Arthur D Little

High Throughput Satellites

Delivering future capacity needs
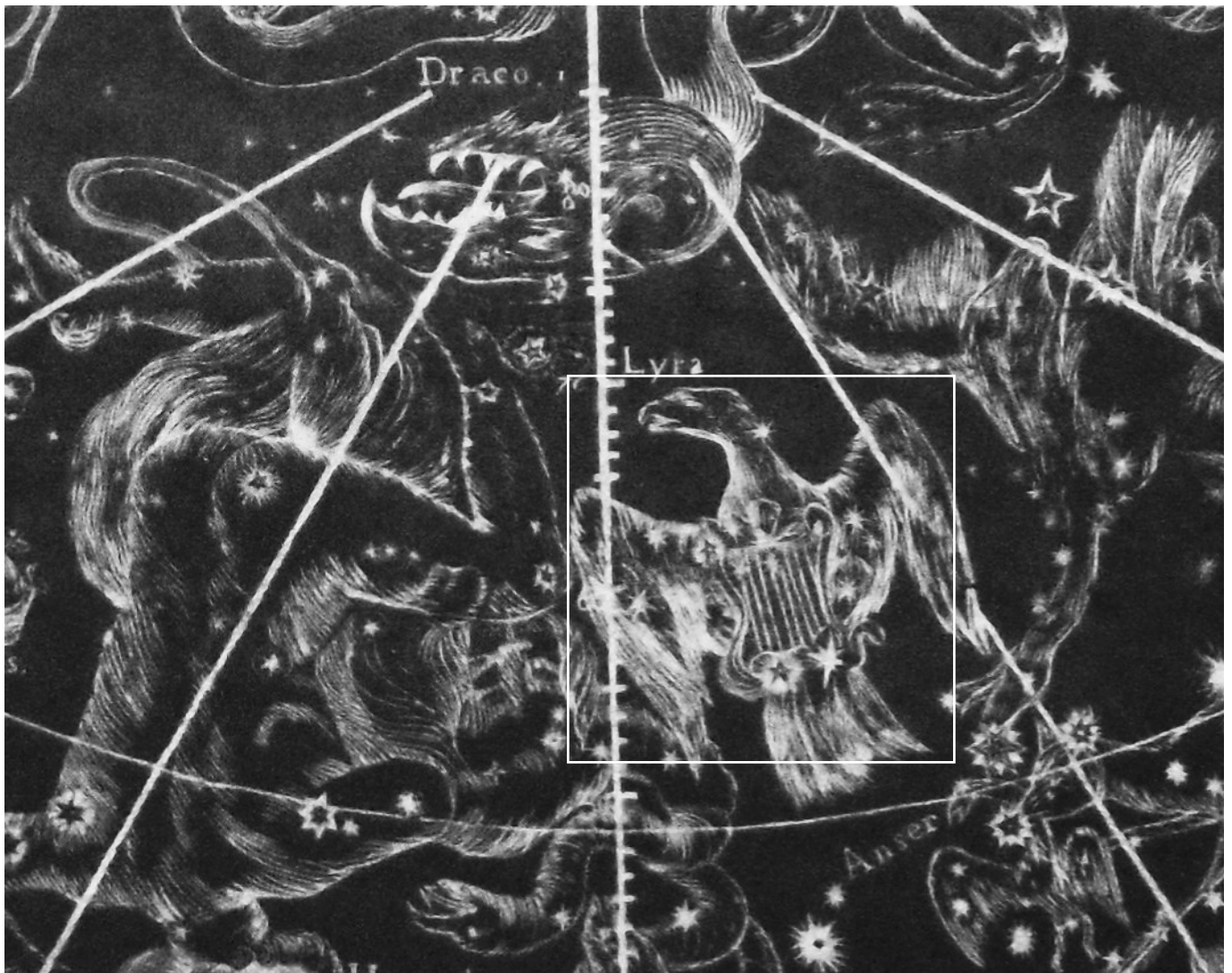
Content

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Executive summary

Advances in satellite communications technology in recent years have led to a significant increase in throughput delivered from a raft of new 'High Throughput Satellite' (HTS) systems. More than a dozen such satellites have been launched in recent years and several more will go into orbit in the coming years. These satellites support diverse user requirements and use cases – from 'connecting the unconnected' to providing secure and resilient communications to industries, SMEs and all end users.

In this extended commercial and technical white paper we explore in particular the performance tradeoffs, and note the growing importance of higher frequency systems, given the significant spectrum allocations and high performance in key deployment areas. HTS systems offer a step change in bandwidth delivery to support a host of diverse customer requirements. The raft of systems launched must balance tradeoffs that affect system performance, user experience and cost of service.

The satellite communications industry supports a wide range of customers whose varying use cases and deployment locations place exacting requirements that must be fulfilled. Connectivity must be delivered to consumers located beyond the reach of traditional terrestrial networks and yet also to business and corporate clients requiring bespoke systems to support critical communications needs in locations as challenging as the North Sea and the deserts of the Sahara. Satellites also play a critical role in the delivery of broadcast services, media links and other industry specific applications.

HTS systems represent a new generation of satellite communications systems, capable of delivering vast throughput compared to conventional fixed, broadcast and mobile satellite services (FSS, BSS and MSS). The one fundamental difference in the architecture of an HTS system is the use of multiple 'spot beams' to cover a desired service area, rather than wide beams, which bring a two-fold benefit:

➔ **Higher transmit/receive gain:** because of its higher directivity and therefore higher gain, a narrower beam results in increased power (both transmitted and received), and therefore enables the use of smaller user terminals and permits the use of higher order modulations, thus achieving a higher rate of data transmission per unit of orbital spectrum.

➔ **Frequency reuse:** when a desired service area is covered by multiple spot beams, several beams can reuse the same frequency band and polarization, boosting capacity of the satellite system for a given amount of frequency band allocated to the system.

The overall performance of satellite systems depends on many factors – some determined by user requirements (terminals, operational customer locations) and some by the system overall design (satellite antenna configuration, spacecraft power, frequencies, etc.). A number of HTS systems have been placed into orbit and already supply many Gbps of capacity, massively expanding offered capacity since the 1990s. They can be deployed in a few spectrum bands, but typically the Ku-band (referring to the band directly *under* the K-band) and Ka (referring to the band directly *above* the K-band) are used.

The selection of the system frequency band has an important bearing on the overall experience:

→ Ka-band enables narrower beams and therefore higher satellite antenna gain, improved link budget and therefore higher throughputs for a given antenna dimension – this is important because antenna size can be constrained (by the size of the launch vehicle placing the satellite into orbit).

→ For a given required end user antenna gain, Ka-band results in a smaller user terminal antenna or for a given end user antenna size, a larger gain and therefore better radio-frequency link budget.

→ A better link budget allows the use of higher order modulation and coding schemes, resulting in a higher spectral efficiency, increased throughput and thus more cost-effective Mbit/s.

→ A better link budget offers the possibility to operate with a higher level of interference in system design.

→ Ka-band enables more reuse of frequency and therefore more capacity, due to the typically smaller beams deployed. This also allows very tailored, optimized coverage to be delivered.

→ Ka-band is more sensitive to severe atmospheric perturbations. However, these only occur during very limited time periods, and can be mitigated using Fade Mitigation Techniques (FMT).

