budget both the receive antenna gain (G) and the receive system noise temperature (T) must be accounted for.

While G and T can be measured individually, it is often more convenient to measure their ratio (G/T) directly. This measurement requires a calibrated source of energy at the frequencies of interest; for many systems, this source is taken to be the sun.

We will start this paper by reviewing the procedure for solar-based G/T measurement and examine the sources of variability inherent in this approach. We will then describe an alternate method that makes no use of the sun and explore the variability in this approach as well.

SOLAR G/T MEASUREMENTS

The solar-based method of measuring G/T is widely documented in the literature. See [1] and [2] for particularly comprehensive treatments. Here's a high-level overview:

- Point the antenna at the sun, measure P_h in dBm on the attached receiver.
- Point the antenna at cold sky, measure P_c in dBm on the attached receiver.
- Calculate $Y_{dB} = P_h - P_c$
- Calculate Y factor: $Y = 10^{(Y_{dB}/10)}$
- Estimate beam correction factor, C (frequently set to 1)
- Estimate atmospheric attenuation factor, A (frequently set to 1)

Then simply insert values and turn the crank to get G/T, as follows:

$$\left(\frac{G}{T}\right) = \left(\frac{8\pi k(Y-1)}{S_0\lambda^2 CA}\right) \tag{1}$$

where

k = Boltzmann's constant (1.38 x 10^{-23} J/K)
λ = wavelength (m)
S_0 = radiation flux-density of the sun (W/(m^2 Hz))

Adopting the common approximation of both C = 1 and A = 1, the value of G/T essentially depends on the measured values of P_h and P_c, and the published value of S_0. Simple, or so it would seem. Upon closer examination, however, this is not quite so straightforward as it appears, as both the solar flux and the Y factor have sizeable uncertainties.

The solar flux value is fundamentally a measurement of noise power in an electromagnetic wave of unknown and continually varying polarization, meaning the polarization loss between the sun and the ground station under test is not constant and cannot be controlled. Also, the solar flux is measured at only a handful of observatories around the world and each observatory only measures the flux at a few frequencies (some at only one frequency, 2800 MHz). No location measures the solar flux at any frequencies used for aeronautical telemetry. Furthermore, there are both cyclic and random variations in solar flux, so measurements need to be “fresh”.

Taking all these variables into account requires interpolation across location, time, and frequency. This leads to significant uncertainty in the actual value of S_0 at the location, time, and frequency of interest.

The accuracy of the Y factor in equation (1) is often even worse. Since the sun is a noise source, the value of P_h is never constant, but averaging can be used to estimate P_h with a reasonably small variance. The “cold sky” power, P_c , on the other hand is influenced by a host of variables that cannot be averaged away. These include actual sky temperature variations, background environmental noise (entering through antenna sidelobes), and the height of the antenna above the ground (higher locations pick up less of the warm earth).

The conventional solution to resolving these unknowns is to point the antenna to multiple sky locations and find the *lowest* value of P_c . While this may reduce the *variance* in the measured Y factor, it also yields the most *optimistic* value for G/T. The ground station only actually delivers that G/T when the antenna is pointed toward that “coldest” sky; in all other directions, the G/T is certainly worse. *A link budget based on this value will be optimistic.*

An additional unknown in the Y factor calculation arises from the accuracy of the power measurements, P_h and P_c. Most modern receivers offer accurate, calibrated input signal strength displays right in the user interface. Older designs, however, did not have the signal processing power to provide calibrated signal strength values and therefore the power was measured with external equipment (power meter or RMS voltmeter) while the receiver was in manual gain control mode. Unfortunately, the P_h and P_c values are small, and the linearity of the receiver is often poor at such low levels. This contributes another difficult-to-repeat term to the calculation.

