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Ka vs Ku band HTS

A performance assessment and comparison of

Ka vs Ku Band HTS

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Executive Summary

This paper presents a fair and unbiased comparison of Ku- and Ka-band High Throughput Satellite (HTS) systems. It will be shown that:

- C/N (and therefore throughput) is dependent on beamwidth. However, as beamwidth is dependent on frequency, so too is the C/N.
- When moving to Ku- instead of Ka-band frequencies, for the C/N not to be negatively affected, the Ku-band HTS must employ a much larger diameter antenna on the satellite in space than the Ka-band HTS. The Ku-band HTS must also achieve comparable spot beam beamwidths.
- While Ka-band HTS spot beams' can achieve beamwidths of < 0.5°, state-of-the-art Ku-band HTS antennas can only produce spot beams with beamwidths of > 0.8°, with typical Ku-band spot beams having beamwidths of about 2°.
- Even when considering greater atmospheric losses and noisier receivers at Ka-band, the Ka-band HTS system performs better than the Ku-band HTS system both in clear sky conditions (95% availability) and poor weather conditions (99% availability). This is true for both the uplink and downlink.
- During severe weather conditions (99.9% availability) the Ku-band HTS system outperforms the Ka-band HTS system, but only if the Ku-band spot beam has a beamwidth of less than ~1.3° and ~1° for uplink and downlink respectively. This benefit will only be seen for approximately 8.8 hours in a calendar year.
- There is much more spectrum available at Ka-band than at Ku-band, and given that Ka-band transponders are much wider than Ku-band transponders (250 MHz vs. 36 Hz), Ka-band HTS operators can deliver high-throughput services using single transponders. To provide a comparable service, Ku-band HTS operators will have to use several transponders, thus depleting an already more meagre resource.

1. Introduction

1.1. An Introduction to High Throughput Satellites

High Throughput Satellites (HTS) are a new type of satellite that are capable of providing a large amount of throughput compared to older FSS, BSS and MSS satellites, whilst using the same amount of allocated orbital spectrum. There is one fundamental difference in the architecture of a HTS system compared to a non-HTS system that allows them to achieve this:

- HTS systems use several spot beams to cover the desired service area (see Figure 1 as an example);
- Non-HTS systems uses one or more wide beams to cover the desired the desired service area (see Figure 2 as an example).

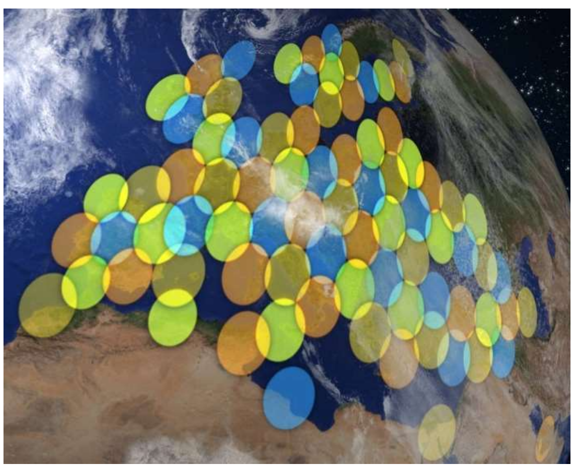

Figure 1: KA-SAT coverage over Europe (1)

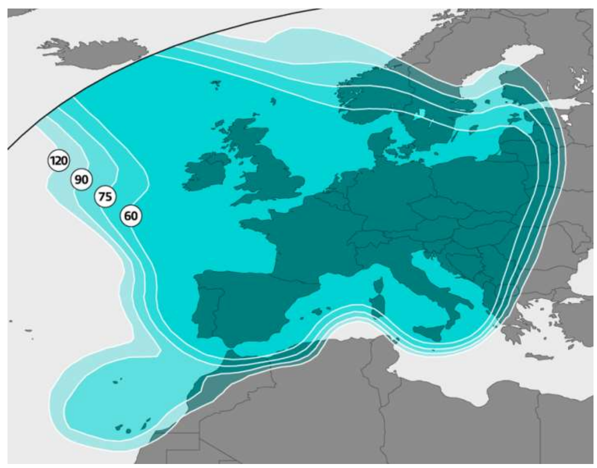

Figure 2: Partial ASTRA 2A coverage over Europe (2)

The benefits of using spot beams as opposed to wide beams are two-fold:

1. **Higher transmit / receive gain**
The gain of an antenna is proportional to its beamwidth which means that using a spot beam instead of a wide beam leads to an increase in power transmitted from the satellite and power received by the satellite. This in turn leads to an increase in the rate of data transmission per unit of orbital spectrum (known as the spectral efficiency), i.e. the throughput increases.
2. **Frequency re-use**
High Throughput Satellites often have a much greater frequency capacity than conventional satellites, even though their frequency allocation might be the same. This is due to the fact that High Throughput Satellites position their spot beam footprints such that several beams use the same frequency and polarisation. This can be achieved due to the high directivity of the spot beam antenna.

The italicised terms are described below:

- Directivity :
  - As opposed to wide beams where the transmitted power is spread over a large area, the transmitted power in a spot beam is spread over a small area. This means that the spot beams have high directivity, i.e. the gain rolls off rapidly as we move away from the centre.
- Frequency:
  - The high roll-off associated with the gain of spot beam antennas means that the same block of frequency can be re-used multiple times for different spot beams as long as each beam has sufficient geographical separation because the interference from a nearby spot beam operating in the same block of frequency will be minimised.
- Polarisation:
  - Circularly polarised signals[1] (RHCP or LHCP) are also used to increase the frequency re-use factor. Antennas are able to receive one type of polarisation and effectively ignore the orthogonal type of polarisation even if both polarised signals are sent on the same frequency.

The allocation of a certain frequency block and polarisation to a spot beam is often called a 'colour'. The usage of 2 separate frequency blocks and 2 polarisations results in 4 unique colours which can be allocated to a High Throughput Satellite's spot beams. Neighbouring spot beams are not permitted to use the same 'colour' as that would lead to excessive interference.

Indeed, '4-colour frequency re-use schemes' are commonly employed in High Throughput Satellites as this scheme leads to a very high frequency re-use factor. An example of such a scheme can be viewed in Figure 1.

