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Considerations about the use of the Moon in X-band antenna G/T measurements

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Abstract: The most common G/T quality factor measurement methods applicable for operational X-band (8 GHz - 12 GHz) parabolic antennas with a reflector aperture diameter between 7 and 13m are reviewed. Analyses have shown that the most adequate astronomical source for the G/T measurement of the antennas with the size of interest is the Moon.

Since the Moon's angular diameter is wider than the antenna's Half Power Beam Width (HPBW), a thorough analysis of the extended source size correction factor is performed. As a result, an efficient correction factor approximation method which is more accurate in case of efficiency losses is identified, and a best-fit estimation method for the HPBW verification is introduced.

The proposed G/T quality factor measurement procedure is verified on an operational X-band 11 meter Cassegrain antenna, used for Low Earth Orbit (LEO) satellite data acquisition. The results obtained with the proposed method, have provided accurate G/T factor estimations that are consistent and in line with the expectations. As further confirmation, the validity of the measurement method results is also verified against a G/T measurement done with the Cassiopeia A radio star as an RF source.

Keywords: X-band, G/T measurements, Moon, Satellite communications, Extended source size correction factor

Ugotovitve o uporabi Lune pri G/T meritvah antenskih sistemov frekvenčnega pasu X.

Izvleček: Najbolj pogoste metode za merjenje kakovostnega faktorja G/T pri operativnih paraboličnih antenah frekvenčnega pasu X (8 GHz – 12 GHz) s premerom zaslonke zrcala med 7 in 13 metrov so bile pregledane v tej študiji. Analiza je pokazala, da je Luna najbolj ustrezen astronomski vir za G/T meritve omenjenih anten.

Ker je Lunin zorni kot širši od -3dB širine snopa antene (HPBW), je narejena celovita analiza korekcijskega faktorja za uporabo porazdeljenega vira. Na podlagi tega je identificirana najbolj učinkovita metoda približka korekcijskega faktorja za omenjene antene. Uvedena je tudi najbolj prilegajoča metoda ocene HPBW z ciljem preverjanja izmerjenih vrednosti.

Predlagani postopek merjenja G/T kakovostnega faktorja je bil preverjen na operativni 11 metrski Cassegrain anteni v frekvenčnem pasu X, ki se uporablja za pridobivanje podatkov s satelitov LEO (nizka Zemljina orbita). Rezultati dobljeni z uporabo omenjene predlagane metode so dali konsistentne in točne ocene G/T faktorja v skladu s pričakovanji. Dodatna potrditev veljavnosti postopka je dana s primerjanjem dobljenih rezultatov in izmerjenega G/T faktorja z uporabo radio zvezde Cassiopeia A kot RF izvora.

Ključne besede: G/T, frekvenčni pas X, Luna, satelitske komunikacije, korekcijski faktor razširjene velikosti vira

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1 Introduction

The antenna power Gain over system noise Temperature ratio (G/T), sometimes also labelled as "figure of merit", can be regarded as a quality factor used to indicate the ground station capability to discriminate between signal and noise in a radio communication system [1]. The higher the ratio, more efficient the ground station is in receiving a weak signal.

At the European Space Agency, as a part of the standard requirements for Earth Observation Satellites acquisition service contracts, a minimum G/T ratio is always specified to ensure the service is capable of properly acquiring uncorrupted data. Periodic measurements of the G/T are therefore required to ensure that the antennas selected to deliver the service maintain the required performance.

Typical antennas, for the purposes of Earth Observation (EO) satellite data acquisition, are receiving X-band with a main reflector aperture in the range of 7 to 13 meters. These ground station antennas perform routinely full elevation and azimuth rotations and accelerations which, beside the wind and gravity effects, add to the possibility of antenna distortions.

Because of their intense use, the antennas are constantly operational with small allotments of time available for performing the G/T measurements. Short pauses between satellite passes and frequent performance verifications require an accurate, efficient and time saving G/T measurement method.

Considering the antenna size range of interest, and the corresponding far field region distance, the optimal RF source has to be found in the skies. Direct G/T measurement using the Moon as an RF source, for the antenna size range of interest, has been selected and elaborated in this paper, providing a simple, fast and highly accurate G/T quality factor estimation method.

This paper is organized as follows. In Section II, the analysis of the available celestial sources has been described. Direct G/T calculation procedure, correction factor analysis and concerns from practical point of view are given in Section III. Section IV presents detailed G/T measurement procedure and the quality factor measurement results obtained with an operational 11 meter X-band antenna located at the e-GEOS station in Southern Italy. Finally, Section V draws some conclusions.

2 Analysis of the adequate available sources

For the antenna size range of interest in the X-band, the far-field region determined by the Fraunhoffer's distance, results always more than 2.5km from the antenna location. In that case, terrestrial measurements with a distant antenna set as a source are highly impractical due to the terrain variety, high multi-path and various man-made or natural sources. Therefore, celestial sources were considered. As the measurement procedure must be valid and applicable for any antenna location, the selected source has to be well-defined and frequently visible.