The combination of estimation and interpolation in developing the value of S_0, together with the uncontrolled variables in the Y factor, leads to computed G/T values that vary by up to ±1 dB at any one location and even larger variations when moving a system from one location to another. **Even if the variations can be reduced, we are still left with the fact that the "coldest sky" approach yields an unrealistically optimistic value for G/T.**

MODULATED SIGNAL SOURCE G/T MEASUREMENTS

The sun is a noise source so by definition, any value calculated from a solar observation must have some variance to it. Here, we will describe a deterministic approach to measuring G/T, using a man-made signal source instead of the sun. Let's make some assumptions:

- Signal source renders high-fidelity modulated telemetry signals, with adjustable bit rate.
- EIRP of the signal source is calibrated and adjustable.
- Polarization of the signal source is known (better yet, programmable).
- Ground station includes a receiver with known BER vs. E_b/N_0 characteristics.
- Ground station includes a BER tester (or a receiver with accurate Data Quality Metric).
- Distance between the signal source and the ground station under test is known.
- Path between signal source and ground station under test is line-of-sight and long enough to ensure the signal source is in the far field of the receiving antenna.

We will start with the standard link budget equation below.

$$\frac{E_b}{N_0} = \frac{P_t L_t G_t}{k R_b} \left(L_\theta\right) \left(\frac{G}{T}\right) \left(\frac{\lambda}{4\pi D}\right)^2 \quad (2)$$

Picking equation (2) apart and converting the factors to dB, we see that

- 10 log $(P_t L_t G_t)$ = EIRP, dBm
- 10 log $\left(\frac{\lambda}{4\pi D}\right)^2$ = L_p, Path loss, dB
- 10 log (L_θ) = $(L_\theta)_{dB}$, Polarization loss, dB
- 10 log (k) = -198.6, dBm/(K-Hz)
- 10 log $\left(\frac{G}{T}\right)$ = G/T, dB/K
- 10 log (R_b) = Bit rate, dB-Hz

Then rewriting (2) in dB format, we get

$$\left(\frac{\boldsymbol{E_b}}{\boldsymbol{N_0}}\right)_{\boldsymbol{dB}} = \boldsymbol{EIRP_{dBm}} + (\boldsymbol{L_p})_{\boldsymbol{dB}} + (\boldsymbol{L_\theta})_{\boldsymbol{dB}} + \left(\frac{\boldsymbol{G}}{\boldsymbol{T}}\right)_{\frac{\boldsymbol{dB}}{\boldsymbol{K}}} - (-\boldsymbol{198.6}) - \boldsymbol{10\ log}\ (\boldsymbol{R_b}) \quad (3)$$

Finally, a simple rearrangement of terms yields a closed form expression for G/T in dB/K.

$$\left(\frac{G}{T}\right)_{\frac{dB}{K}} = \left(\frac{E_b}{N_0}\right)_{dB} - EIRP_{dBm} - (L_p)_{dB} - (L_\theta)_{dB} - 198.6 + 10\log(R_b) \tag{4}$$

In equation (4), we know everything on the right side:

- E_b/N_0 can be determined from the known BER performance of the receiver.
  - Or from the Data Quality Metric (DQM) if it's accurate.
- Calibrated signal source gives us a known EIRP.
- Polarization control give us control of the polarization loss.
- GPS or Google maps gives us distance, which gives us path loss.
- We get to set the bit rate.

Armed with equation (4), we have a simple experimental technique that yields G/T. Once the calibrated source and ground station under test are accurately located and within line of sight, carefully point them at each other. Cameras at each end can be helpful here. Ensure that the source is in the far field of the ground station; that is, separated by at least ($2D_a^2 / \lambda$), where D_a is the diameter of the antenna under test (in the same length units as λ).

Now adjust the source EIRP, modulation, polarization, and bit rate to achieve a BER yielded by a known E_b/N_0. The curves in Figure 1 below were used for the results in this paper, but other curves can be employed, so long as they are known and repeatable. For most of the results presented here, we used SOQPSK (ARTM Tier I) with a target BER of 10^{-5} (or a DQM of 5). This is known to correspond to an E_b/N_0 of 11.4 dB with this receiver. In general, higher bit rates will make this adjustment simpler because the normal interval-to-interval variation in BER will be largely smoothed out at higher bit rates. The results here were taken at 10 Mbps.