Table 1: The benefits of using spot beams as opposed to wide beams

1.2. Scope of the White Paper

The question of Ku- vs. Ka-band is contested online and in the media, and recent releases by Harris CapRock (3) (4) and Panasonic (5) (6) (7) are keen to state that Ku-band HTS satellites are superior to Ka-band HTS systems. The claims made in these papers cannot be taken at face value as the paper and the authors are not impartial; both Harris CapRock[2] and Panasonic[3] have agreed to lease significant amounts of capacity from Ku-band HTS systems.

As such, this white paper will assess the claims made in these papers and present an impartial, unbiased and factual exposition on the advantages and disadvantages of Ku-band HTS systems compared to Ka-band HTS systems. It will be shown that generally, Ka-band HTS systems outperform Ku-band HTS systems except in very specific cases where several assumptions must hold.

[1] Circularly polarised signals can be thought of in non-technical terms as rotating signals. The signal is said to be 'left-hand circularly polarised' (LHCP) or 'right-hand circularly polarised' (RHCP) dependent on whether the signal is rotating in a clockwise or counter-clockwise fashion with respect to the direction of propagation. LHCP is said to be orthogonal to RHCP, and vice-versa.

[2] In 2012, Intelsat announced an agreement with Harris CapRock, with Harris CapRock agreeing to lease more than 1.2 Gbps from Intelsat 29e over a period of 10 years (42).

[3] In 2012, Intelsat announced an agreement with Panasonic Avionics Corporation, with Panasonic agreeing to lease 1 Gbps over a period of 10 years (43).

2. Ka- and Ku-band High Throughput Satellites: Advantages and Disadvantages

2.1. Definitions

The introductory section of this white paper provided a brief overview of the typical architecture and features of a High Throughput Satellite. We saw that the main benefits of a HTS system were:

1. ***Higher transmit / receive gain*** due to the narrower nature of the beams, leading to more power transmitted from the satellite to the user terminals, and more power received from the user terminals by the satellite;
2. ***Frequency re-use*** where allocated orbital spectrum can be reused multiple times on HTS systems to vastly increase the spectral capacity, thus reducing the cost per bit.

However, we have not yet assessed and compared the qualities of Ku-band and Ka-band HTS systems.

The metric that is used to measure the efficacy of a High Throughput Satellite is the throughput – the amount of information that can be transmitted to or by the user over the satellite communications link over a given unit of time. The throughput essentially depends on the amount of orbital spectrum dedicated to send that data (the carrier bandwidth, B) and the overall quality of the signal with respect to noise (the carrier-to-noise ratio, C/N).

Before satellite operators order a satellite from a manufacturer, they must ensure that their envisioned system will be capable of producing signals with adequate C/N values; an analytical assessment known as a 'link budget' is undertaken to show what kind of service could be expected. These analyses show that the link between the satellite and the gateway is never a limiting factor due to the powerful amplifiers used by the gateway and the installation of a large antenna.

The weakest part of the overall satellite communications link is the link between the satellite and the user:

1. If the data is being transmitted from the gateway to the user, the weakest part of the link is the **forward downlink**;
2. If the data is being transmitted from the user to the gateway, the weakest part of the link is the **return uplink**.

Let us now look at how the C/N for both of these links is calculated. In the following discussion the definitions below shall apply:

A_e	Effective antenna aperture area	[m^2]
B	Bandwidth	[Hz]
c	Speed of light	[ms^{-1}]
C/N	Carrier-to-noise ratio	[none]
D	Diameter of the antenna	[m]
f	Frequency	[Hz]
G	Maximum gain of the antenna (at the centre of the beam, the boresight)	[none]
k	Boltzmann constant	[WK^{-1}Hz^{-1}]
L_{FS}	Free space path loss	[none]
L_{atm}	Atmospheric loss	[none]
P	Power supplied to the antenna by its high power amplifier	[W]
r	Slant range between the ground earth station (user terminal or gateway) and the satellite	[m]
T	Receive system noise temperature	[K]
η	Antenna efficiency	[none]
θ_{3dB}	3 dB beamwidth (the angular offset from the antenna boresight where the gain is half of its maximum value)	[°]

Any terms with a subscript s refer to the satellite and any terms with a subscript t refer to the user terminal.

2.2. Frequency Dependence on Throughput

The C/N of the forward downlink can be shown to be

$$\frac{C}{N} = \frac{P_s G_s G_t}{L_{atm} L_{FS} k B T_t} \qquad \textit{Eq 1}$$

where the definitions above apply. But what is the dependence of C/N on the frequency of transmission? To answer this question, we must further define some of the terms in Eq.1. The gain of an antenna can be shown to be

$$G = \frac{4\pi A_e f^2}{c^2} \qquad \textit{Eq 2}$$

where A_e is the effective area of the antenna aperture. Assuming that the antenna reflector is parabolic, we can re-write the gain in terms of the diameter of the reflector:

$$A_e = \frac{\eta \pi D^2}{4} \rightarrow G = \eta \left(\frac{\pi D f}{c} \right)^2 \qquad \textbf{Eq 3}$$

Additionally, the free space path loss can be shown to be:

$$L_{\mathrm{FS}} = \left(\frac{c}{4\pi r f} \right)^2 \qquad \textbf{Eq 4}$$

Inserting Eqs 3 and 4 into Eq 1, we obtain

$$\frac{C}{N} = \frac{P_{\mathrm{s}}}{L_{\mathrm{atm}} k B T_{\mathrm{t}}} \times \eta_{\mathrm{s}} \left(\frac{\pi D_{\mathrm{s}} f}{c} \right)^2 \times \eta_{\mathrm{t}} \left(\frac{\pi D_{\mathrm{t}} f}{c} \right)^2 \times \left(\frac{c}{4\pi r f} \right)^2 \qquad \textbf{Eq 5}$$

We can remove duplicate terms and simplify to show that

$$\frac{C}{N} = \frac{P_{\mathrm{s}} \eta_{\mathrm{s}} \eta_{\mathrm{t}}}{L_{\mathrm{atm}} k B T_{\mathrm{t}}} \times \left(\frac{\pi D_{\mathrm{s}} D_{\mathrm{t}} f}{4cr} \right)^2 \rightarrow \frac{C}{N} \propto \frac{(D_{\mathrm{s}} D_{\mathrm{t}} f)^2}{L_{\mathrm{atm}} B T_{\mathrm{t}}} \qquad \textbf{Eq 6}$$

The equation above shows that the C/N is proportional to (∝) several variables, including the square of frequency. This means that if the frequency is decreased from Ka-band to Ku-band, and all other variables are kept constant, there will be a decrease in C/N[4]. A decrease in C/N results in a decrease in throughput. This is in direct contradiction to the claims made in several pro Ku-band papers, who say that the C/N and hence throughput are not dependent on frequency. So what is the truth?

