High Throughput Ku-band for Aero Applications

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Recent advancements in high throughput Ku-band satellites will allow commercial Ku-band aeronautical mobile satellite systems (AMSS) to equal or exceed commercial Ka-band AMSS systems on cost and performance. The first example of this is Panasonic's acquisition of capacity on Intelsat-29e satellite, the first satellite to use Intelsat's Epic^{NG} platform.

Ku-band currently dominates the AMSS broadband market. Systems like Panasonic's eXConnect, Row44 and Yonder provide service to the commercial market while other providers such as Tachyon and Boeing serve the government market. All of these systems use conventional continental-scale wide beams that are leased from Fixed Satellite Service (FSS) providers like Intelsat.

However, in several years the dominance of Ku-band in the AMSS market will be challenged by forthcoming Ka-band systems, such as Inmarsat-5. These systems use customized satellites with multiple spot beams to offer enhanced performance over conventional wide beam Ku-band.

This paper demonstrates that the key to the high throughput of Ka systems such as Inmarsat-5 is not the frequency of operation, but rather the use of spot beams. This means a Ku band satellite using similarly sized spot beams can equal or exceed the performance of Ka-band satellites. Intelsat's Epic^{NG} platform takes full advantage of this fact.

Panasonic and Intelsat have collaborated on Intelsat-29e, the first Epic^{NG} satellite, to serve the needs of the AMSS market in North America and the North Atlantic – two of the densest aviation markets in the world. This will allow existing Ku-band customers to gracefully transition to a high throughput service without transitioning to expensive new terminals.

Nomenclature

A_{eff} = effective terminal antenna area, m^2
B = bandwidth, Hz

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C = the speed of light, m/s
C/N_{therm} = carrier to thermal noise ratio
C/I = carrier to interference ratio
d = slant range from the satellite to the terminal, m
EIRP = equivalent isotropic radiated power, W
ESD = EIRP spectral density, dBW/Hz
f = frequency, Hz
k = Boltzmann's constant, W/Hz-K
G_{sat} = satellite antenna gain
G_{term} = terminal antenna gain
G/T = gain over temperature, dB/K
HPBW = half power beam width, radians
L_s = space loss
L_{atm} = rain and atmospheric loss
P = amplifier power, W
T = receiver noise temperature, K

I. Introduction

The broadband AMSS field is burgeoning today with multiple providers – Panasonic, ViaSat, Gogo, Row44, Tachyon, Boeing and others – going head to head in the commercial and government markets or carving out their own unique niches. AMSS is used to provide everything from passenger Internet connectivity, to voice services, to aircraft operational data, to situational awareness updates for in-route Special Forces, to back hauling reconnaissance data. Ku-band is the dominant means of providing broadband AMSS today using leased wide beams from FSS providers like Intelsat and Eutelsat. The availability of wide beams developed originally for fixed services like video distribution and VSAT services, along with a few purpose built wide beams over ocean regions, has allowed Ku-band AMSS to develop rapidly.

These Ku-band systems are now being challenged by forthcoming Ka-band systems like Inmarsat-5. Inmarsat-5 Global Xpress uses three dedicated satellites, with more than 70 spot beams each, to provide near global coverage for land, maritime and aeronautical mobile satellites communications. Each beam is approximately 2.1 degrees in diameter[1]. The performance of these Ka-band spot beams is better than that of conventional Ku-band wide beams because the smaller spot beams have higher EIRP and G/T.

Ku-band providers, however, are not standing still. Panasonic and Intelsat are collaborating to bring the first high throughput Ku-band AMSS system to market. Intelsat-29e, the first of Intelsat's Epic^{NG} platform satellites, includes customized coverage to provide Ku-band AMSS over North America and the North Atlantic. Intelsat-29e uses a combination of spot beams for data service in dense regions and wide beams for video and data service in low density areas. Combining spot beams that are considerably smaller than Inmarsat-5 and wide beams tailored for the aero market allows Panasonic to achieve superior performance and economics.