The most obvious celestial sources are geostationary satellites, and natural sources like Sun, Moon and radio stars. Unfortunately, commercial geostationary satellites operating in the X-band, with well-known characteristics are uncommon. Hence, geostationary satellites could not have been taken as a suitable RF source. The strongest celestial natural source observed from Earth is the Sun. However, the Sun is subject of a possible and unpredictable variations with time due to Sun storms and Sun bursts [2, 3]. These variations, along with the extended source size of the Sun in respect to the antenna's HPBW, can introduce a significant uncertainty in the final quality factor estimation.

Radio star flux densities have been well-defined in [4, 5, 6]. For the antenna size range of interest, 7-13 meters, a radio star can be considered a point-like source. The latter means that using a radio star as an RF source in G/T measurement minimizes the error introduced by using G/T correction factors. However, the brightness of radio stars is much lower than those of the Sun or the Moon. For X-band antennas with reflector diameter smaller than 18m [7], using a direct G/T measurement method with radio stars may introduce significant uncertainties. These uncertainties, and consequently the errors in G/T estimation, are caused by the very small Y-factor, i.e. the ratio between the received noise power while pointing at the radio star, and the received noise power while pointing at the cold sky.

The Moon's radiation can be modelled with the black-body radiation that changes with the lunar phases and the Earth-Moon geometry. Y-factor readings using the Moon as a source are well above 1dB for the antennas of interest. Considered as a black-body, the Moon's radiation can be efficiently approximated as the radiation from a uniform brightness disk, introducing minimal errors [8, 9] in G/T estimation. Uniform brightness disk flux density approximation depends on the Moon's solid angle that changes with Earth-Moon geometry, and on the average brightness temperature of the Moon. For the X-band, it can be approximated using the Rayleigh-Jeans law:

$$S_{Moon} = \frac{2 f^2 k_B \overline{T_{Moon}}}{c_0^2} \Omega_{Moon} \qquad (1)$$

where S_{Moon} is black-body flux density given in [W m^{-2} Hz^{-1}], f is the frequency in [Hz], k_B is Boltzmann constant given with $k_B \cong 1.38 \cdot 10^{-23}$ [m^2 kg s^{-2} K^{-1}], c_0 [m s^{-1}] is the speed of light, and Ω_{Moon} is the Moon's solid angle in [sr].

The Moon average brightness temperature $\overline{T_{Moon}}$ [K], is a function of the frequency, lunar phase and solar mean anomaly. In this paper, the yearly variation in the solar irradiation at the lunar surface due to the Earth's eccentric orbit has been neglected. Approximation of the Moon's average brightness temperature has been given by [8, 9]:

$$\overline{T_{Moon}} = \overline{T_0}\left[1 - \frac{\overline{T_1}}{\overline{T_0}}\cos(\phi - \psi)\right] \quad (2)$$

In the above equation, $\overline{T_0}$ represents the constant brightness temperature term expressed in [K], $\overline{T_1}$ is the first harmonic of the brightness temperature given in [K], ϕ is the lunar phase angle in degrees and ψ is the phase lag in degrees [°]. In case that the lunar phase angle is in the decreasing cycle, a value of $\phi' = 360 - \phi$ should be used in the Equation (2) calculation. According to [8] the error introduced using the approximation of the Moon's average brightness temperature given by the Equation (1) is less than 0.18%.

The values $\overline{T_0}$ [K], $\overline{T_1}$ [K], ψ [°] and the ratio $\overline{T_1}/\overline{T_0}$, were determined from accurate radio measurements at few selected frequencies and have been interpolated in between [8, 9]. Given parameters can be estimated using the following interpolation equations depending on the frequency of interest f_{GHz} given in [GHz]:

$$\overline{T_0} = 207.7 + \frac{24.43}{f_{GHz}}$$
$$\frac{\overline{T_1}}{\overline{T_0}} = 0.004212 \cdot f_{GHz}^{\;1.224} \quad (3)$$
$$\psi = \frac{43.83}{1 + 0.0109 f_{GHz}}$$

The Moon ephemeris, as are lunar angular diameter, lunar phase and other parameters depending on the observer location and on the current orbital positions of the Earth, Moon and Sun are provided by NASA web interface in [10].

The Moon's flux density dependence on the lunar angular diameter and on the lunar phase are shown on the Figure 1 and Figure 2. Both results were calculated for the frequency of interest f = 8.1775 [GHz], and individually presented with the fixed lunar phase angle of ϕ = 240° and the fixed angular diameter of θ_{Moon} = 0.5° respectively.