The Truth:
From Eq 6 we can see that assuming that the user terminal diameter and the denominator is held constant, **the only way for the C/N to be independent of frequency is for the satellite antenna diameter to increase in order to offset the decrease in frequency.**

Table **1** and Table **2** below shows typical downlink and uplink frequencies associated with the Ku- and Ka-bands:

Band	Downlink frequency [GHz]	Midpoint [GHz]
Ku-band	10.9 – 12.75	11.8
Ka-band	18.0 – 20.0	19.0

Table 1: Ku- and Ka-band downlink frequencies and midpoints **(iDirect, 2014)**

[4] It should be noted that in reality L_{atm} and T_t also increase as the frequency increases, i.e. L_{atm} and T_t are greater at Ka-band than they are of Ku-band. The effect this has on the C/N is not being ignored, but will be assessed later.

Band	Uplink frequency [GHz]	Midpoint [GHz]
Ku-band	14.0	14.0
Ka-band	26.5 – 40.0	28.4[5]

Table 2: Ku- and Ka-band uplink frequencies and midpoints **(34)**

We can use the midpoint downlink frequencies outlined in the Table **1** above to show the effect on C/N of dropping from Ka-band to Ku-band (assuming D_t, L_{atm}, B and T_t remain constant). Eq 6 can be manipulated to compare the C/N of the Ku-band HTS system to the C/N of the Ka-band HTS system:

$$\left(\frac{C}{N}\right)_{\mathrm{Ku}} \propto \left(\frac{D_{\mathrm{s,Ku}} f_{\mathrm{Ku}}}{D_{\mathrm{s,Ka}} f_{\mathrm{Ka}}}\right)^2 \left(\frac{C}{N}\right)_{\mathrm{Ka}} \qquad \textit{Eq 7}$$

If we keep the diameter of the antenna the same and drop from the Ka-band frequency to the Ku-band frequency, we find that

$$\left(\frac{C}{N}\right)_{\mathrm{Ku}} = 0.38 \left(\frac{C}{N}\right)_{\mathrm{Ka}} \qquad \textit{Eq 8}$$

or in terms of dB,

$$\left(\frac{C}{N}\right)_{\mathrm{Ku}} - \left(\frac{C}{N}\right)_{\mathrm{Ka}} = -4.14 \text{ dB} \qquad \textit{Eq 9}$$

In order to counteract this effect, the Ku-band satellite's antenna diameter will have to increase substantially:

$$D_{\mathrm{Ku}} = 1.61 \times D_{\mathrm{Ka}} \qquad \textit{Eq 10}$$

[5] Frequencies greater than 30 GHz are reserved for governmental and military applications. As such, the mid-point between 26.5 GHz and 30.0 GHz has been used.

2.3. Beamwidth Dependence on Throughput

So what assumptions did the pro-KuBand HTS authors make to come to the conclusion that the C/N was frequency independent?

Well, for a given antenna diameter, as the frequency transmitted by an antenna increases, the beamwidth decreases, i.e. the beam becomes 'tighter' and more like a spot beam. This is because the beamwidth is inversely proportional to the frequency:

$$\theta_{3\mathrm{dB}} = \frac{70c}{fD_{\mathrm{s}}} \qquad \textbf{\textit{Eq 11}}$$

By rearranging and substituting Eq 11 into Eq 3, we can re-write the gain of the satellite antenna in terms of the beamwidth:

$$G = \eta \left(\frac{70\pi}{\theta_{3\mathrm{dB}}}\right)^2 \qquad \textbf{\textit{Eq 12}}$$

In a fashion similar to Eq 5, we can then show that

$$\frac{C}{N} = \frac{P_{\mathrm{s}}}{L_{\mathrm{atm}}kBT_{\mathrm{t}}} \times \eta_{\mathrm{s}} \left(\frac{70\pi}{\theta_{3\mathrm{dB}}}\right)^2 \times \eta_{\mathrm{t}} \left(\frac{\pi D_{\mathrm{t}} f}{c}\right)^2 \times \left(\frac{c}{4\pi r f}\right)^2 \qquad \textbf{\textit{Eq 13}}$$

and in a fashion similar to Eq 6 we can remove duplicate terms and further simplify to show that

$$\frac{C}{N} = \frac{P_{\mathrm{s}}\eta_{\mathrm{s}}\eta_{\mathrm{t}}}{L_{\mathrm{atm}}kBT_{\mathrm{t}}} \left(\frac{70D_{\mathrm{t}}}{4r\theta_{3\mathrm{dB}}}\right)^2 \rightarrow \frac{C}{N} \propto \frac{{D_{\mathrm{t}}}^2}{{\theta_{3\mathrm{dB}}}^2 L_{\mathrm{atm}} BT_{\mathrm{t}}} \qquad \textbf{\textit{Eq 14}}$$

What can be inferred from Eq 14?

The Truth:

From Eq 14 we can see that assuming that D_t, L_{atm}, B and T_t are held constant as before, the C/N is dependent on the beamwidth (i.e. smaller beamwidth, larger C/N). However **the C/N cannot be said to be independent of frequency as the beamwidth is dependent on both the frequency and diameter of the satellite antenna diameter.**

It is true however that **two Ku-band and Ka-band HTS systems that employ spot beams with identical beamwidths will have a similar C/N** (maintaining the assumptions described above).