The choices available in terms of geographic footprint, performance and cost are many, so it is increasingly important for users to carefully consider their actual use case requirements. Here the Ka-band frequencies have multiple advantages over the Ku-band for high-capacity systems. Satellite communications remains one of the most technically advanced industries, leveraging the very latest technology to continually increase the capabilities, capacity and performance delivered to its customers, wherever and whenever they need it.

1. HTS systems in satellite communications

1.1 Overview of satellite communications

The first commercial communications satellite in a geosynchronous orbit was 'Early Bird' and was launched in 1965. This spacecraft has been used to relay international communications as well as TV programs. It had a capacity of 240 telephony circuits and a single television channel. It was placed at 28° East longitude and enabled direct communications between Europe and the United States.

Since then, the satellite communications industry has dramatically evolved thanks to numerous technological innovations, such as:

- **Increasingly powerful satellites:** moving from just a few kilowatts of power in the early 2000s to greater than 20kW at present. This has been made possible by the usage of more efficient solar arrays (triple junction systems with efficiency close to 30% compared to about 12% for standard silicon ones), Li-ion batteries, mastering of thermal control, use of electric propulsion (plasma thrusters), etc.

- **Improved payload technology:** multibeam antennas with large number of beams (up to a few 100 on a single satellite), light-weight shaped reflectors, more integration and processing power for on-board electronics, reduction in size and mass of RF components (e.g. Monolithic Microwave Integrated Circuits (MMICs)), increased efficiency of high power amplifiers, availability of Ka-band RF components, etc.

- **Radio frequency link development:** better characterisation of propagation channels via improved channel models (including Ka-band and above); investigation and implementation of Fade Mitigation Techniques, etc.

- **Enhanced digital communication techniques:** advanced digital modulations and more efficient channel coding techniques (Turbo-codes, Low-Density Parity-Check (LDPC), etc.), implementation of adaptive modulation and coding techniques (e.g. DVB-S2X standard), improvement of multiple access techniques, etc.

- **TCP acceleration techniques:** improved performance over satellite communications networks through the utilisation of techniques such as TCP spoofing, window scaling and the usage of alternative congestion avoidance mechanisms.

Figure 1: 'Early Bird' satellite
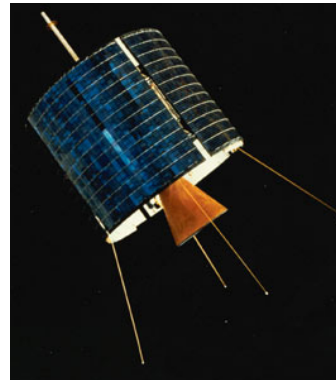
Source: Boeing

- **Ground terminals:** have also developed in parallel, but typically with a trend towards miniaturization and reduction in cost relative to performance characteristics.

The sector remains at the forefront of technical endeavour and brings much needed connectivity and broadcast services to businesses, governments and citizens throughout the world. Satellite systems are increasingly integrated into diverse telecoms system deployments and play fundamental roles in realizing the global digital society.

Communication satellites fulfil a range of user needs

Commercial communication satellites today support diverse user requirements and use cases – from 'connecting the unconnected' to providing secure and resilient communications to the industries for which this matters most.

Primarily the main communications requirements remain the provision of connectivity services, particularly internet and intranet access for customers from many segments. Within the satellite sector, there are a variety of use cases for potential customers. These use cases are often at specific deployment locations, which in the case of satellite services are often (but not exclusively) beyond the reach of terrestrial networks, or where those networks begin to experience specific performance and capacity limitations.

For example, the following use cases typify some of the requirements of users:

■ **High throughput connectivity for corporates and consumers:** in areas where high quality broadband through the terrestrial infrastructure is not available, satellite technology is the most appropriate solution for providing high bitrates.
Example: European countryside areas

■ **Basic connectivity in remote areas:** in remote areas not served with terrestrial infrastructure, satellites are the only solution for providing connectivity.
Example: Connectivity in schools in Sub-Saharan Africa

■ **Cellular backhaul:** providing high capacity links to support otherwise isolated base stations of terrestrial mobile networks.
Example: Remote mobile base stations in Northern England

■ **Media links and resilient connections:** providing high capacity and resilient network links for industries (media, banking, lotteries, etc.) with distributed sites and bespoke security requirements.
*Example: Connection of lottery ticket retailers in North Africa*

■ **Satellite TV broadcasting:** supporting Direct to Home (DTH) with efficient delivery of one-to-many content distribution and Satellite News Gathering (SNG) services.

■ **Offshore energy:** customer platforms located at sea, and not connected by seabed submarine cables.
Example: Production oil fields in the North Sea

■ **Onshore energy:** even when within reach of terrestrial systems, there is a need for resilient communications to allow managed shutdowns and remote control of facilities.
Example: Production gas fields in Algeria

1.2 Basic principles of two-way satellite communications

The basic principles of a two-way satellite communication system providing "access" services relies on the effective interworking of three components (Figure 2):

■ The satellite itself – usually, but not always, placed in a geostationary orbit[1] (at an altitude of ~ 35,800km) above the earth, in order to provide continuous coverage of a specific area with dedicated antenna beams. Satellites normally remain in orbit for a defined life (usually greater than 15 years) before being retired from service.

Figure 2: Essential elements of a two-way satellite system providing access services (1/2)
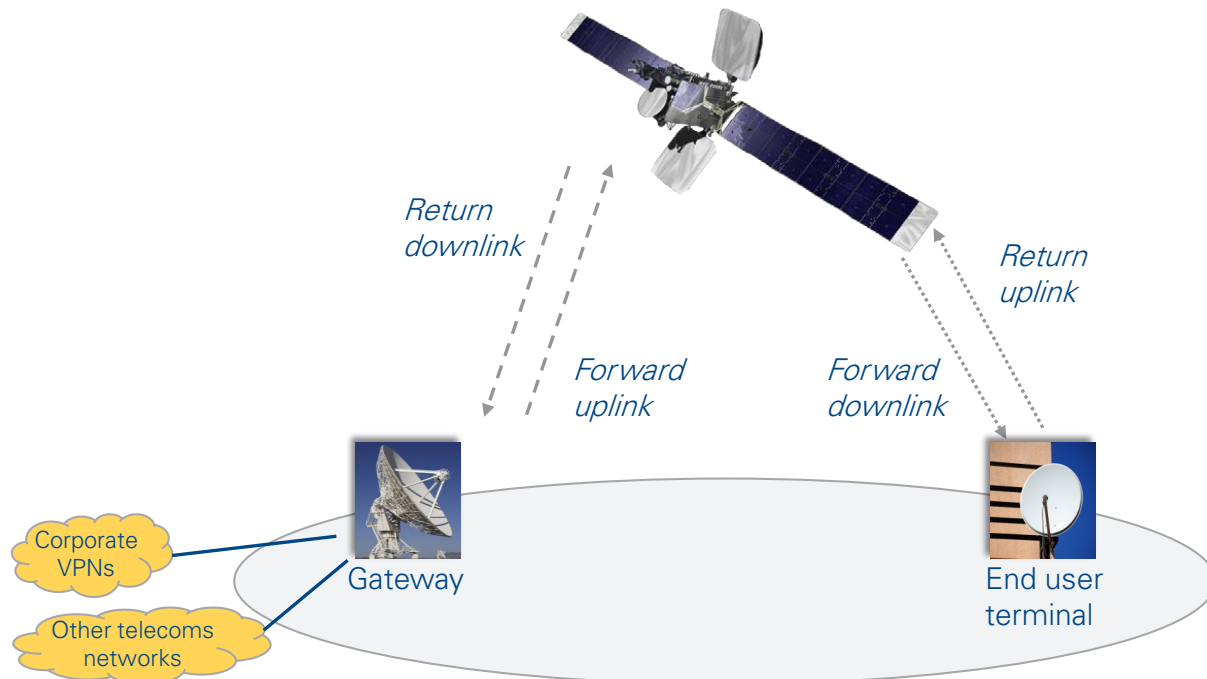
Source: Arthur D. Little, Avanti Communications

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1 Such Geostationary systems are collectively known as GEO systems. Other orbital altitudes, such as Low Earth Orbit (LEO) and Middle Earth Orbit (MEO), which require many more satellites to maintain continuous coverage, are not discussed within this paper.