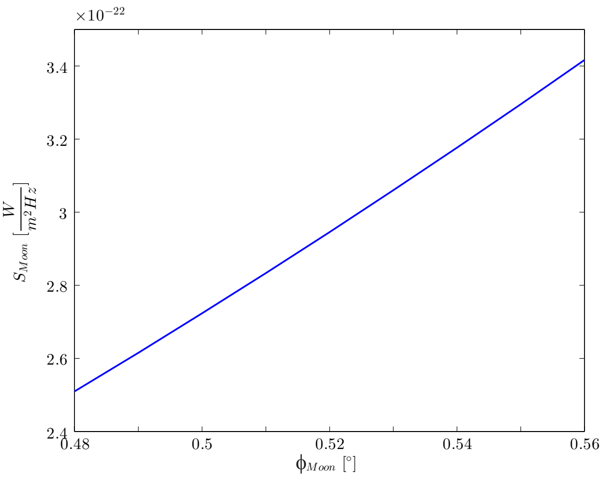

Figure 1: Lunar flux density change with angular diameter

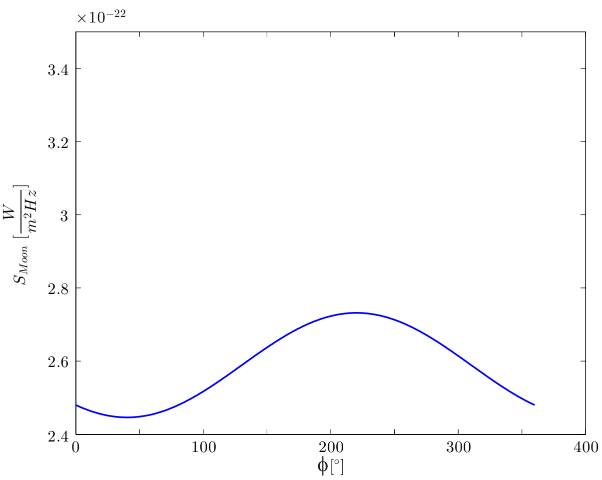

Figure 2: Lunar flux density change with phase angle

2.1 Uncertainties and proposed RF source

The overall G/T measurement uncertainty is given "in quadrature" and presented for the Moon, the Sun and the radio star Cassiopeia A [5, 7, 8, 11]:

Table 1: G/T measurement uncertainties

	Moon	Sun	Cassiopeia A
S	0.33 dB	0.3 dB *	0.1 dB
Y-factor	0.1 dB	0.1 dB *	1 dB
K_1	0.05 dB	0.05 dB	0.05 dB
K_2	0.2 dB	0.2 dB	0.01 dB
G/T	0.4 dB	0.38 dB *	1 dB

It must be noted that values in the Table 1 represent the G/T uncertainties due to the flux density *S*, the *Y*-factor and correction factors K_1 and K_2, not their uncertainties themselves. Also, the (*) sign marks that the possible sunspot contribution is not considered because of its complicated computability.

Considering the Moon's good stability, high flux density and low uncertainty, it has been selected as the most adequate source for an accurate G/T measurement, for parabolic antennas with reflector sizes in the range of 7-13 meters.

3 G/T direct measurement method

G/T direct calculation method requires a measurement of two well-defined signal sources [12]. Hence, the measurement is obtained by received noise power readings when the antenna is pointing at i) the Moon - P_{Moon} [W Hz^{-1}], and ii) the cold sky - P_{sky} [W Hz^{-1}]. Derivation of the G/T direct calculation method equation can be found in [13], while the final expression for the direct G/T quality factor calculation, expressed in [K^{-1}], is given with the Equation (4):

$$\frac{G}{T}(\theta_i) = \frac{8\pi \cdot k_B \cdot \left(Y(\theta_i)-1\right)}{\lambda^2 \cdot S_{Moon}} \cdot K_1 \cdot K_2 \tag{4}$$

where k_B [m^2 kg s^{-2} K^{-1}] is Boltzmann constant, S_{Moon} [W m^{-2} Hz^{-1}] is the Moon's flux density, λ [m] is the wavelength of interest, and Y represents the well known Y-factor noise power ratio given in linear scale. K_1 and K_2 are correction factors due to atmospheric attenuation and extended source size respectively. Finally, θ_i is the elevation angle at which the measurement was performed.

Atmospheric attenuation for the X-band is very low, and is mostly composed of the attenuations due to gases, water vapour and scintillation. Those attenuations can be efficiently estimated using advanced mathematical models given in [15, 16, 17, 18]. However, the estimation of attenuations caused by fog, rainy clouds, and precipitation is based on empirical and static models. Therefore, the measurements should be performed in clear sky conditions. The correction factor for the atmospheric attenuation is expressed in linear scale and given as a sum of the attenuation contributors. Impact of the atmospheric attenuation correction on the final G/T quality factor calculation can be within few tenths of decibel, whereas the impact of the extended source size correction can result in few-decibel change of the final G/T quality factor calculation. The extended source size correction factor K_2 is therefore a factor of great importance when using the Moon as an RF source in G/T measurements, and will be further discussed in a separate subsection.

3.1 Elevation angle adjustment

The measurement of G/T quality factor, using the Moon as an RF source, is performed at different elevation angles, depending on the Moon's ephemeris. Therefore, it was important to establish a reference elevation angle, to which all measurement results will be adjusted. This was done in order to provide more realistic results and to allow mutual comparison of the results.