To examine this point further let us again consider a Ku- and a Ka-band HTS system, transmitting at the midpoint downlink frequencies outlined in Table **1**. As before, we can manipulate Eq 14 to compare the C/N of the Ku-band HTS system to the C/N of the Ka-band HTS system:

$$\left(\frac{C}{N}\right)_{\mathrm{Ku}} \propto \left(\frac{\theta_{\mathrm{Ka}}}{\theta_{\mathrm{Ku}}}\right)^2 \left(\frac{C}{N}\right)_{\mathrm{Ka}}$$ ***Eq 15***

The equation above assumes that D_t, L_{atm}, B and T_t are held constant. If this is the case, we can see that if the Ka-band and Ku-band HTS systems spot beams have the same beamwidth, their C/N values will be the same.

However, we can insert the definition of the beamwidth (Eq 11) to find that Eq 15 becomes

$$\left(\frac{C}{N}\right)_{\mathrm{Ku}} \propto \left(\frac{D_{\mathrm{s,Ku}} f_{\mathrm{Ku}}}{D_{\mathrm{s,Ka}} f_{\mathrm{Ka}}}\right)^2 \left(\frac{C}{N}\right)_{\mathrm{Ka}}$$ **Eq 16**

Note that **Eq 16 is exactly the same as Eq 7**. Inserting the frequencies once more will result in the exact same statements as those described in Eq 8 and Eq 9, thus showing that unless the diameter of the Ku-band satellite antenna increases substantially, the C/N of the Ku-band system will be approximately 60% less than the Ka-band system.

Above we looked at the case where the Ku- and Ka-band spot beam beamwidths were equal. However, as the frequency decreases, it becomes harder to maintain a small beamwidth. This is because the satellite antenna diameter must increase, as previously shown in Eq 11. As a result, Ka-band spot beam beamwidths can be less than 0.5°[6], but Ku-band spot beam beamwidths are more likely to be around 2° (this is the approximate size of Intelsat 29e's spot beams, see (26)). According to McLain et al., the most state-of-the-art Ku-band satellite antennas are capable of transmitting spot beams with beamwidths of 0.8° (6).

[6] Ka-band spot sizes of less than 0.5° are achievable, and although the throughput for such narrowed beams would be increased, they would not provide a sufficiently large footprint. As such, these narrower Ka-band beams are not considered in our analysis.

Band	Minimum achievable beamwidth, θ3dB [°]
Ku-band	0.8° < θ_{3dB} < 2°
Ka-band	θ_{3dB} < 0.5°

Table 3: Minimum achievable beamwidths for Ku- and Ka-band spots

In Figure **3** below, we can see the effect on the Ku-band HTS C/N as the beamwidth is varied between the values outlined above. In this example, the Ka-band spot beam beamwidth has been kept constant at 0.5°. The data has been plotted using the following formula, where Eq 14 has been rearranged to show that

$$\left(\frac{C}{N}\right)_{\mathrm{Ku}} - \left(\frac{C}{N}\right)_{\mathrm{Ka}} = 20\log_{10}\left(\frac{\theta_{3\mathrm{dB,Ka}}}{\theta_{3\mathrm{dB,Ku}}}\right)\ [\mathrm{dB}] \qquad \textbf{\textit{Eq 17}}$$

assuming L_{atm}, B and T_t remain constant.

Even when the beamwidths are most similar, it can be seen that there is still an approximate -4 dB difference between the Ku-band C/N and the Ka-band C/N.

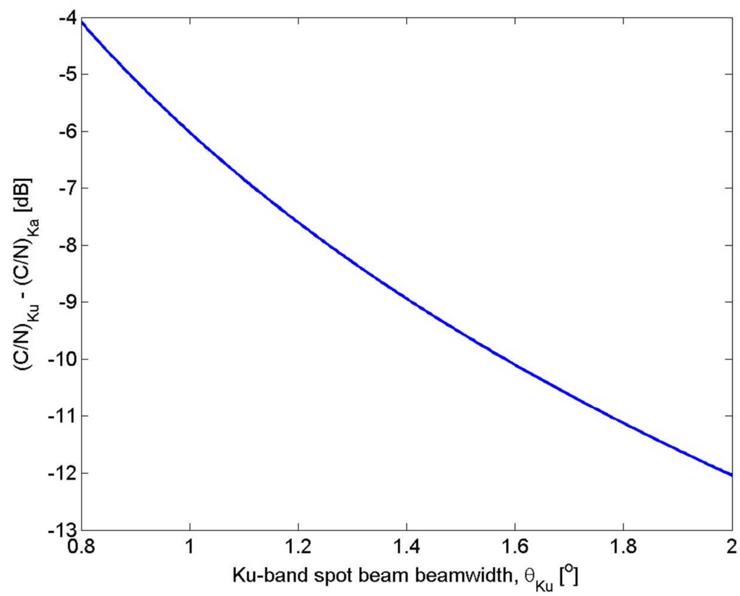

Figure 3: Disadvantage of (C/N)Ku compared to (C/N)Ka for a varying Ku-band spot beam beamwidth

Table 4 outlines the best-case and worst-case Ku-band C/N disadvantage when compared to Ka-band HTS systems:

Ku-band C/N disadvantage	
Best-case	- 4.1 dB
Worst-case	- 12.0 dB

Table 4: Ku-band C/N disadvantage

In conclusion, for a given user terminal size, it could be valid to say that the carrier-to-noise ratios and hence throughputs achieved through a Ku-band and Ka-band HTS are comparable, but only if the antenna diameter on the Ku-band HTS is significantly greater than the antenna diameter on the Ka-band HTS.

2.4. Consideration of Atmospheric Loss and System Noise Temperature

In the previous section, we showed that the C/N was proportional to

$$\frac{C}{N} \propto \frac{{D_{\mathrm{t}}}^2}{{\theta_{3\mathrm{dB}}}^2 L_{\mathrm{atm}} B T_{\mathrm{t}}} \qquad \textbf{\textit{Eq 18}}$$

as we moved from Ka-band to Ku-band, and we assumed that the following variables remained constant:

Dt	:	The user terminal diameter
L_{atm}	:	The atmospheric loss
B	:	The carrier bandwidth
T_t	:	The user terminal

This allowed us to compare the C/N values of the Ku- and Ka-band systems using Eq 17:

$$\left(\frac{C}{N}\right)_{\mathrm{Ku}} - \left(\frac{C}{N}\right)_{\mathrm{Ka}} = 20\log_{10}\left(\frac{\theta_{3\mathrm{dB,Ka}}}{\theta_{3\mathrm{dB,Ku}}}\right) [\mathrm{dB}] \qquad \textbf{\textit{Eq 17}}$$