Figure 3:   Essential elements of a two-way satellite system providing access services (2/2)
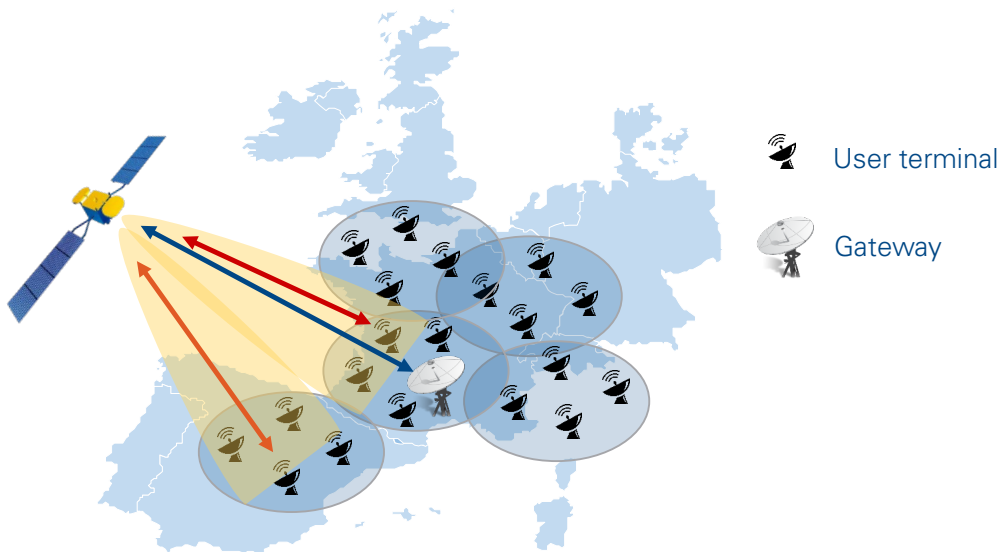
Source: Arthur D. Little, Avanti Communications

■ End user terminals – which can be satellite dishes or portable antennas. The choice of user equipment is subject to many design parameters – operating frequencies, physical resilience, the need for intrinsically safe operation, cost performance factors etc. These can be replaced and upgraded, but since satellite services are often deployed in remote locations this is, where possible, avoided during the life cycle of the equipment.

■ A Ground Earth Station or Gateway, from which data is fed to and from the satellite (via feeder uplink and downlink). A Gateway typically serves a large number of user terminals located in one or several user beams (Figure 3). The combination of the feeder uplink and the user downlink provides outroute connectivity (called forward link) between the Gateway and an User Terminal. Conversely, the return link (combination of user uplink and feeder downlink) allows inroute connectivity between the ground elements.

Many elements of this system can be optimized to suit specific client requirements and operating locations, which we further explore in this paper, in the context of the latest generation of satellite systems.

HTS offer a step change in satellite communications

Like other telecommunications technologies, satellite systems are subject to technology life cycles. New generations of equipment yield step changes in performance, decreases in the cost of operation of systems, and yield the obsolescence of older systems.

HTS systems are a new generation of spacecraft, capable of delivering vast throughput when compared to conventional FSS, BSS and MSS satellite systems. These systems began to slowly launch ten years ago, but we have recently witnessed a raft of new deployments, bringing fundamental change to the marketplace.

The one fundamental difference in the architecture of an HTS system compared to previous systems is the use of multiple 'spot beams' to cover a desired service area, rather than wide beams.

Figure 4:   Example of spot beams – covering Iberia
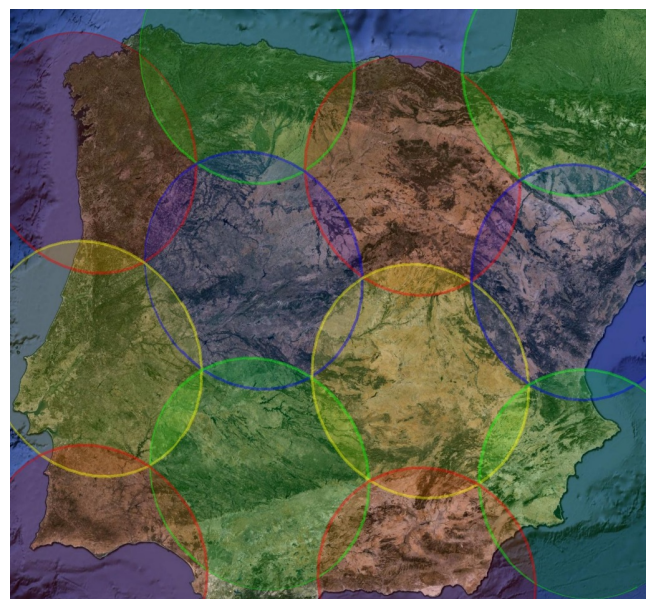
Source: Avanti Communications

These spot beams bring a two-fold benefit:

- **Higher transmit/receive gain:** The gain of an antenna is inversely proportional to its beamwidth, so a narrower beam results in increased power (both transmitted and received), and therefore enables the use of smaller user terminal antennas. The larger available power also permits the use of higher order modulation and coding schemes (MODCODs). These higher MODCODs offer a "high spectral efficiency" defined as the transmitted bit rate per unit of utilized frequency band. The higher the spectral efficiency, the higher the rate of data transmission per unit of orbital spectrum utilized. This is a very important feature because of the congestion of orbital slots as well as the limitations in the spectrum available.

- **Frequency reuse:** HTS systems utilise the high directivity of the spacecraft antennas to position spot beam footprint, allowing several beams to reuse the same frequency. A frequency reuse factor using narrow separated beams is in theory equal to the number of beams if the beams are separated far enough. However, continuous coverage of a given area requires overlapping of beams, which implies the use of different frequencies and polarizations[2] in adjacent beams to avoid interference.

A 4-color reuse frequency scheme can be defined, allowing frequency reuse with minimal interference between neighboring spot beams. Each beam is being assigned half of the available bandwidth, and operates on one of the two polarizations (RHCP and LHCP) (Figure 5).