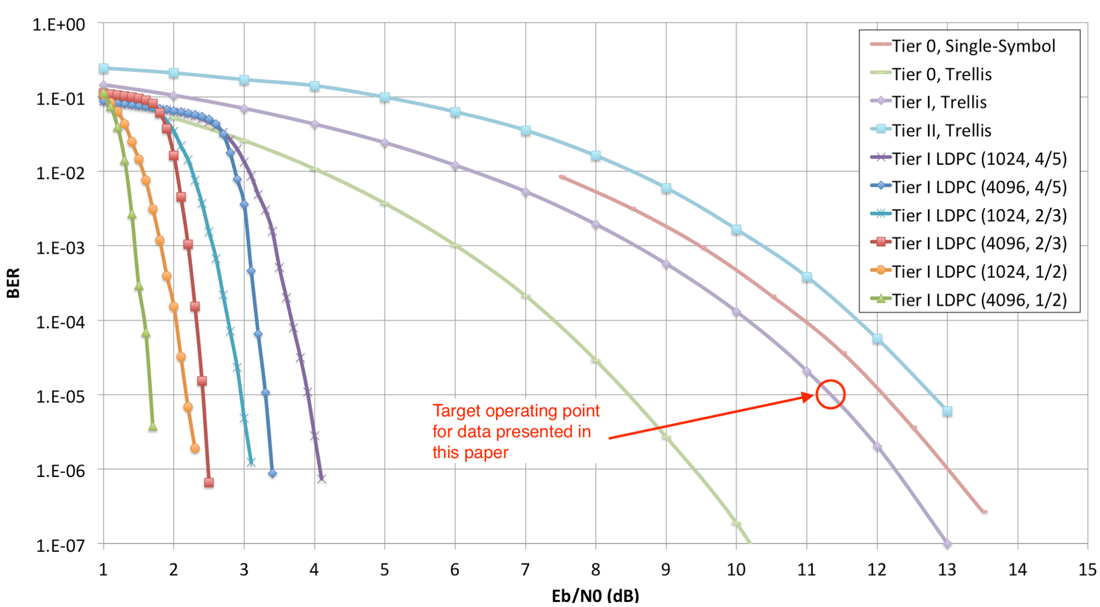

Figure 1 BER vs. Eb/No for Receiver Used in this Paper.

EXPERIMENTAL RESULTS

To verify the math presented above, we assembled the test system shown in Figure 2 . The antenna under test used a 6-foot parabolic reflector with an SCM feed in a Cassegrain configuration. The signal source was a QSight™ mounted to a portable 125-foot hydraulic lift, to allow testing at different distances and elevations. We were particularly interested in the performance variation with elevation, as the warm earth would be within the beamwidth of this small 6-foot antenna at low elevations.

Figure 2 G/T Test Configuration.

Figure 3 QSight™ Modulated Signal Source with Programmable Polarization.

The signal source is shown in Figure 3 above. This integrated transmitter-with-antenna can generate any of the standard telemetry modulations at data rates from 100 kbps to 46 Mbps. The EIRP (including the underlying transmit antenna) is adjustable from -80 dBm to +40 dBm and calibrated to within ±1 dB from -40 dBm to +40 dBm.

In addition to the EIRP control, the polarization of the transmitted signal can be remotely controlled to be linear at any orientation, rotating linear, left-hand circular, and right-hand circular. We took advantage of this capability to achieve a near-zero polarization loss on the individual LHCP and RHCP channels in the antenna under test.

With the experimental setup shown in Figure 2, we measured G/T at several frequencies and multiple elevations on four days in early May 2023. All testing was done at the Quasonix facility in West Chester, OH, but both the 6-foot antenna and the signal source were moved to storage at the end of each day, so positioning varied slightly from day to day. On most of the test days, we were also able to make solar G/T measurements.