In reality however, L_{atm}, B and T_t will change, as they are dependent on the frequency of transmission, so Eq 17 will no longer be valid. To compare the C/N values of the Ku- and Ka-band systems, the following equation must be used:

$$\left(\frac{C}{N}\right)_{\mathrm{Ku}} - \left(\frac{C}{N}\right)_{\mathrm{Ka}} = 20\log_{10}\left(\frac{\theta_{3\mathrm{dB,Ka}}}{\theta_{3\mathrm{dB,Ku}}}\right) + \Delta L_{\mathrm{atm}} + \Delta B + \Delta T_t \quad [\mathrm{dB}] \qquad \textbf{\textit{Eq 19}}$$

where $\Delta B = B_{\mathrm{Ku}} - B_{\mathrm{Ka}}$, etc. The following sections look at the effect of L_{atm}, B and T_t on

2.4.1. Atmospheric Loss

Let us consider the atmospheric losses at Ka- and Ku-band. Table 5 below shows the expected atmospheric losses for uplink and downlink signals and Ku- and Ka-band. Please note that in the following examples, the frequencies used are as defined in Table 1 and Table 2.

Availability [%]	Atmospheric loss, Latm [dB]					
	Uplink			Downlink		
	Ku-band	Ka-band	$\Delta\ L_{atm}$	Ku-band	Ka-band	$\Delta\ L_{atm}$
95% (clear skies)	0.5	2.0	1.5	0.3	0.9	0.6
99%	1.0	4.1	3.1	0.7	2.1	1.4
99.9%	3.1	11.6	8.5	2.4	6.6	4.2

Table 5: Ku- and Ka-band atmospheric losses at various availabilities

From the table above, we can see that generally the atmospheric losses for Ka-band systems are greater than for Ku-band systems. However, we note that:

- In relatively poor weather conditions (99% availability) the extra Ka-band uplink atmospheric loss (3.1 dB) is **less than** the best-case Ku-band C/N disadvantage (4.1 dB).
- In severe weather conditions (99.9% availability) the extra Ka-band uplink atmospheric loss (8.5 dB) is **less than** the worst-case Ku-band C/N disadvantage (12.0 dB).

We can also see that the downlink losses are less than the uplink losses so the above statements are also true in that case.

Table **6** below shows the various innovative techniques can be used in satellite communications systems to negate the effect of atmospheric loss:

Large antennas:	The gateways use large antennas (typically 9.2m). This means that the power received and transmitted is increased.	Improves: • Forward uplink • Return downlink
Powerful amplifiers:	The gateways use high-power amplifiers that can supply the antenna with large amounts of power.	Improves: • Forward uplink
UPC (Uplink Power Control):	Both the gateways and the user terminals can use amplifiers that can increase the power supplied to the antenna in accordance to the measured atmospheric loss. For example, if the gateway senses that there is 5 dB of rain fade, the power supplied to the uplink antenna can be increased by that exact amount to negate the atmospheric loss.	Improves: • Forward uplink • Return uplink
ALC (Automatic Level Control)	In a similar fashion to UPC, the satellite can be instructed to ensure that same amount of power is	Improves: • Forward downlink

	downlinked to the Earth, regardless of the amount of atmospheric loss.[7]	• Return downlink
ACM (Adaptive Coding and Modulation)	Almost all of today's VSATs use ACM. A user terminal will be transmitting data using a certain modulation and coding (MODCOD) scheme. All VSATs will attempt to translate at the most efficient MODCOD, which results in the greatest throughput. However, this MODCOD is simultaneously the least robust to atmospheric losses as a certain C/N is required, below which the receiver will not be able to extract the transmitted data. As a result, as atmospheric losses increase, the VSAT terminal can choose to transmit at a less efficient but more robust MODCOD, maintaining connectivity at the expense of reduced throughput. The number of MODCODs available for choice by the transmitting antenna depends on the modem and air interface employed. This technique is also used by gateways.	Improves: • Forward uplink • Return uplink
Diverse gateway sites:	Heavy storm clouds that can cause atmospheric loss have a maximum diameter of about 10 km depending on the region. Through detailed local statistical analyses, it is possible to select two antenna locations where the probability of having severe weather over both geographic locations is extremely low. Gateway antennas can be built in these two locations, and whenever there is poor weather conditions at one antenna, services can be switched to the diverse antenna.	Improves: • Forward uplink • Return downlink

Table 6: Fade mitigation techniques

2.4.2. System Noise Temperature

The receive system noise temperature will also not remain constant as the frequency changes. In this section we will consider the downlink, i.e. the receive system noise temperature of the earth station, because the system noise temperature of a satellite varies dependent on the different types of components, antennas and amplifiers used.

The analysis in Table 8 shows how the system noise temperature varies for a Ku- and a Ka-band receiver, whilst Table 7 shows the equipment specifications used:

[7] It should be noted that this does not entirely negate the effect of atmospheric loss experienced in the uplink stages because, although the faded carrier will have been amplified, so too will its noise. The main benefit of ALC is to ensure that every signal comes down to the gateway / users at the power, regardless of what the weather conditions were like at the uplink.

	Antenna	LNB
Ku-band	GD SATCOM, 1.2m Ku-band Rx/Tx, Series 1132 (35)	Norsat Ku-band DRO 4000 Series (36)
Ka-band	GD SATCOM, 1.2m Ka-band Rx/Tx, Series 3122 (37)	Norsat Ka-band DRO 9000 Series (38)

Table 7: Technical specifications used for system noise temperature analysis

Availability [%]	System noise temperature, Tt				
	Ku-band		Ka-band		ΔT_t [dB]
	T_t [K]	T_t [dBK]	T_t [K]	T_t [dBK]	
95% (clear skies)	173	22.4	254	24.0	1.7
99%	189	22.8	296	24.7	1.9
99.9%	251	24.0	396	26.0	2.0

Table 8: System noise temperature analysis

As can be seen above, the Ka-band receiver indeed suffers from a greater system noise temperature than a Ku-band receiver. The reasons for this are:

- The Ku-band LNB usually has a slightly better noise figure that the Ka-band LNB;
- Atmospheric loss is a contributor to total system noise temperature.