Intelsat Epic^{NG}

Intelsat Epic^{NG} is Intelsat's next-generation open-architecture satellite platform. Epic^{NG} uses a combination of C-, Ku-, and Ka-bands along with a combination of spot beams and wide beams to provide high throughput communications for media, broadband, mobility and government service. The first two satellites using the Epic platform are Intelsat-29e and Intelsat-33e, as shown in Fig. 1.

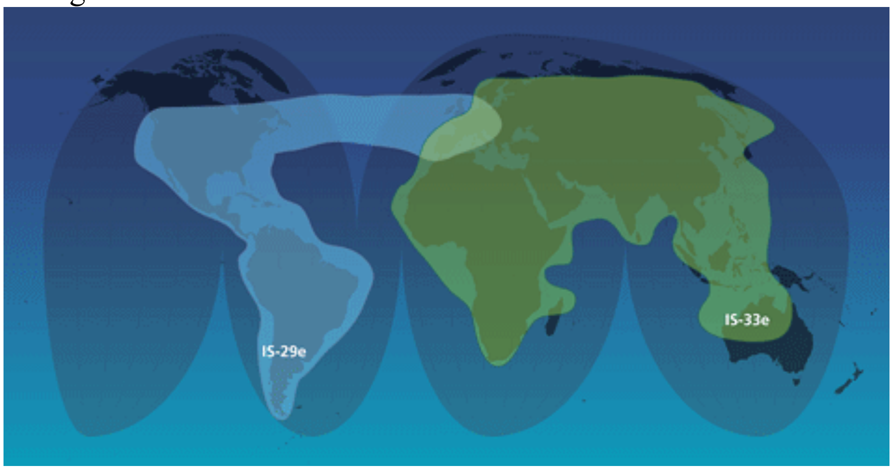

Figure 1. Coverage for Intelsat-29e and Intelsat-33e[§].

Intelsat-29e

Panasonic and Intelsat have collaborated to tailor Intelsat-29e for AMSS service over North America and the North Atlantic, which together represent the largest aviation market in the world and the densest long haul air corridor. Panasonic has committed to up to 1 Gbps of capacity on the Intelsat-29e. Intelsat has added spot beams over the North Atlantic air corridor and a wide beam that will carry rebroadcast TV as well as serve low traffic density regions. Intelsat-29e will support up to 200 Mbps of throughput in a single region (160 Mbps spot beam and 40 Mbps wide beam) and up to 80 Mbps to a single aircraft. The high throughputs supportable by Intelsat-29e exceed those of similar Ka-band systems, such as Inmarsat-5, as a direct result of using spot beams smaller than 2 degrees. The relative performance of both is shown in Table 1.

Table 1. High Throughput Ku vs. Ka for Aero Terminals.

	Intelsat IS-29e	Inmarsat Global Xpress
Beam size	<< 2 deg	2.1 deg[1]
Spot beam downlink	160 Mbps	42 or 84 Mbps[2]
Wide beam downlink	40 Mbps	NA
Spot beam uplink	4 Mbps	4 Mbps[2]

II. Frequency, Performance and Spot beam size

The key to understanding why a Ku-band AMSS system can equal or outperform similar Ka-band systems is the fact that spot beam performance is largely independent of frequency band but strongly dependent on spot beam size.

Performance is Independent of Frequency

The fact that Ku- and Ka-band satellites can offer similar performance may come as a surprise, given that Ka-band has been closely associated with high throughput satellite

[§] Figure provided by Intelsat.

architectures, while Ku-band is associated with existing wide beam satellites. These associations are more reflective of the progression of the satellite business rather than the suitability of either Ka- or Ku-band for high throughput applications. Existing Ku-band systems were developed for video distribution and widely dispersed VSAT networks, with mobile services evolving more recently. By the time high throughput direct-to-home (DTH) Internet services like SpaceWay and ViaSat-1 were envisioned, all of the prime Ku-band slots had been claimed by incumbent FSS operators, limiting new entrants to previously unused spectrum within the Ka-band. Since these services were designed for high throughput from the beginning, Ka-band is often associated with high throughput.