A reference value for the G/T measurement elevation angle adjustment was chosen to be the elevation of θ_{REF} = 5° measured from the local horizon [13]. This reference value adjusts a G/T quality factor for the worst case scenario, i.e. minimum elevation angle for satellite data acquisition, providing the most relevant G/T quality factor result. The antenna power gain G is a property of the antenna and is constant with elevation angle variation. Therefore, the G/T quality factor values can be adjusted by noting that the variation of G/T factor with elevation angle is equal to the variation of the cold sky noise power with elevation angle:

$$\frac{\frac{G}{T}(\theta_i)}{\frac{G}{T}(\theta_{REF})} = \frac{\frac{G}{T_{sys}(\theta_i)}}{\frac{G}{T_{sys}(\theta_{REF})}} = \frac{T_{sys}(\theta_{REF})}{T_{sys}(\theta_i)} = \frac{P_n(\theta_{REF})}{P_n(\theta_i)} \tag{5}$$

Where G/T(θ_i) is the quality factor value obtained for the elevation angle at the moment of measurement, and G/T(θ_{REF}) is the quality factor value adjusted to the reference value T_{sys} and P_n are the system noise temperature and the received noise power respectively, given for both measurement and reference elevation angles. The ratio of $P_n(\theta_i)$ and $P_n(\theta_{REF})$ can be labelled as K_{EA} and can be expressed both in linear and logarithmic scale, yielding a shortened expression of the adjusted *G/T* quality factor:

$$\begin{gathered} K_{EA} = \frac{P_n(\theta_i)}{P_n(\theta_{REF})} \\ \frac{G}{T}(\theta_{REF}) = \frac{G}{T}(\theta_i) \cdot K_{EA} \\ \left[\frac{G}{T}(\theta_{REF})\right]_{dB} = \left[\frac{G}{T}(\theta_i)\right]_{dB} + \left[K_{EA}\right]_{dB} \end{gathered} \tag{6}$$

3.2 Extended source size correction factor

The radio source whose angular diameter exceeds one fifth of the antenna's half power beamwidth (HPBW) is considered an extended radio source. Each portion of the RF source contributes to the received noise power according to the antenna radiation pattern. In the case of extended source, the peak of the antenna beam is assumed to be aligned with the center of the source, while the edges of the source are received by parts of the antenna beam with lower gain. This can result in the measured noise power smaller than what would be expected for the antenna's effective collecting area and the aperture illumination [19]. Therefore it is necessary to correct the measurement by the extended source size correction factor K_2 given by [13]:

$$K_2 = \frac{\int_0^{2\pi}\int_0^{\frac{\theta_{Moon}}{2}} B(\theta,\phi)\sin(\theta)\,d\theta d\phi}{\int_0^{2\pi}\int_0^{\frac{\theta_{Moon}}{2}} B(\theta,\phi)\,g(\theta,\phi)\sin(\theta)\,d\theta d\phi} \tag{7}$$

Where θ_{Moon} [°] is the Moon's angular diameter, $B(\theta,\phi)$[W m^{-2} sr^{-1} Hz^{-1}] is the Moon's brightness distribution, and $g(\theta,\phi)$ is the antenna radiation pattern normalized to the maximum directivity value, given in the linear scale.

Considering the Moon's radiation as that from a uniform brightness disk, the expression of the K_2 correction factor can be simplified as:

$$K_2 = \frac{\int_0^{2\pi}\int_0^{\frac{\theta_{Moon}}{2}} \sin(\theta)\,d\theta d\phi}{\int_0^{2\pi}\int_0^{\frac{\theta_{Moon}}{2}} g(\theta,\phi)\sin(\theta)\,d\theta d\phi} \tag{8}$$

This approximation restricts measurement window to during the near full Moon phase. However, the integration over the antenna's radiation pattern is a rather complicated task and some alternative methods will be presented. Using the Moon as an RF source, the ratio of angular source size to the antenna's HPBW is less than 3, which makes it possible to obtain a good approximation of the normalized antenna radiation pattern using the normalized Gaussian far-field radiation pattern. The normalized Gaussian approximation of a radiation pattern, and the derivation of the K_2 correction factor expression using the Gaussian pattern, are presented in [20, 13]:

$$K_2 = \frac{\ln(2)\cdot\left(\frac{\theta_{Moon}}{\theta_{HPBW}}\right)^2}{1-e^{-\ln(2)\cdot\left(\frac{\theta_{Moon}}{\theta_{HPBW}}\right)^2}} \tag{9}$$

The approximated K_2 correction factor depends on the Moon's angular diameter θ_{Moon} [°] and the antenna's HPBW θ_{HPBW} [°]. While the Moon's angular diameter can be easily obtained on [10], the antenna's θ_{HPBW} has to be properly measured.

For the purpose of the HPBW verification, the well known estimation expression was used [21]:

$$\theta_{HPBW} = k\cdot\frac{\lambda}{d} \tag{10}$$

where λ is wavelength in [m], d is the antenna reflector diameter in [m] and k is the antenna beamwidth factor. In the published literature, it is possible to find different definitions of the beamwidth factor, like $k = 70$ in [22], and $k = 65$ in [21]. However, the beamwidth factor is dependent on the feed's edge-tapering and cannot be approximated with a constant value. For that purpose, using the reflector antenna analysis software GRASP, numerous radiation patterns for the antenna range of interest were produced. Beside changing the antenna reflector size, the edge tapering was also varied. The feed used in the simulations was a Gaussian beam pattern feed. Results were then analysed and extrapolated in order to find a best fitting expression for bandwidth factor definition:

$$k = 58.96\left(1+0.0107\cdot T_e\right) \tag{11}$$

Where T_e represents the absolute value of the edge taper given in the logarithmic scale [dB].