2.5 Effect on Disadvantage of Ku-band C/N compared to Ka-band C/N

In Figure 4 below we have taken the downlink results from Table 5 and Table 8 and applied them to the data used to plot Figure 3 to see what effect including the frequency-dependence on atmospheric loss and system noise temperature has when comparing the C/N values of a Ku- and Ka-band HTS system. (The bandwidth remains the same for both systems, so $\Delta B = 0$).

From this figure we can see that in almost all cases, the Ka-band HTS system outperforms the Ku-band system. This is true for clear sky conditions (95% availability) and also relatively poor weather conditions (99% availability), and true even when the Ku-band HTS system employs the smallest possible spot beams. The only time that the Ku-band system performs better than the Ka-band system is when severe weather conditions are present (99.9% availability) and even then, only if the Ku-band spot beam has a beamwidth of approximately less than or equal to 1°. This benefit would only be realised for 100% - 99.9% = 0.1% of any given time period; for example ~44 minutes of an average month.

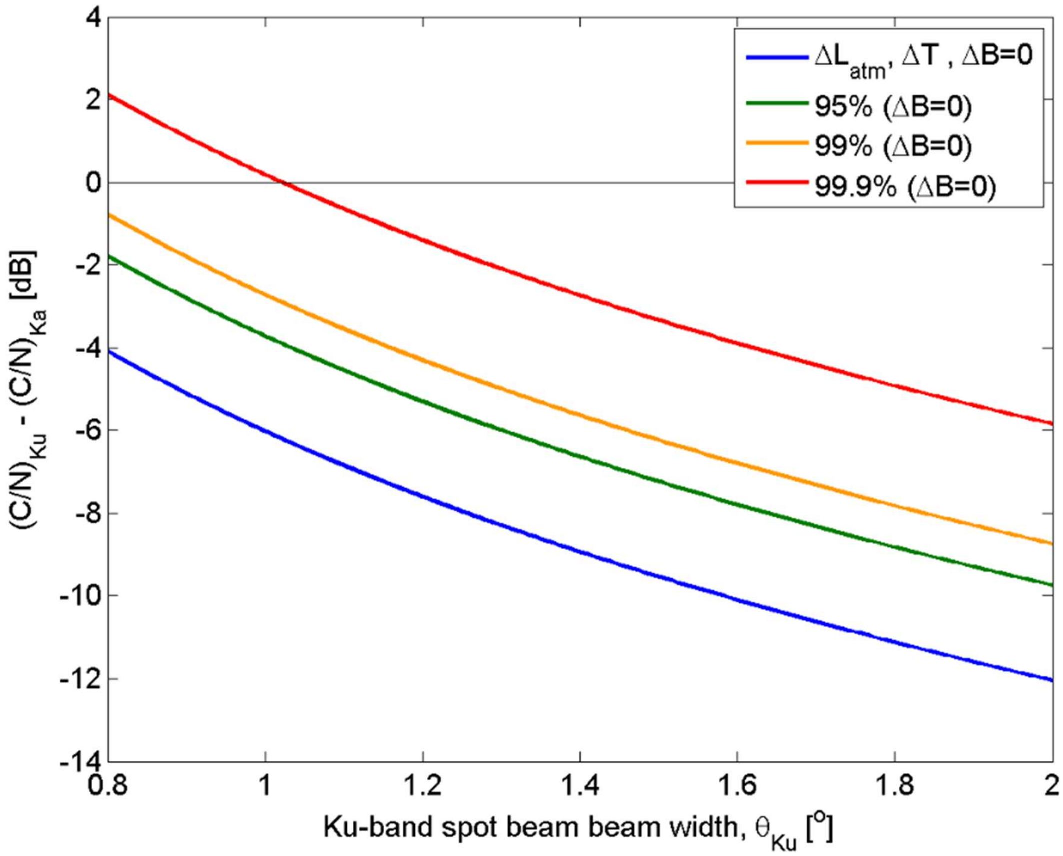

Figure 4: Comparison of downlink (C/N)Ku to (C/N)Ka at 3 availabilities with ΔLatm and ΔT ≠ 0, and ΔB = 0

To assess the uplink case, we shall assume that the system noise temperature of the satellite does not vary dependent on the frequency of operation, as it is non-trivial to calculate the system noise temperature of the satellite and reasonable to assume that the Ku- and Ka-band HTS noise temperature shall be similar. We can then use the uplink atmospheric losses to compare the uplink C/N values of the Ku- and Ka-band HTS system:

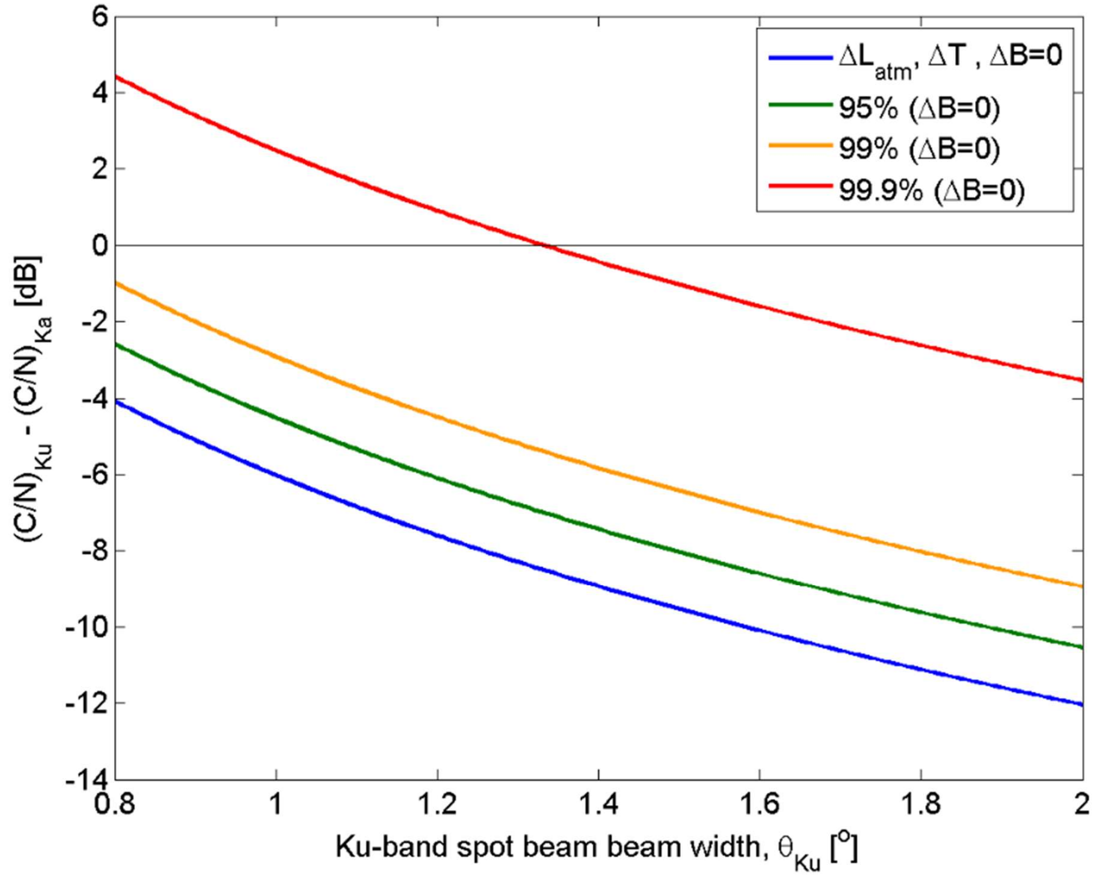

Figure 5: Comparison of uplink (C/N)Ku to (C/N)Ka at 3 availabilities with ΔLatm ≠ 0, and ΔB, ΔT = 0

Here we see that as before, the Ka-band system outperforms the Ku-band system in clear sky (95% availability) and relatively poor weather conditions (99% availability). During severe weather conditions, the Ku-band system can outperform the Ka-band system, but only if the Ku-band spot beam is approximately less than or equal to 1.3°. As before, this benefit would only be realised for 0.1% of any given time period (for example ~44 minutes of an average month).

It should be pointed out that the results presented in Figure **4** and Figure **5** above *do not include any of the fade mitigation techniques described in Table 6.* In the forward direction, techniques such as UPC and site diversity could be able to counter any fade experienced in both Ka- and Ku-band. Indeed, Ku-band systems do not use site diversity, so this advantage is only available to Ka-band systems.

2.6 Additional Spectrum at Ka-band and Effect on C/N

Let us now assess the bandwidth available in the Ku- and Ka-band systems. In Table **9** below, we can see the frequency allocations of each respective band, as decreed by the CEPT (European Conference of Postal and Telecommunications Administrations).

	Uplink	Downlink	Total uplink?	Total downlink?
Ku-band	12.75 – 13.25 GHz & 13.75 – 14.5 GHz	10.7 – 11.7 GHz & 12.5 – 12.75 GHz	1.25 GHz	1.25 GHz
Ka-band	27.5 – 30.0 GHz	17.3 to 20.2 GHz	2.5 GHz	2.9 GHz

Table 9: Frequencies allocations at Ku- and Ka-band **(Electronic Communications Committee (ECC) within the European Conference of Postal and Telecommunications Administrations (CEPT), 2010)**

It can be seen that the Ka-band has at least twice as much allocation of spectrum than the Ku-band in both the uplink and the downlink. This provides various advantages for the Ka-band HTS system.

The allocation of additional spectrum means that if necessary the Ka-band system could use a frequency re-use scheme with several colours which would negate the effect of any inter-spot-beam interference. Alternatively, the same colour scheme as a Ku-band system could be used, but with transponders that are much larger in size. Indeed, the average Ku-band transponder has a bandwidth of 36 MHz, but it is very common to see Ka-band transponders with bandwidths of up to 250 MHz.

Let us consider the most recent satellite transmission air interface standard, DVB-S2X (40). The introduction of this standard has resulted in ground equipment manufacturers creating modems / hubs that are capable of transmitting carriers at speeds of up to 225 MBaud. To calculate how much bandwidth would be required to transmit such a carrier, we can use the equation below,

$$B = R_{\text{sym}} \times (1 + \alpha) \qquad \textit{Eq 20}$$

where R_{sym} is the symbol rate and α is the filter roll-off factor. Assuming a roll-off factor of 10%, we can see that 250 MHz of bandwidth would be required to transmit such a carrier. This could be achieved by Ka-band HTS systems, but Ku-band HTS systems would only be able to transmit at 32.7 MBaud. These results are summarised in Table **10**:

	Available transponder bandwidth	Achievable symbol transmission rate
Ku-band	36 MHz	32.7 MBaud
Ka-band	250 MHz	225 MBaud

Table 10: Available transponder bandwidths and achievable symbol transmission rates at Ku- and Ka-band

In Figure **6** and Figure **7** below, the Ku-band C/N is compared to the Ka-band C/N when taking into account ΔL_{atm}, ΔT_t and ΔB, where $\Delta B = 10 \log_{10}(36/250)$.