Down Link Performance is Independent of Frequency

The fact that link performance is relatively independent of frequency between Ku- and Ka-band can be seen by examining the equation for down link carrier to noise ratio shown in Eq. (1).

$$\frac{C}{N}_{Therm} = \frac{P_{sat} \cdot G_{sat} \cdot G_{term}}{L_s \cdot L_{atm} \cdot T_{term} \cdot k \cdot B} \qquad (1)$$

C/N in Eq. (1) is a metric for link performance. To assess the effect of frequency on link performance we will hold satellite power, satellite spot beam size, and terminal antenna size constant while varying the frequency and look at the resulting change in C/N using Eq. (1).

We are holding satellite HPA power, $P_{sat,}$ constant as a condition of the scenario and, it turns out, the antenna gain of the satellite, G_{sat}, as well. A key point is that antenna gain is proportional to beam width, so equal size satellite beams must have equal gains, regardless of frequency, as shown in Eq. (2).

$$G_{sat} \approx \frac{4\pi}{HPBW^2} \qquad (2)$$

Note that keeping the satellite antenna beam width, hence gain, fixed requires increasing the antenna size as the frequency is reduced.

However, since we are holding the terminal antenna size (area) constant rather than its beam width, the gain of the terminal does vary with the square of the frequency as given in Eq. (3).

$$G_{term} = \frac{4\pi \cdot A_{eff} \cdot f^2}{C^2} \qquad (3)$$

The space loss also varies as the square of the frequency as given in Eq. (4).

$$L_s = \frac{4\pi \cdot d \cdot f^2}{C^2} \qquad (4)$$

Since the gain of the terminal is in the numerator, and the space loss is in the denominator, the two first order frequency dependent terms in Eq. (1) cancel each other out. This can be seen by substituting Eq. (2) to (4) into Eq. (1), yielding Eq. (5), which has no first order frequency dependencies.

$$\frac{C}{N}_{Therm} \approx \frac{P_{sat} \cdot 4\pi \cdot A_{eff}}{HPBW^2 \cdot d \cdot L_{atm} \cdot T_{term} \cdot k \cdot B} \qquad (5)$$

Of the remaining terms, only T_{term} and L_{atm}, have second order dependencies on frequency. Since receiver noise temperatures along with rain and atmospheric losses generally increase with frequency, all else being equal, C/N_{Therm} and link performance will generally be lower at higher frequencies, particularly if rain availability is a consideration.

There are a number of other factors in the end-to-end link equation but these are also largely frequency independent. End-to-end C/(N+I) is a function of uplink and downlink thermal C/N, C/I co-channel interference, and C/I adjacent satellite interference, as shown in Eq. (6).

$$\frac{C}{N+I} = \frac{1}{\left(\frac{C}{N}\right)_{UL}^{-1} + \left(\frac{C}{N}\right)_{DL}^{-1} + \left(\frac{C}{I}\right)_{CCI}^{-1} + \left(\frac{C}{I}\right)_{ASI}^{-1}} \tag{6}$$

In a well-designed system the C/N thermal on the downlink to the terminal should dominate the end-to-end C/(N+I). The uplink (feeder link) can make use of very large earth stations and is usually designed so that the uplink thermal C/N degrades the end-to-end performance by less than 0.5 dB. C/I co-channel interference is a function of the satellite beam roll-off and satellite frequency reuse plan so similar Ku- and Ka-band systems will have similar C/I co-channel interference values. The only remaining value that has any frequency dependence is C/I adjacent satellite interference (ASI).

C/I ASI can be a significant factor for a smaller antenna and is generally worse for Ku-band because antennas have wider beam widths at lower frequencies. However, aeronautical antennas wider than 0.85 m, such as those used by Panasonic, offer significant rejection at adjacent orbital slots and suffer from relatively little ASI. The level of ASI is also very dependent on the number and location of adjacent satellites operating at the same frequency. Overall, C/I ASI at Ku-band usually results in less than a 1 dB end-to-end impact, which is less than the difference in receiver noise temperatures between Ku- and Ka-band.