Usually, the extended source size correction factor estimation method is provided by the antenna vendor in polynomial expression form. It represents the best fit for the specific antenna reflector sizes, and is given with relation to the frequency, f_{GHz} [GHz], and the Moon's angular diameter, θ_{Moon}. An example of the polynomial K_2 expression and corresponding coefficients can be found in [13].

The comparison of the K_2 polynomial expression, with K_2 correction factor expression using the Gaussian pattern and HPBW estimation equation, is presented in Figure 3 - Figure 5. The K_2 factor values were calculated for Cassegrain antennas designed with the reflector diameters of: 5.4, 7.3, 9.1, 10.26 and 11.28 meters, and have been interpolated in between using the polynomial interpolation and then adjusted to the uniform circular aperture illumination (k = 58.96 [14]). For the reference value, simulated radiation patterns were used in the general expression for the K_2 correction factor, given by Equation (8). The purpose of this comparison has been to analyse the K_2 approximation method's fit to the reference values for different edge tapering and antenna reflector sizes. Results presented in Figure 3 - Figure 5 were calculated for the frequency of f_{GHz} = 8.1775 [GHz], including blockage effect, with edge tapering of both T_e = - 10 dB and T_e = - 15 dB. On the figures, red curve presents the K_2 reference value, blue curve presents the polynomial K_2 expression, magenta curve presents the K_2 values obtained with the Equations (9, 10) considering the beamwidth factor k = 70. Finally, the black curve presents the K_2 values obtained with the Equations (9, 10) considering the novel beamwidth factor given with Equation (11).

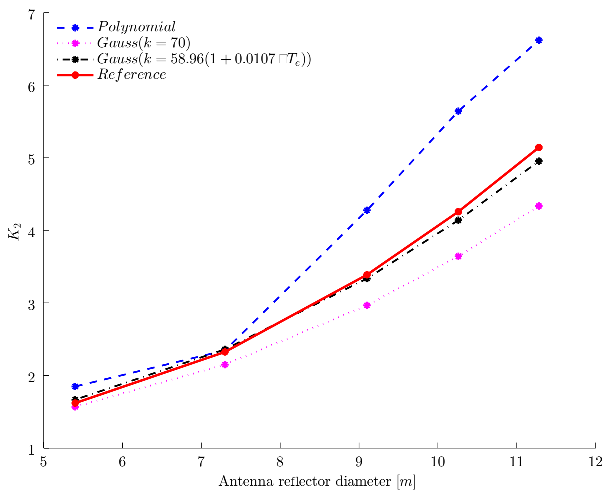

Figure 3: K2 approximation method comparison for Cassegrain antenna with T_e = -10 dB and θ_{Moon} = 0.56°.

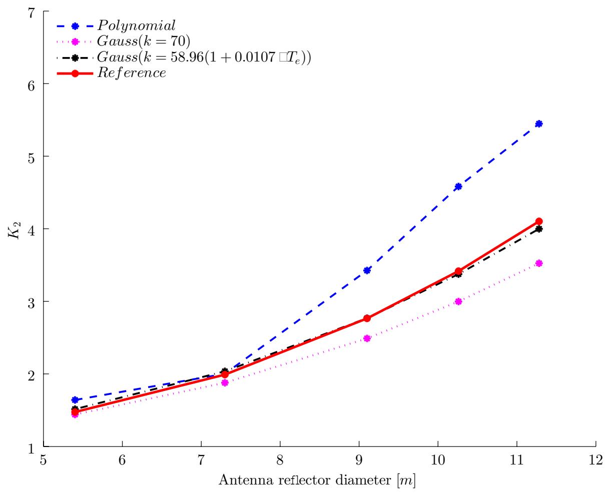

Figure 4: K2 approximation method comparison for Cassegrain antenna with T_e = -10 dB and θ_{Moon} = 0.5°

From the figures given above it can be observed that the polynomial approximation method diverges by the largest factor from the reference level. The divergence of the polynomial approximation is assumed to be due to possible double-shaping of the antenna reflectors. To estimate beamwidth factor in order to use Gaussian approximation for double-shaped antennas, the value

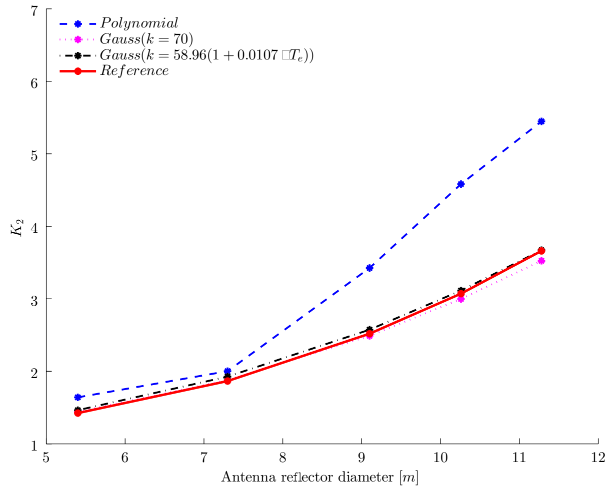

Figure 5: K2 approximation method comparison for Cassegrain antenna with T_e = -15 dB and θ_{Moon} = 0.5°

of uniform illuminated aperture k =58.96 can be taken for a rough estimation.