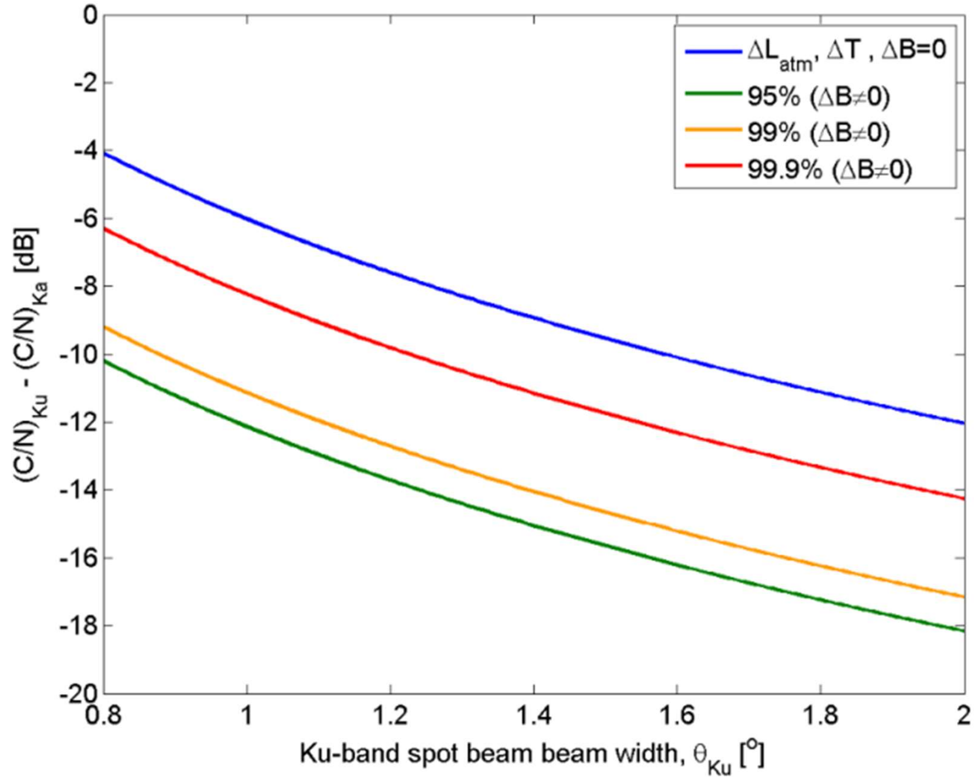

Figure 6: Comparison of downlink (C/N)Ku to (C/N)Ka at 3 availabilities with ΔLatm, ΔT and ΔB ≠ 0

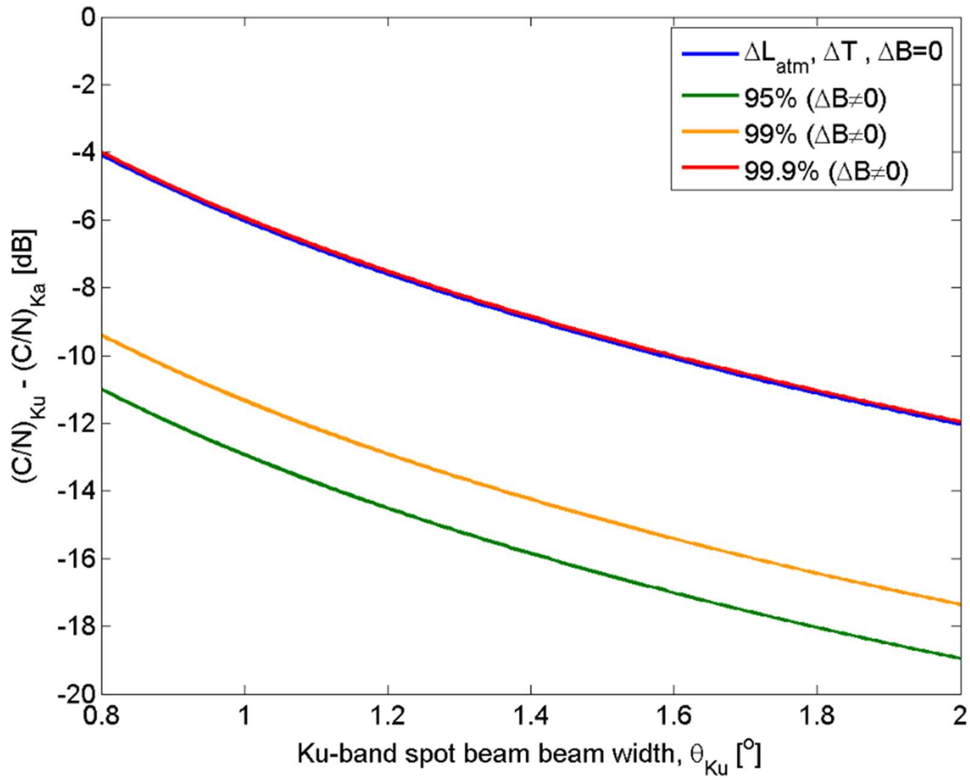

Figure 7: Comparison of uplink (C/N)Ku to (C/N)Ka at 3 availabilities with ΔLatm, ΔB ≠ 0 and ΔT = 0.

We can see that like-for-like, the Ka-band transponder out-performs the Ku-band transponder in all categories.

It should be pointed out that this advantage is only realised when considering single carriers; the Ka-band HTS can theoretically provide a service to a customer which delivers a 225 MBaud carrier using 250 MHz of spectrum but in comparison a Ku-band HTS cannot achieve this with a single transponder. Several transponders would need to be bonded together in an architecture that could be difficult to manage. Furthermore, by utilising several Ku-band transponders, the Ku-band HTS operator will decrease the amount of available spectrum, from a resource that is already smaller than at Ka-band.

3. Conclusion

This paper presented a fair and unbiased comparison of Ku- and Ka-band HTS systems. It was shown that:

- C/N (and therefore throughput) can be shown to be dependent on beamwidth. However, as beamwidth is dependent on frequency, so too is the C/N.
- When moving to Ku- instead of Ka-band frequencies, for the C/N not to be negatively affected, the Ku-band HTS must employ a much larger satellite antenna than the Ka-band HTS. The Ku-band HTS must also achieve comparable spot beam beamwidths.
- While Ka-band HTS spot beams' can achieve beamwidths of < 0.5°, state-of-the-art Ku-band HTS antennas can only produce spot beams with beamwidths of > 0.8°, with Ku-band HTS spot beams expected to have beamwidths of about 2°.
- Even when considering greater atmospheric losses and noisier receivers at Ka-band, the Ka-band HTS system performs better than the Ku-band HTS system in both clear sky conditions (95% availability) and relatively poor weather conditions (99% availability). This is true for both the uplink and downlink.
- During severe weather conditions (99.9% availability) the Ku-band HTS system outperforms the Ka-band HTS system, but only if the Ku-band spot beam has a beamwidth of less than ~1.3° and ~1° for uplink and downlink respectively. This benefit will only be seen for approximately 44 minutes per average month.
- There is much more spectrum available at Ka-band than at Ku-band, and given that Ka-band transponders are much wider than Ku-band transponders (250 MHz vs. 36 Hz), Ka-band HTS operators can deliver high-throughput services using single transponders. To provide a comparable service, Ku-band HTS operators will have to use several transponders, thus depleting an already more meagre resource.

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