A cluster of 4 beams benefits from an equivalent bandwidth equal to twice the bandwidth (Bw) allocated to the satellite, because of the frequency reuse by orthogonal polarizations. The total satellite system bandwidth is therefore equal to:

$$B_{wtotal} = \frac{2N_b B_W}{N_C}$$

where

N_b is the number of beams of the satellite
N_c is the number of colors (here 4) in the cluster
B_{wtotal} is the total bandwidth

$2N_b/N_c$ is called the frequency reuse factor and multiplies by the same factor the capacity (total transmitted bitrate) of the satellite enabling significant capacity increases by comparison with a single beam satellite.

The decision on the number of colors and the related frequency reuse factor results from a trade-off between system capacity and acceptable amount of interference.

1.3 HTS systems services

HTS systems provide the same types of services as regular satellites

Although HTS systems are designed to provide high bandwidth connectivity services, given the significant increase in system throughputs that are achievable, they can provide a range of services in a similar fashion to traditional legacy satellites. However, it is typically less relevant to use HTS satellite to broadcast television over wide areas, because it would imply the use of several beams transmitting the same information to cover large countries (see the example of Spain on Figure 4). A simpler satellite can provide the service at a lower cost (or a wider beam on another system).

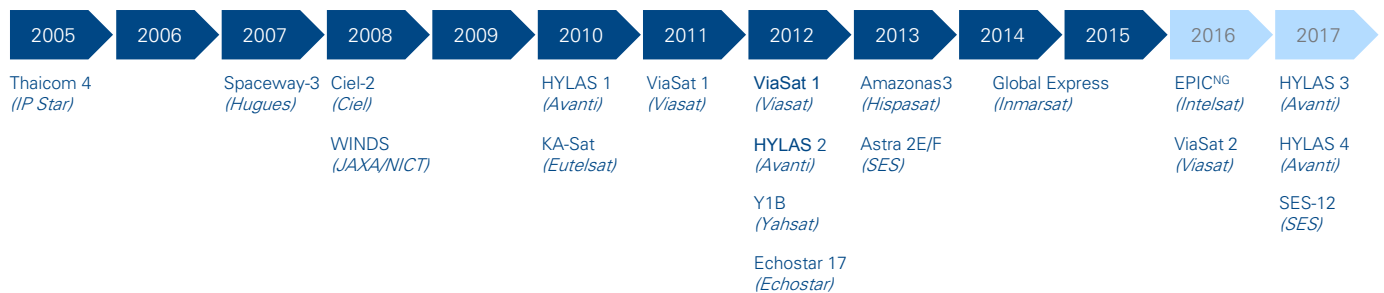**Figure 5:   Example of a 4-color pattern and allocation of colors to multiple beams providing continuous coverage**
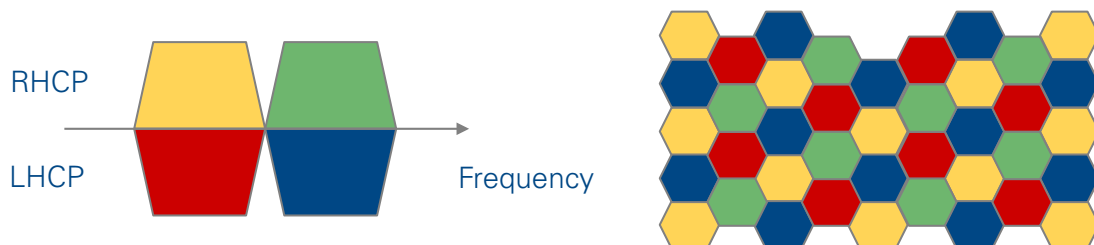
Source: Arthur D. Little, Avanti Communications

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2   Characteristic of a radio wave, that allows in specific configuration to reuse a frequency band twice while carrying different information signals, for instance RHCP -Right Hand Circular Polarization and LHCP -Left Hand Circular Polarization.

Figure 6: Major High Throughput commercial satellites launches (examples)

2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017

Thaicom 4
(IP Star)

Spaceway-3
(Hugues)

Ciel-2
(Ciel)

WINDS
(JAXA/NICT)

HYLAS 1
(Avanti)

KA-Sat
(Eutelsat)

ViaSat 1
(Viasat)

ViaSat 1
(Viasat)

HYLAS 2
(Avanti)

Y1B
(Yahsat)

Echostar 17
(Echostar)

Amazonas3
(Hispasat)

Astra 2E/F
(SES)

Global Express
(Inmarsat)

EPIC^NG
(Intelsat)

ViaSat 2
(Viasat)

HYLAS 3
(Avanti)

HYLAS 4
(Avanti)

SES-12
(SES)

Source: Arthur D. Little analysis

A number of HTS satellites have been launched over the past recent years

More than a dozen HTS satellite systems have already been launched and several more will go into orbit in the coming years. These systems are backed by a variety of commercial providers, who sell capacity direct or through resellers to end users within the specific coverage area of each system – obviously this varies greatly, depending on the final geostationary orbital position chosen, and the selection of antennas and beams deployed on the platform.

The introduction of these systems has significantly expanded the total amount of capacity supplied to the market, with launched and known planned systems approaching 1Tbps[3] of capacity within a few years. Since each system has a specific coverage zone, total capacity supplied at any given location is clearly lower than this aggregate total.
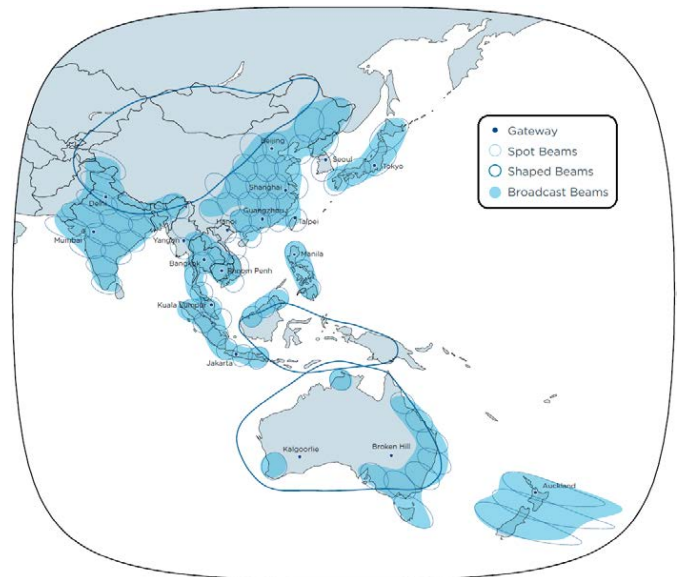
Example of an Early HTS System (Thaicom 4/IPSTAR)

Each HTS system launched varies significantly in terms of technical design, payload and coverage. For example, the early Thaicom 4/IPSTAR system carried a variety of spot, shaped and broadcast beams, in order to tailor its coverage footprint and service offering to the needs of potential customers in South East Asia.

As illustrated in the Figure 7, the IPSTAR satellite is using a combination of spot beams and wider beams. The figure illustrates the relative difference in covered areas of the different types of beams.

Figure 7:   Specification of a sample HTS system

Thaicom 4/IPSTAR		
Beams:	■ 84 Ku-band spot beams (two-way)	
	■ 8 Ku-spot spot beams (Augment) (two-way)	
	■ 3 Ku-band shaped beams (two-way)	
	■ 7 Ku-band broadcast beams (one-way)	
Transponders:	■ Minimum 104 transponders	
Fixed Throughput:	Minimum Case:	■ 30 Gbps
	Medium Case:	■ 37.5 Gbps
	Maximum Case:	■ 45 Gbps

Source: Satellite operator (www.thaicom.net), Arthur D. Little

Key design parameters of HTS systems

HTS systems continue to evolve, each with bespoke design characteristics. Many specifications are confidential but public domain information profiles the frequencies used and the capacity available.