Up Link Performance is Independent of Frequency

Up link performance can similarly be demonstrated to be frequency independent for power-limited terminals, including larger mobile terminals that are not off-axis limited. Considering a similar case with a fixed spot beam size and a terminal with a fixed size antenna and power, we can convert the down link Eq. (1) into the analogous uplink Eq. (7).

$$\frac{C}{N}_{Therm} = \frac{P_{term} \cdot G_{term} \cdot G_{sat}}{L_s \cdot L_{atm} \cdot T_{sat} \cdot k \cdot B} \tag{7}$$

Making similar substitutions for a fixed size beam, space loss, and terminal antenna gain yields Eq. (8), which is the uplink analog to Eq. (5).

$$\frac{C}{N}_{Therm} \approx \frac{P_{term} \cdot 4\pi \cdot A_{eff}}{HPBW^2 \cdot d \cdot L_{atm} \cdot T_{sat} \cdot k \cdot B} \tag{8}$$

As with the downlink, the link equation is frequency independent to the first order, at least for power limited terminals. Many small terminals, however, will be regulatory limited, which heavily favors Ku-band.

Up Link Regulatory Limits Favor Ku-band

Small mobile terminals are often regulatory limited. The FCC, ITU and other regulatory bodies have established limitations on the off-axis EIRP spectral density (ESD) that may be radiated from a terminal towards adjacent satellites to prevent interference between systems. Table 2 shows the ITU limits for Ku-band and Ka-band. For historical reasons these limits vary substantially - the limits for Ku-band exceed the equivalent Ka-band limits by 14 dB.

Table 2 Off-Axis EIRP Density Limits

Band	Off-Axis Angle	EIRP Density Limit
Ku - ITU	2.5° ≤ ϕ ≤ 7°	-13 – 25 x log(ϕ) dBW/Hz
Ka - ITU	2° ≤ ϕ ≤ 7°	-27 – 25 x log(ϕ) dBW/Hz

The relative advantage of the Ku-band off-axis limits is somewhat offset by the lower directivity of Ku-band antennas. Figure 2 shows the off-axis ESD performance of 0.45 m Ku- and Ka-band antennas operated at their respective limits. Each antenna is modeled as a uniformly illuminated circular aperture using Bessel functions in order to conservatively model sidelobe behavior. The lower directivity of the Ku-band antenna reduces its advantage in on-axis ESD to 6 dB from the 14 dB difference in off-axis limits, but the net advantage is still substantial.

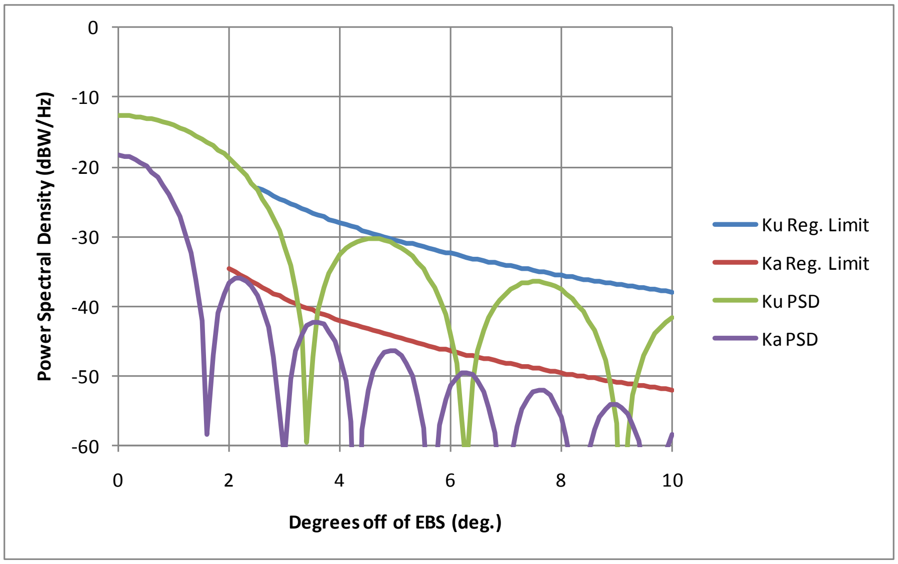

Figure 2. Transmit ESD for 0.45 m antennas vs. regulatory limits.