Also, it can be seen that the Gaussian approximation when beamwidth factor is given as k = 70 yields significantly lower values than the reference. That beamwidth factor is probably suitable just for one specific edge tapering, usually used for the transceiver antennas.

It can be concluded that the Gaussian pattern approximation method for the K_2 estimation is the best fitting K_2 approximation method. Also, the HPBW approximation expression using the proposed bandwidth factor provides a good estimation, and therefore the verification value, for the antenna of interest HPBW. Finally, the polynomial approximation method values can be too optimistic resulting in significant error in G/T estimation.

Another important observation is that the polynomial approximation values, are constant for the antenna of interest, calculated for the optimal geometry antenna configuration. In case of antenna distortion the electrical properties of the antenna change. As a consequence, the extended source size factor value is reduced, and use of a constant K_2 can introduce significant errors in the G/T quality factor estimation. Analysis of the possible discrepancies in G/T estimation using the constant K_2 factor in case of antenna distortions has been made (Figure 6 - Figure 8).

For this purpose, every antenna was firstly designed and simulated for optimal performance. The K_2 was in this case calculated with the numerical integration of the simulated antenna radiation pattern. This was done to neglect the uncertainties, as the scope of this test is to provide an insight in problems occurring when using the constant correction factor values. Then, the radiation pattern simulation was performed for few axial displacements of the secondary reflector, in order to simulate antenna distortions. Therefore, the figures (Figure 6 - Figure 8) present the G/T quality factor results of: i) Optimal geometry antenna and optimal geometry antenna's K_2 – green curve, ii) Distorted antenna keeping the optimal geometry antenna's K_2 – red curve, and iii) Distorted antenna with K_2 calculated for the distorted antenna – blue curve.

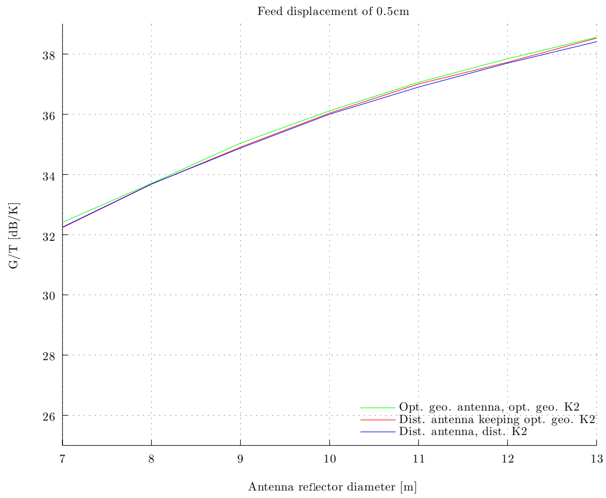

Figure 6: Secondary reflector displacement of 0.5 cm

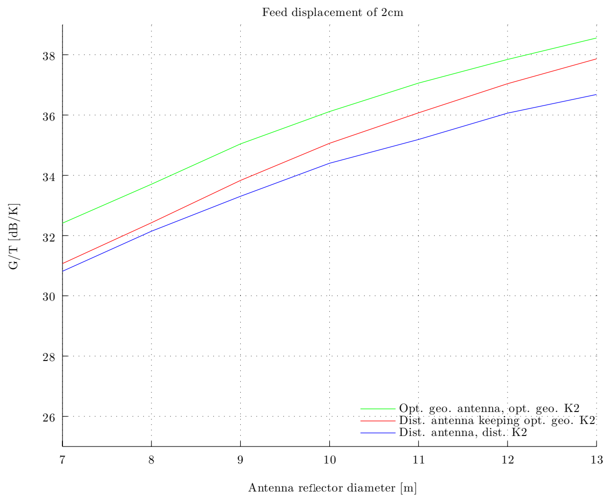

Figure 7: Secondary reflector displacement of 2 cm

It can be concluded that *G/T* estimation using the constant K_2 factor value, for the antennas with efficiency degradation due to distortions, is too optimistic. Also, the real degradation of distorted antenna *G/T* quality factor, expressed in logarithmic scale, can be more than twice the *G/T* quality factor degradation using the constant K_2 factor value.