A summary of the data is shown in Figure 4, showing both the solar and signal source results.

Freq, MHz	Lambda, m	D, meters	Eb/No, dB	EIRP, dBm	Path loss, dB	Polarization loss, dB	-198.6	10 log (bps)	G/T, dB/K	Solar G/T (dB/K)	Solar Optimism, dB
114 feet, CH1											
1465.5	0.2046	109.73	11.4	-40.0	-76.57	0	-198.6	70	-0.63	0.97	1.60
1825.5	0.1642	109.73	11.4	-41.5	-78.48	0	-198.6	70	2.78	3.24	0.46
4500.5	0.0666	109.73	11.4	-38.0	-86.32	0	-198.6	70	7.12	8.04	0.93
4880.5	0.0614	109.73	11.4	-38.5	-87.02	0	-198.6	70	8.32	9.29	0.97
4920.5	0.0609	109.73	11.4	-38.0	-87.09	0	-198.6	70	7.89	9.51	1.61
5111.5	0.0587	109.73	11.4	-38.5	-87.43	0	-198.6	70	8.73	10.97	2.24
114 feet, CH2											
1465.5	0.2046	109.73	11.4	-40.0	-76.57	0	-198.6	70	-0.63	1.88	2.51
1825.5	0.1642	109.73	11.4	-41.0	-78.48	0	-198.6	70	2.28	3.38	1.10
4500.5	0.0666	109.73	11.4	-37.0	-86.32	0	-198.6	70	6.12	8.36	2.24
4880.5	0.0614	109.73	11.4	-38.5	-87.02	0	-198.6	70	8.32	9.14	0.81
4920.5	0.0609	109.73	11.4	-38.5	-87.09	0	-198.6	70	8.39	8.56	0.17
5111.5	0.0587	109.73	11.4	-39.0	-87.43	0	-198.6	70	9.23	10.25	1.03
50 feet, CH1											
1465.5	0.2046	105.46	11.4	-37.5	-76.23	0	-198.6	70	-3.47	0.97	4.44
1825.5	0.1642	105.46	11.4	-41.0	-78.14	0	-198.6	70	1.94	3.24	1.30
4500.5	0.0666	105.46	11.4	-38.0	-85.97	0	-198.6	70	6.77	8.04	1.27
4880.5	0.0614	105.46	11.4	-37.5	-86.68	0	-198.6	70	6.98	9.29	2.31
4920.5	0.0609	105.46	11.4	-37.5	-86.75	0	-198.6	70	7.05	9.51	2.46
5111.5	0.0587	105.46	11.4	-38.0	-87.08	0	-198.6	70	7.88	10.97	3.09
50 feet, CH2											
1465.5	0.2046	105.46	11.4	-38.5	-76.23	0	-198.6	70	-2.47	1.88	4.35
1825.5	0.1642	105.46	11.4	-40.0	-78.14	0	-198.6	70	0.94	3.38	2.45
4500.5	0.0666	105.46	11.4	-36.5	-85.97	0	-198.6	70	5.27	8.36	3.09
4880.5	0.0614	105.46	11.4	-38.0	-86.68	0	-198.6	70	7.48	9.14	1.66
4920.5	0.0609	105.46	11.4	-38.0	-86.75	0	-198.6	70	7.55	8.56	1.02
5111.5	0.0587	105.46	11.4	-38.5	-87.08	0	-198.6	70	8.38	10.25	1.87

Figure 4 G/T Measured by Solar and Signal Source Methods, for Two Elevations.

Freq, MHz	STD dev	
	CH 1	CH 2
1465.5	0.64	0.27
1825.5	0.33	0.25
4500.5	0.36	0.43
4880.5	0.49	0.62
4920.5	0.29	0.26
5111.5	0.15	0.46

Figure 5 Standard Deviation of Signal-Source G/T Values, Measured on Four Days.