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3   Broadband Access Terabit/s Satellite Concepts: Bousquet, Radzic, Jeannin, Castanet, Thompson, Evans; American Institute of Aeronautics and Astronautics.

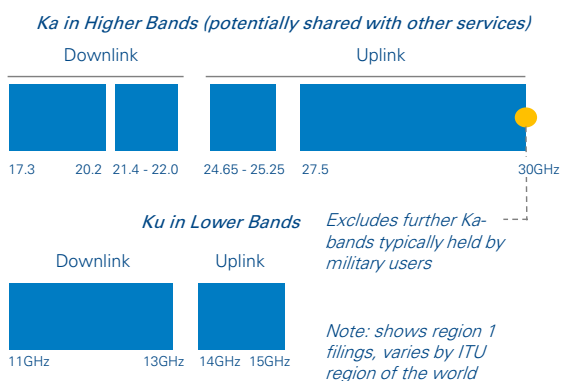| Operator/ Partner	GEO/MEO	Coverage region	Manufacturer	System	Launch date
Thaicom	GEO	Asia-Pacific	Space Systems Loral (SSL)	Thaicom 4 (IPSTAR)	2005
Hughes	GEO	North America	Boeing (Hughes)	Spaceway 3	2007
Ciel	GEO	North America	Thales Alenia Space	Ciel 2	2008
JAXA	GEO	Asia-Pacific	JAXA/NICT	WINDS (Kizuna)	2008
Avanti	GEO	Europe	EADS Astrium	HYLAS 1	2010
Eutelsat	GEO	Middle East	EADS Astrium	KA-SAT	2010
Yahsat	GEO	Middle East, Africa	EADS Astrium	Yahsat 1B	2012
Viasat	GEO	North America	Space Systems Loral (SSL)	Viasat-1	2012
Echostar	GEO	North America	Space Systems Loral (SSL)	Echostar 17 (Jupiter 1)	2012
Avanti	GEO	Europe, Middle East	Orbital Sciences Corporation (OSC)	HYLAS 2	2012
Hispasat	GEO	North America, LATAM	Space Systems Loral	Amazonas 3	2013
SES	GEO	Europe, Africa	EADS Astrium	ASTRA 2E/2F (2 satellites)	2013
Inmarsat	GEO	Europe, Middle East, Africa, Asia	Cobham Satcom, Paradigm Comm, Skyware Global	Global Express (3 satellites)	2013-2016
Viasat	GEO	North America, LATAM	Boeing Satellite Systems	Viasat-2	2016
Intelsat	GEO	North America, LATAM	Boeing Satellite Systems	EPIC (2 first satellites)	2016
Avanti	GEO	Africa	MDA	HYLAS 3	2017
Avanti	GEO	Africa, Europe	Orbital ATK	HYLAS 4	2017
SES	GEO	Asia-Pacific	Airbus Defence and Space	SES-12	2017

Source: Arthur D. Little, Satellite operators

HTS satellites typically operate on two main frequency bands: Ku and Ka-bands

Many HTS systems have already been placed into orbit and already supply many Gbps of capacity, massively expanding supply since the 1990s. They can be deployed in many spectrum bands, but are mainly found in the Ku-band (lower) and the Ka-band (higher) bands. Launches will continue from 2015 onwards, most notably *Intelsat EPIC[NG]* (in Ku), *Inmarsat Global Xpress* and *Avanti HYLAS 3 and HYLAS 4* (in Ka), and will continue for the foreseeable future, especially in the larger and somewhat less densely occupied Ka-band.

Frequency allocations are defined by the International Telecommunications Union at the international level and are homogenized by regions of the world. Three regions have been defined globally and region 1 is covering all of Europe, Russia, the Arabic peninsula and the whole African continent.

Figure 8: Typical band positions for Ka and Ku satellites

Ka in Higher Bands (potentially shared with other services)

Downlink   Uplink

17.3   20.2   21.4 - 22.0   24.65 - 25.25   27.5   30GHz

Ku in Lower Bands   *Excludes further Ka-bands typically held by military users*

Downlink   Uplink

11GHz   13GHz   14GHz   15GHz   *Note: shows region 1 filings, varies by ITU region of the world*

Source: Arthur D. Little analysis, Avanti Communications

On the Ka-band, the frequency bands available for satellite in the region 1 are:

- For the downlinks : 17.7 - 20.2 GHz, 17.3 – 17.7 GHz and 21.4 – 22.0 GHz.

- For the uplinks: 27.5 - 30.0 GHz and 24.65 – 25.25 GHz.

The band 19.7-20.2 GHz (satellite downlink) band and the band 29.5-30 GHz (satellite uplink) are exclusively reserved for satellite use (2 x 500 MHz). By decision of Europe's Electronic Communications Committee (ECC), in these bands Ka-band VSATs are exempt from individual licensing for low power terminals[4].

The 17.3-18.1 GHz FSS (satellite downlink) is shared with Broadcasting Satellite Service (BSS) feeder up links. All other parts of Ka-band at 27.5 – 29.5 GHz, 24.65 – 25.25 GHz, 17.7 – 19.7 GHz and 21.4 – 22.0 GHz have co-primary frequency allocations to satellite services shared with terrestrial services (e.g. Fixed Services - FS) and thus the use by satellite services would be subject to frequency coordination at particular earth station sites with nearby terrestrial radio systems.

Hence in ITU region 1:

- 3.1 GHz is available for satellite uplinks between 27.5 – 30.0 GHz and 24.6 – 25.2 GHz, but with various restrictions as noted above.

- 3.5 GHz is available for satellite down links between 17.3 – 20.2 GHz and 21.4 – 22.0 GHz, but with various restrictions as noted above.

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4   Generally lower than 50 dBW in most CEPT countries, up to 55 dBW in UK and in a few countries up to 60 dBW.

2. Relative performance of frequency bands for HTS systems

The overall performance of satellite systems depends on many factors – some determined by user requirements (terminals, operational customer locations) and some by the system overall design (physical antenna configuration, frequencies, etc.).

Fundamentally, an important measure of the performance of a system is its capacity or overall throughput (the total amount of bitrate conveyed by the system assuming a nominal quality defined by the bit error rate (BER) that characterizes the quality of the transmission). The system capacity depends on amount of spectrum available, B_w, the frequency reuse factor F and the spectral efficiency of the modulation (see section 1.2).

Indeed Bits/s total = B_{wtotal} x spectral efficiency = B_w x Frequency reuse factor x spectral efficiency.

With wireless communications, the information is conveyed onto a radio wave thanks to a modulated carrier (a sinewave at a selected frequency of which either amplitude, frequency or phase is varied). The radio link performance, characterized by the carrier-to-noise power density ratio, or C/No, conditions the ability of the carrier to convey a given bitrate with a given bit error rate, and therefore constitutes another system performance parameter.

The most challenging part of the system is normally the user link (to/from Satellite from/to user terminal) which is driven by constraints on the characteristics of the end user terminal.