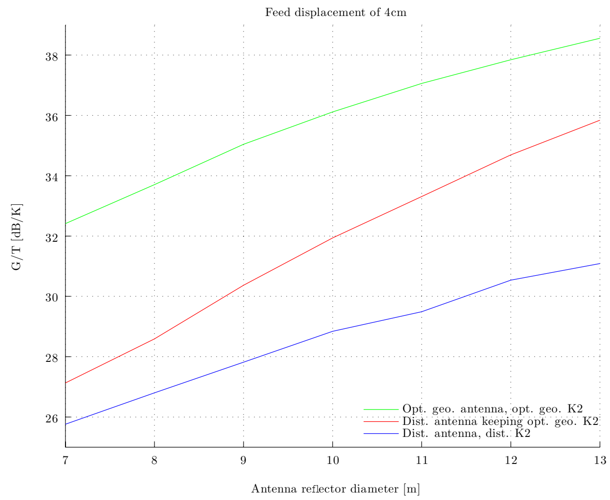

Figure 8: Secondary reflector displacement of 4 cm

4 Measurements

The measurement procedure is a result of detailed study and analysis, while the proposed settings for the spectrum analyser have been traded-off and selected in order to provide the best compromise between stability and measurement error. The measurements were performed on the operational 11m Cassegrain antenna, using the proposed procedure. Finally, obtained results were compared with well-defined G/T measurements using the radio star as a source.

4.1 Measurement procedure

To ensure the maximum possible Y-factor readings, it is advised performing the measurements in the days between waxing and waning Moon phase. The Moon's elevation should be higher than 30° to ensure that the sidelobes looking at the ground are 40 dB below the maximum directivity. Also, it should be verified that no other RF source is in the near vicinity of the Moon.

Before performing the set of measurements for *G/T* factor calculation, the antenna's horizontal and vertical radiation pattern cut should be measured. This is done to verify the antenna's HPBW, nulls and sidelobe behaviour. Measurement can be roughly performed letting the Moon pass over the antenna boresight. Then, the final check of the measured HPBW can be performed following the Equation (4).

Proposed spectrum analyser settings for the appropriate noise power readings are as follows:

Table 2: Proposed spectrum analyser settings

Center frequency	IF (typically 750 MHz)
Frequency span	0 Hz
dB/div	1
RBW	100 kHz
VBW	10 Hz
Marker	ON
Sweep time	100 ms
Average	10

Each measurement consists of three different values: i) On-source – received noise power when pointing the Moon, ii) Off-source – received noise power pointing the cold sky, at the same elevation and 5° tilt in azimuth, and iii) 5°elevation – received noise power pointing the cold sky at the elevation of 5°, and same azimuth as the Off-source measurement.

The measurements are repeated several times to minimize the Y-factor reading uncertainty. Correction factors and flux density are calculated using the methods described in this paper, and finally, the average values in linear scale of Y-factor and K_{EA} values are used to estimate the G/T quality factor of measured antenna.

4.2 Performed measurements - Moon

Measurements were performed following the proposed procedure, first using the Moon and then using the Cassiopeia A radio star as a source, with the purpose of proposed method validation. The antenna under measurement is shown in Figure 9, and its characteristics are given in Table 3.

Table 3: Antenna characteristics

Type	Cassegrain
Frequency	f = 8.1775 GHz
Reflector diameter	d = 11.28 m
Approx. gain	G ≈ 57.5 dBi

Figure 9: X-band ground station with d = 11.28 m

The Moon ephemeris were obtained from [10] in order to estimate its flux density, which is given in Table 4:

Table 4: Lunar ephemeris and flux density

Parameter	Value
$\overline{T_0}$	210.687 K
$\overline{T_1} / \overline{T_0}$	0.05515
$\overline{T_{Moon}}$	214.0622 K
Ψ (lunar phase leg)	40.243 °
$\overline{\phi}$ (average lunar phase angle)	147.114 °
Lunar phase cycle	Increasing
$\overline{\theta_{Moon}}$ (lunar angular diameter)	0.549 °
S_{Moon} (lunar flux density)	3.1710^{-22} W m^{-2} Hz^{-1}

Table 6: Measurement results with Moon as a source

	Time (UTC) [hh:mm]	Elevation [°]	On-source [dBm]	Off-source [dBm]	5°elevation [dBm]
Set 1	19 :23	40.30	-79.26	-82.87	-81.48
Set 2	19 :28	40.66	-79.38	-82.90	-81.50
Set 3	19 :31	40.75	-79.28	-82.87	-81.48
Set 4	19 :33	40.91	-79.38	-82.90	-81.50
Set 5	19 :36	40.98	-79.34	-82.87	-81.59
Set 6	19 :38	41.04	-79.30	-82.85	-81.60

The atmospheric attenuation correction factor was calculated using the local weather data at the time of the measurement, according to the latest ITU-R recommendation. Extended source size correction factor, however, is calculated using the measured antenna's HPBW, and the Gaussian pattern K_2 approximation expression. Measured HPBW has been verified with the proposed beamwidth approximation equation. Both correction factors are given in Table 5.

Table 5: Local weather information and correction factors

Parameter	Value
Weather	Cloudy
Date	13.10.2016
Local Temperature	14.9 °C
Local Humidity	91 %
Local Pressure	960.9 hPa
K_1	1.033
θ_{HPBW}	0.19 °
K_2	5.71

The next step was to perform the measurements of the Y-factor following the proposed procedure. Measurement was repeated six times and the results are given in Table 6.