We can reformulate Eq. (7) in terms of on-axis ESD by gathering the terminal power, gain, and bandwidth terms in Eq. (9)

$$\frac{C}{N}_{Therm} = \frac{ESD \cdot G_{sat}}{L_s \cdot L_{atm} \cdot T_{sat} \cdot k} \qquad (9)$$

We can now substitute for space loss and satellite gain as before but not terminal gain, which is embedded in the ESD term. This yields Eq. (10). Note that frequency no longer cancels. This is a consequence of the frequency term in the terminal gain being embedded in the ESD and not being available to cancel the frequency term in the space loss. As a result, the link performance for an ESD limited terminal will degrade with the square of increasing frequency. Between Ku-band at 14.25 GHz and Ka-band at 29.5 GHz, this represents another 6.3 dB advantage for Ku-band.

$$\frac{C}{N}_{Therm} \approx \frac{ESD \cdot C^2}{HPBW^2 \cdot d \cdot f^2 \cdot L_{atm} \cdot T_{sat} \cdot k} \qquad (10)$$

Taking the ESD limit advantage from the example in Fig. 2 and the performance advantage from Eq. (10), a 0.45 m off-axis ESD limited Ku-band terminal will be able to achieve an uplink C/N that is 12 dB higher than an equivalent size Ka-band terminal in equivalent sized beams. This is a substantial advantage for Ku-band. For regions in the US orbital arc and elsewhere where coordinated to lower levels the Ku limits in Table 2 may be 8 dB lower, which decreases the Ku-band band regulatory advantage to a still substantial 4 dB. Since these regions comprise a small portion of the routes of interest we conclude that the regulatory environment favors Ku-band for long haul international aero system operators.

In the best case for Ka-band, a power limited Ka-band terminal will perform no better than power limited Ku-band terminal when equivalent size spot beams are used, but may perform considerably worse if the terminals are regulatory limited.

Performance is Inverse to Spot Size

The previous sections derived equations showing the frequency dependence of link performance, or lack thereof, based on equal sized spot beams. In each case the C/N was proportional to $1/HPBW^2$, wich means that the performance is inversely proportional to the area of the beam. As spot beam width decreases, performance increases as the square. The increasing performance can be taken advantage of by operating with higher C/N, which enables higher order modulations and codings and better spectral efficiencies, at least up to a point. Eventually, the downlink will hit power spectral density limits and the additional performance advantage will have to be taken as supporting a larger bandwidth at a fixed C/N. In either case, the path to increasing performance is decreasing beam size rather than increasing frequency.

III. System Architecture

Having shown that Ku-band can equal or exceed the performance of Ka-band for similar size spot beams and that performance increases as spot beam area decreases, we can now look at optimum Ku-band AMSS system architectures.

The Right Spot Beam Size

The right spot beam size is a critical question for AMSS system designers. While spot beam performance increases as spot beam area decreases, both the number and the size of spot beams are subject to multiple constraints. Most current high throughput satellites can support a maximum of 70 to 80 spot beams.