2.1 Basics of link budget

In practice, the communication link performance is a function of the ratio of the amount of available carrier power by the amount of unwanted signals (called noise). The radio frequency link performance is evaluated as the ratio of the received carrier power, C, to the noise power spectral density, N_0, and is quoted as the C/N_0 ratio, expressed in hertz (Hz).

Received carrier power

The amount of available carrier power C (in Watts) is obtained by the following equation:

$$C = \frac{P_t G_t G_r \left(\frac{\lambda}{4\pi R}\right)^2}{L_a} = \frac{(EIRP) G_r}{L_{fs} L_{atm}} \quad \text{(W)}$$

where
P_t: power fed to the transmit antenna
G_t: actual gain of the transmit antenna in direction of the receiving system
G_r: actual gain of the receiving antenna in direction of the transmitting system
L_{fs}: free space loss depending on wavelength λ and distance R
L_{atm}: atmospheric losses
$EIRP = P_t G_t$, the effective isotropically radiated power characterizes the performance of the transmitting system
R is the distance between the satellite and the earth station (35786 to 41680 km for a geostationary satellite)

A formula for this distance R is:

$$R^2 = R_0^2 \left[1 + 0.42 \left(1 - \cos I \cos L \right) \right] \quad \text{(m)}$$

where
I is the latitude of the ground earth station
L is the relative longitude of the ground earth station with regard to the subsatellite point
R_0 is the satellite altitude (35786 km)

Receiver input noise power spectral density

At receiver input, the wanted carrier power is not the only contribution. Different unwanted signals contribute to what is called the system noise temperature T.

Those sources of noise include the noise captured by the antenna and generated by the feeder, which can actually be measured at the receiver input, plus the noise generated downstream in the receiver, which is modelled as a fictitious source of noise at the receiver input, treating the receiver as noiseless.

T is the system temperature can be written as:

$$T = \frac{T_A}{L_{FRX}} + T_F \left(1 - \frac{1}{L_{FRX}} \right) T_F + T_R \quad \text{(K)}$$

where
T_A is the antenna noise temperature, depending on the natural radiation captured by the antenna
L_{FRX} are the antenna – receiver feeder losses
T_F is the feeder temperature
T_R the receiver effective input noise temperature (function of noise generated inside receiver components)

Link budget

The calculation of carrier power, noise power spectral density for a complete communication link is the link budget. The link budget may be established for the uplink or downlink according to the equation expressing C/N_0:

$$\frac{C}{N_0} = P_t G_t \frac{1}{L_{fs}L_A} \frac{G_r}{T} \frac{1}{k} = EIRP \frac{1}{L_{fs}L_A} \frac{G_r}{T} \frac{1}{k} \quad (\text{Hz})$$

The system noise temperature T has been used to infer the amount of noise power spectral density No at receiver input:

$$N_0 = kT \quad (\text{W/Hz})$$

where k is the Boltzmann constant

In this equation, term G_r/T is called the figure of merit (K^{-1}) and characterizes the performance of the receiving system.

The link budget equation can be written using values in dB:

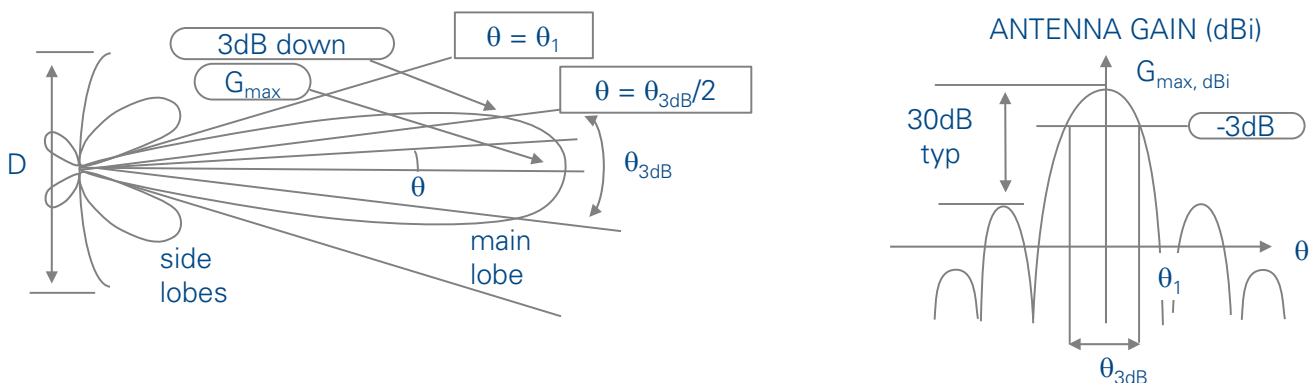$$\frac{C}{N_0} = EIRP - L + \frac{G}{T} - k \quad (\text{dB.Hz})$$

where $L = 10 \log (L_{fs} L_A)$ are the path losses (dB)

Overall link budget

The overall performance of the total satellite connection depends on that of the uplink and the downlink, interference, and nonlinear effects in the repeater.

The nonlinear effects in the satellite high power amplifier generate spurious frequencies that can be considered as adding on a power basis to the thermal noise. This is called intermodulation noise $(N_0)_{IM}$ and is a function of the number of carriers, their modulation characteristics and the amplitude and phase characteristics of the power amplifier. The intermodulation noise is taken into account in the link budget considering the $(C/N_0)_{IM}$ ratio.

Similar terms can be added for other sources of noise, such as interference. Indeed, in real situations, interference is present and must be accounted for. It is common practice to consider interference as a noise and to define a carrier-to-interference ratio $(C/N_0)_I$ including all contributions from the interfering sources. The overall C/N_0 for a nonlinear transponder operated in a multi-carrier mode and with interference is given by:

$$\left(\frac{C}{N_0}\right)^{-1} = \left(\frac{C}{N_0}\right)_U^{-1} + \left(\frac{C}{N_0}\right)_D^{-1} + \left(\frac{C}{N_0}\right)_{IM}^{-1} + \left(\frac{C}{N_0}\right)_I^{-1} \quad (\text{ratio})$$

2.2   Antenna characteristics

Antenna gain and radiation pattern

The **power gain** G, or simply the gain, of an antenna is the ratio of its radiation intensity to that of an isotropic antenna radiating the same total power.

A radiation pattern plot for a generic directional antenna is shown in Figure 9, illustrating the **main lobe**, which includes the direction of maximum radiation (sometimes called the **boresight** direction) and several **side lobes** separated by **nulls** where no radiation occurs.

For a reflector antenna of diameter **D**, the maximum gain expresses as:

$$G_{max} = \eta \left(\frac{\pi D}{\lambda}\right)^2 = \eta \left(\frac{\pi D f}{c}\right)^2 \quad (\text{ratio})$$

where η is called the efficiency of the antenna.

The efficiency η of the antenna is the product of several factors which take account of the illumination law, spill-over loss, and surface impairments, resistive and mismatch losses etc.

Figure 9:   Antenna radiation pattern

Source: Satellite Communications Systems: Systems, Techniques and Technology; Maral, Bousquet, Sun, 2009

θ_{3dB} Beamwidth

The θ_{3dB} *beamwidth* is the angle subtended by the half-power points of the main lobe *(half-power beamwidth)*. This parameter is used to characterize the width of the beam or angular beamwidth. The 3dB beamwidth is related to the ratio λ/D.