OBSERVATIONS

As shown in Figure 4 above, the solar method yielded significantly optimistic values for G/T, by over 4 dB in some cases. This comes as no surprise, given the previously described "coldest sky" measurement technique used in the solar method. The signal source method yields a value that is relevant (and unbiased) for the pointing angles at which the data is collected. The solar method yields a "better" value, which is *only* relevant while the test article is at that azimuth and elevation.

Comparing the data at high elevation (114 feet) to that taken at 50 feet, we can clearly see that the warm earth in the main lobe of the antenna degrades G/T. Again, this is as expected. We speculate that this effect would be less dramatic for larger antennas, where the main lobe is narrow. This is an area slated for future evaluation.

We also collected a limited set of data to explore the repeatability of the G/T values determined with the calibrated signal source. We found that data taken at one position, with neither end of the link adjusted in azimuth or elevation, was highly repeatable. In other words, once the link was operating at a DQM of 5 (BER = 10^{-5}), it would stay in that condition essentially stable indefinitely.

Because our test equipment was outdoors, we moved it to indoor storage at the end of each day. This required repositioning and re-pointing both ends of the link for the next day, introducing a slightly uncontrolled variable. The standard deviation of four measurements, shown in Figure 5, was generally less than 0.5 dB, and some frequencies showed less than 0.3 dB standard deviation. We believe that most of that variation was due to slight variations in the antenna pattern of both the antenna under test and the signal source. More testing is planned to explore this.

COMPARISONS

A comprehensive evaluation of the signal source approach will require considerably more data than has been presented here. However, these preliminary results provide a basis for some qualitative comparisons, as tabulated below.

Characteristic	Solar Method	Signal Source Method
Sources of error	Solar flux interpolation, cold sky measurement	Position error, pointing error, EIRP calibration
Sources of bias	Seeking "coldest sky"	None known
Relevance to link budget	Poor. Measured value is deliberately optimistic.	Excellent. Measured value accounts for real sources of link degradation such as warm earth at low elevations.
Repeatability	Fair, at one location. Poor, across multiple locations.	Good. Improves when both source and receiving antennas are anchored in place and using accurate positioners.

Potential for automation	Fair, but no polarization control.	Good.
Real estate required for source	None	Location to install signal source, less than 10’ x 10’.
Authorization required	None	Requires frequency allocation, ideally at the frequency to be used operationally.
Polarization control	None	Linear at any orientation. Rotating linear. Left hand circular. Right hand circular.

CONCLUSIONS

We have explored the sources of uncertainty and bias in G/T measurements based on observing the sun, and we have pointed out that the conventional solar G/T measurement yields an optimistic result, only valid while the antenna is pointed at “coldest sky”. The day-to-day and place-to-place variations in measured G/T values are fundamentally rooted in the random nature of the sun as a signal source, and these variations can never be controlled.

We have also described a deterministic method of measuring the G/T for a telemetry ground station that eliminates any dependency on observing the sun. In principle, the accuracy and repeatability of the calibrated, modulated source could all be tied back to NIST-traceable test equipment. While these calibrations still entail uncertainties, those uncertainties are under human control; there are no fundamentally random processes involved.

We have used both the signal source method and the solar method to determine the G/T for a small (6-foot) parabolic antenna and have found that the solar method is always optimistic and becomes more so at lower elevation angles.

Future work on the signal source system employed here will be focused on improving the calibration of the signal source EIRP (particularly at low output levels) and adding more automation to the process.

REFERENCES

[1] Recommendation ITU-R S.733-2, “Determination of the G/T Ratio for Earth Stations Operating in the Fixed-Satellite Service”. Jan. 2000.
[2] Test Methods for Telemetry Systems and Subsystems Volume 2: Test Methods for Telemetry Radio Frequency (RF) Subsystems Release 2 RCC 118-22 V2 R2, “Appendix C, Solar Calibration”. October 2022.