It is certainly possible to have spot beams that are too small for a given service from an economic point of view. The smallest spot beams in service are the 0.4 deg on spots used on ViaSat-1 and Jupiter-1 for the DTH Internet service. Each of these satellites supports approximately 60 service beams and 15 feeder link beams and, as a result of the small spot beam size, can support more than 100 Gbps each. The service beams are so limited in area that they only support the populated portions of the Eastern US and the West coast. This might be well suited to the DTH Internet market but to cover the AMSS routes addressed by Intelsat-29e would require several hundred spots of the same size and multiple equivalent satellites. The resulting capacity would exceed the AMSS market demand by orders of magnitude. Most of that expensive capacity would sit idle for the life of the satellites rendering such a solution uneconomical for the AMSS market.

The authors believe that the right size spot beam is the one that is just large enough to operate at full capacity. Since space hardware is inherently expensive, building capacity that goes unused is difficult to justify. Given that AMSS traffic density varies considerably around the world, this leads naturally to the conclusion that different sized beams are appropriate for different regions: Wide beams for low-density regions like the South Atlantic and spot beams for high-density regions such as North America and the North Atlantic.

Tailoring the beam size to the traffic density is analogous to what is done in cellular networks. Rural areas with low traffic density use large cells that may be many km across, whereas dense suburban areas use smaller cells that are sectorized to match the higher traffic density. In very dense urban areas, microcells are deployed that may only cover a few square blocks. Large cells would saturate in a dense urban area while numerous small cells would be an expensive waste in a rural area.

Spot and Wide Beam Overlay

Panasonic is pursuing a mixed system of spot beams for high traffic density regions and wide beams for low traffic density regions, as is done with Intelsat-29e. Matching the beam size to the traffic demand will help to minimize service costs. In addition, even where spot beams are used, Panasonic will overlay the spots with wide beams. This will allow efficient rebroadcast of video content to aircraft without replicating the video in each beam, will enable seamless handovers between beams, and will also provide the flexibility to shift peak loads from one beam to the other. Each aircraft will have two receivers to access the spot beam and the wide beam simultaneously, allowing the aircraft to maintain a continuous connection across spot beam boundaries for video and data services.

Redundancy and Availability

A mixed system of Ku-band spots and wide beams also offers advantages in redundancy and availability. Almost all of the world's flight routes are currently covered by at least one Ku-band wide beam, and often are covered by several such beams. Land regions are often covered by a dozen or more wide beams and key ocean regions, like the North Atlantic, are already covered by more than one wide beam satellite. This provides an inherent back up to a spot beam satellite. This would not be the case in a system that uses three dedicated satellites to provide global coverage; the failure of one satellite will cause a lengthy outage.

Scalability

While Intelsat Epic^{NG}'s combination of spot beams and wide beams is ideally suited to the AMSS market today, it is worth pointing out that high throughput Ku-band AMSS is also scalable into the foreseeable future. Current satellites can support antennas of up to 2.6 m, which can generate a 12 GHz beam of 0.8 deg in diameter. This would allow a quadrupling of beam capacity (because the spot beam area is 1/4 the size) over current Ku-band spot beams and a sixteen-fold increase in capacity density (because four beams will fit in the same area). Future satellites will likely be able to support even larger antennas, meaning high throughput Ku-band satellites can continue to scale to higher capacities as AMSS traffic grows.

IV. Conclusion

Panasonic and Intelsat are collaborating to bring a new generation of high throughput Ku-band AMSS service to market using the Intelsat Epic^{NG} platform starting with the Intelsat-29e satellite. We have shown that Ku-band AMSS can equal or outperform currently planned Ka-band AMSS systems. In fact, the governing link equations are largely frequency independent for equal sized spot beams and terminal antennas. The key to higher performance is using equal or smaller spot beams. A mixed architecture of spot beams for high-density traffic area and wide beams for low-density traffic areas will match capacity to demand. Finally, high throughput Ku-band is scalable to meet demand growth in the aero market for many years to come.

References

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[2]Noris, J., "Inmarsat super-charges its mobile satellite services business," *APEX Editors Blog*, 23 June, 2012. URL: http://blog.apex.aero/ife/inmarsat-supercharges-mobile-satellite-services-mss-business/ [cited 31 July, 2012] Data rate of 42 Mbps for a single carrier, 82 Mbps for two.