For reflector antennas, the coefficient depends on the illumination law. A common value is 70° when the illumination law introduces some tapering at the edge of reflector, which leads to the following expression for an antenna reflector of diameter *D*:

$$\theta_{3dB} = 70\left(\frac{\lambda}{D}\right) = 70\left(\frac{c}{fD}\right) \quad \text{(degrees)}$$

In a direction θ with respect to the boresight, the value of gain is given by:

$$G(\theta)_{dBi} = G_{\max,dBi} - 12\left(\frac{\theta}{\theta_{3dB}}\right)^2 \text{(dBi)}$$

2.3 For a same antenna size, Ka-band offers higher throughputs

This illustrates firstly that *C/N$_o$* is proportional to the square of the link frequency, and thus lower frequencies suffer from lower performance if a similar antenna size is used (all other things being equal).

When replacing in the formula of the link budget above the antennas gain G_t and G_r by their expression as a function of antenna diameter *D* and frequency *f*, the *C/N$_o$* expresses as:

$$\frac{C}{N_0} \propto \left(D_S D_T f\right)^2 \frac{1}{L_{atm}} \frac{1}{T} \quad \text{(Hz)}$$

where
D: Diameter of the antennas (S: satellite, T: terminal)
f: Frequency
L$_{atm}$: Atmospheric loss
T: System noise temperature at receiver side

This provides an advantage to Ka frequency systems as the frequency is higher, hence achieving a greater throughput for a given antenna size, or enabling the usage of smaller and cheaper user terminals for a given throughput.

2.4 Ka-band enables narrower beams and therefore higher throughputs

As the size of the satellite antenna is constrained by the launch vehicle fairing, the use of higher frequencies lead to narrower beams:

- Ku typical achievable beamwidth: Between 0.8° and 2°
- Ka typical achievable beamwidth: Less than 0.5°

The use of Ka frequencies therefore enables narrower beams and higher *C/N$_o$* than Ku frequencies and therefore higher throughputs.

The beamwidth is a function of the satellite antenna diameter:

$$\theta_{3dB} = 70\left(\frac{\lambda}{D}\right) = 70\left(\frac{c}{fD}\right) \text{(degrees)}$$

It can be shown that the link performance grows in inverse proportion to the width of the beam:

$$\frac{C}{N_0} \propto \frac{1}{L_{atm}} \frac{1}{T} \left(\frac{D_T}{\left(\theta_{3dB}\right)_S}\right)^2 \quad \text{(Hz)}$$

where $(\theta_{3dB})_S$ is the satellite antenna beamwidth.

Therefore, as mentioned earlier, narrower beams have higher *C/N$_o$* ratios than wider spot beams. The size of the beam depends on the ratio of satellite antenna diameter by the link frequency.

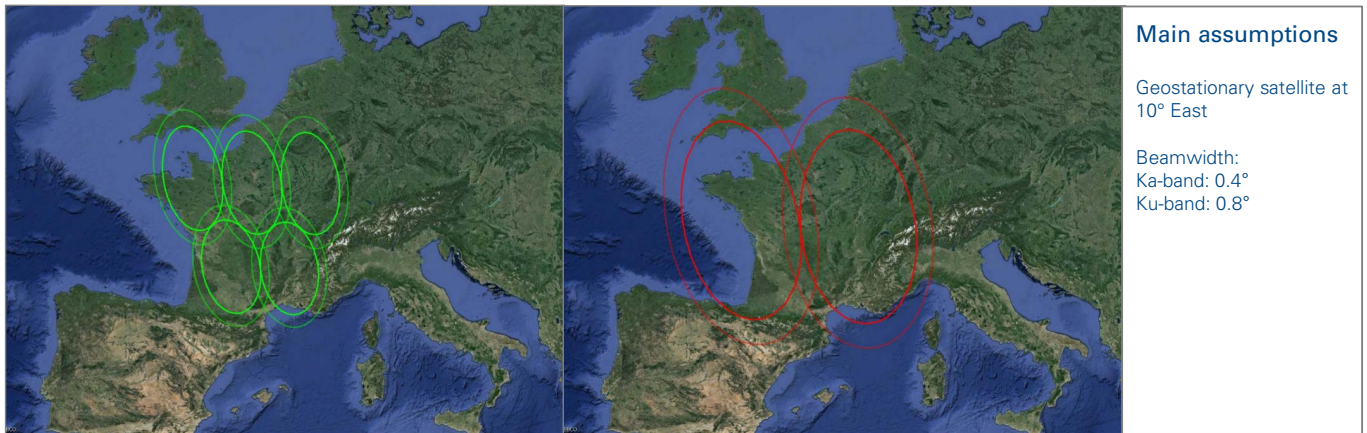$$\theta_{3dB} \propto \frac{1}{fD_S}$$

2.5 Ka-band enables more reuse of frequency and therefore more capacity

Another direct effect of the narrower beams enabled by Ka frequencies is the possibility to tessellate more beams on a given area than with Ku frequency (typically with a ratio of 2 to 5 as illustrated in figure 10 below). This leads to higher potential frequency reuse, even if orbital spectrum allocations are similar (though this is usually not the case). Therefore the total capacity that can be delivered into a specific geography is much greater.

2.6 Ka-band is more sensitive to severe atmospheric perturbations. However, these only occur during very limited time periods

The parameter 'Atmospheric Loss' that appears in the formula above influences HTS system performance and is dependent on the frequency of operation. Atmospheric losses are effectively determined by climatic conditions, and higher frequency systems are more susceptible to high intensity rain fall rates corresponding to extreme weather conditions. However these conditions occur for a small proportion of time in most regions of the world.

Figure 10:   Typical -3dB and -5dB spot beams. Comparison between Ka-band (left) and Ku-band (right)

Main assumptions

Geostationary satellite at 10° East

Beamwidth:
Ka-band: 0.4°
Ku-band: 0.8°

Source: Avanti Communications

The parameter 'System Noise Temperature' also appears in the C/N_o formula and influences HTS system performance. As explained in section 2.1, this parameter is conditioned mainly by the antenna noise temperature and the effective noise temperature of the receiver. On the uplink, the noise of the satellite receiver increases slightly with frequency but by an amount which is much less than the benefit resulting from the use of narrow beams at Ka-band. On the downlink, the antenna noise temperature of the ground receiver is increasing with the atmospheric loss.

To this respect, we have calculated the link budgets on the forward and return links for customers located in typical locations across Europe and Africa, taking into account the typical weather conditions at each location.