Finally it was possible to estimate the G/T quality factor for the antenna under measurement.

Table 7: Quality factor estimation using the Moon as a source

Parameter	Value
Y-factor average	2.266
K_{EA} average	0.733
G/T	4457 K^{-1}
$[G/T]_{dB}$	36.5 dBK^{-1}
G/T uncertainty	0.4 dB

Polynomial expression for K_2 correction factor depending on frequency and Moon's angular diameter provided the result of K_2 = 6.35. Including the polynomial expression K_2 value to the final G/T calculation using the Moon as a source yields the result $[G/T]_{dB}$ = 37 dBK^{-1}. Using the polynomial expression, the K_2 measurement uncertainty is not known.

4.3 Performed measurements – Cassiopeia A

Measurements using Cassiopeia A as a source were performed following the same measurement procedure using the same spectrum analyser. Cassiopeia A has very-well defined flux density and decay factor described in [5, 23]. The weather information at the time of measurement, Cassiopeia A flux density, and corresponding correction factors are presented in Table 8.

Table 8: Local weather information and correction factors

Parameter	Value
Weather	Clear
Date	19.10.2016
Local Temperature	14 °C
Local Humidity	90 %
Local Pressure	960 hPa
K_1	1.012
$\theta_{Cas\ A}$	0.0767 °
θ_{HPBW}	0.19 °
K_2	1.0565
$S_{Casiopeia\ A}$	$401.56 \cdot 10^{-26}$ W m^{-2} Hz^{-1}

The measurements using the Cassiopeia A as a source are presented in Table 9, while the G/T quality factor estimation is presented in Table 10.

Table 10: Quality factor estimation using the Cassiopeia A as a source

Parameter	Value
Y-factor average	1.086
K_{EA} average	0.811
G/T	4794 K^{-1}
$[G/T]_{dB}$	36.8 dBK^{-1}
G/T uncertainty	1 dB

Table 9: Measurement results with Cassiopeia A as a source

	Time (UTC) [hh:mm]	Elevation [°]	On-source [dBm]	Off-source [dBm]	5°elevation [dBm]
Set 1	17 : 28	57.30	-83.25	-83.63	-82.75
Set 2	17 : 31	57.60	-83.32	-83.66	-82.76
Set 3	17 : 33	57.90	-83.29	-83.65	-82.74
Set 4	17 : 36	58.30	-83.28	-83.64	-82.71
Set 5	17 : 38	58.60	-83.26	-83.61	-82.69
Set 6	17 : 42	58.90	-83.28	-83.64	-82.71

From the presented results it can be observed that the estimation of *G/T* quality factor value using Cassiopeia A as a source, provides *G/T* value higher than when using the Moon as a source for 0.3 dB. However, also the uncertainty of *G/T* calculated value is much higher than when using the Moon as a source.

For the small angular diameters as is the case with the Cassiopeia A radio star, the polynomial expression is not valid.

5 Conclusions

In this paper, an accurate and time effective method for G/T quality factor measurement using the Moon as an RF source has been described. The Moon was selected as the most adequate RF source for the antennas of interest, because of its stabile radiation flux density and low introduced uncertainty. The proposed method is considered valid for parabolic antennas with the reflector apertures ranging from 7 to 13 meters. In case of smaller size antennas, the Y-factor readings using the Moon fall under 1dB introducing larger uncertainties. For antennas of larger sizes, however, the K_2 factor uncertainty becomes dominant resulting in significant possible G/T estimation error and in that case a star radio source becomes the preferred option.

As the Moon results to be an extended source for the antennas of interest, the important achievement was to propose an improved method to compute the extended source size correction factor. The improvement of a well-known K_2 expression is given with polynomial expression for more accurate estimation of measured HPBW. This aspect turned out to be of key importance because a small error in the correction factor can result in an error of several tenths of a decibel in the final G/T value.

Results have shown that the best correction factor estimation can be obtained using a Gaussian pattern approximation. Also, it turned out that other estimation methods, such as the use of a fixed polynomial expansion, are often too optimistic.

Besides, by providing a constant correction factor value for the antenna of interest, these methods are hiding possible degradations of the G/T quality factor in case of antenna efficiency degradations. Results have shown that the real degradation of distorted antenna quality factor expressed in dB can be more than twice the degradation using a constant correction factor value. Proposed method uses the measured HPBW value confronted with the proposed polynomial expression, both for verification and for precision value rounding to two digits.

The proposed direct measurement method is of great interest for the G/T measurements of typical X-band LEO satellite reception ground stations that have small pauses between satellite acquisitions.

Some measurements taken on an operational X-band Cassegrain antenna 11 m antenna have been presented to confirm the model. Measurements were performed on site on a tight schedule and following the procedure given in this paper. Measurement results are consistent and in line with expectations, and have shown a good agreement with measurements made on the ground station using the Cassiopeia A as an RF source.

Based on the obtained results, the European Space Agency (ESA/ESRIN) has updated the procedure used for periodic G/T measurement, using the method described in this paper.

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