We have made the following assumptions:

Figure 11: Main assumptions for link budget comparisons between Ka-band and Ku-band systems

| ASSUMPTIONS		Forward (outroute)		Return (inroute)		
		Ka-band	Ku-band	Ka-band	Ku-band	Note
Satellite link						
Transponder bandwidth	MHz	220	72	220	72	Typical
Carrier symbol rate	MBaud	209.000	68.400	3.129	1.024	Single carrier per channel on the outroute, equivalent carrier bandwidth percentage on the inroute
Carrier bandwidth	MHz	219.450	71.820	3.911	1.280	Filter roll-off is 5% for outroute, 25% for inroute
Carrier bandwidth as percentage of transponder bandwidth	%	99.75%	99.75%	1.78%	1.78%	Calculated
Air interface standard	-	DVB-S2X	DVB-S2X	DVB-RCS2	DVB-RCS2	Next generation air interface standards
Uplink frequency	GHz	28.4	14.0	28.4	14.0	Typical
Downlink frequency	GHz	18.4	11.8	18.4	11.8	Typical
Satellite longitude	°	10.0	10.0	10.0	10.0	Assumed
Gateway antenna						
Antenna diameter	m	9.2	9.2	9.2	9.2	Typical
Antenna amplifier	W	1000	650	-	-	Typical
Uplink EIRP density (for nominal weather conditions)	dBW/MHz	57.68	57.68	-	-	Typical
System noise temperature (for nominal weather conditions)	K	-	-	~ 300	~ 230	Estimated
User terminal						
Antenna diameter	m	0.96	0.96	0.96	0.96	Typical
Antenna amplifier	W	-	-	2.0	2.0	Typical
Uplink EIRP density (for nominal weather conditions)	dBW/MHz	-	-	45.1	45.1	Typical
System noise temperature (for nominal weather conditions)	K	~ 220	~ 170	-	-	Depends on user terminal elevation angle
Satellite						
User beam beamwidths	°	0.62	0.95	0.40	0.80	Chosen to define 0.4° and 0.8° beamwidth for Ka- and Ku-band satellites in the return direction. Calculated from corresponding required antenna diameter for the forward direction
Antenna diameter	m	1.85	1.88	1.85	1.88	Calculated from return direction user beam beamwidths
TWTA power	W	140	140	140	140	Typical
System noise temperature	K	~ 500	~ 440	~ 500	~ 440	Estimates

The following figures illustrate the results for the specific location of Brent Field, North Sea.

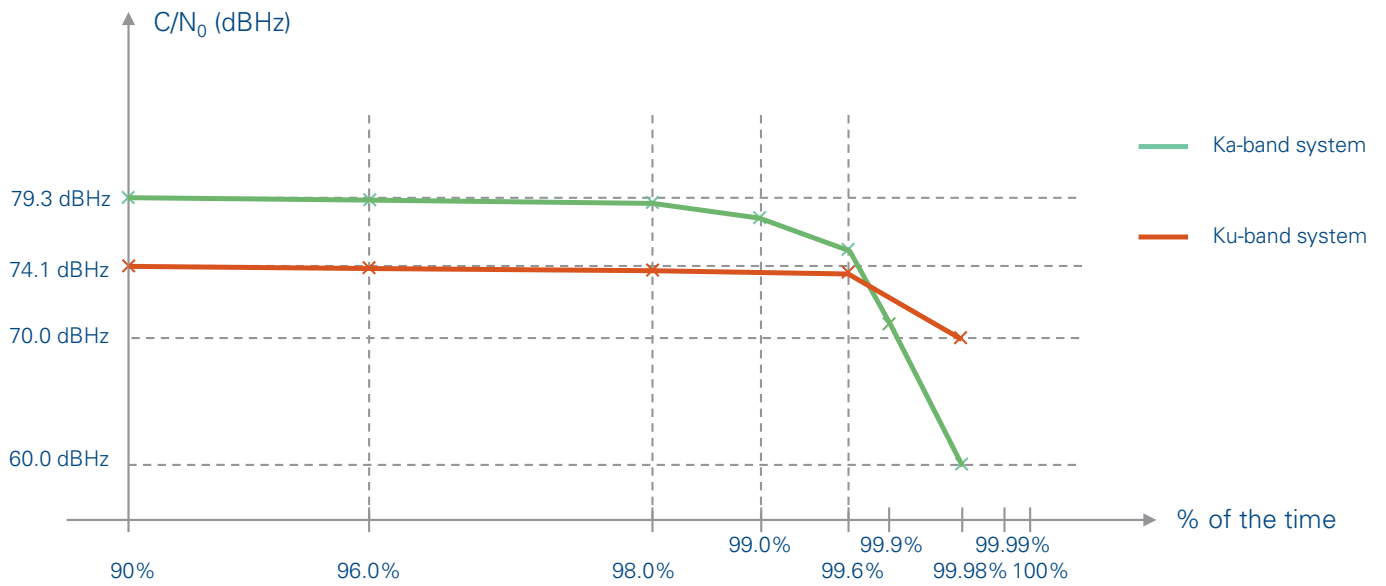**Figure 12: C/N$_0$ comparison between Ka-band and Ku-band systems on the forward link**
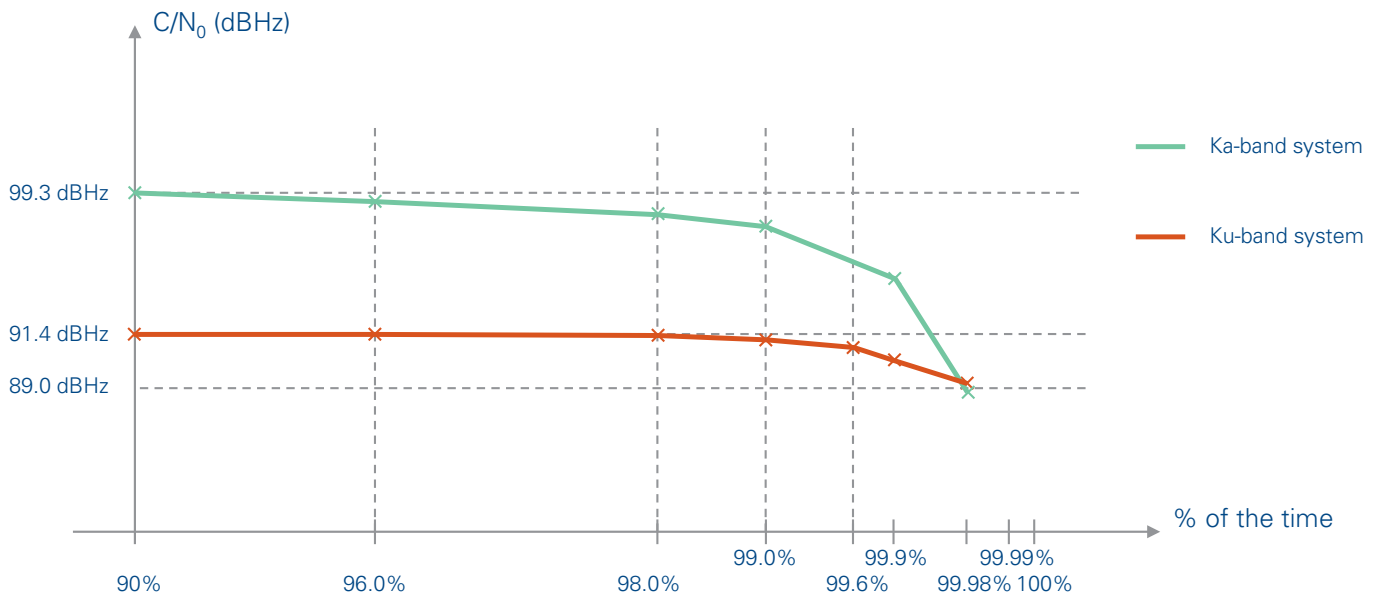
Source: Arthur D. Little analysis, Avanti Communications

**Figure 13: Throughput comparison between Ka-band and Ku-band systems on the forward link**
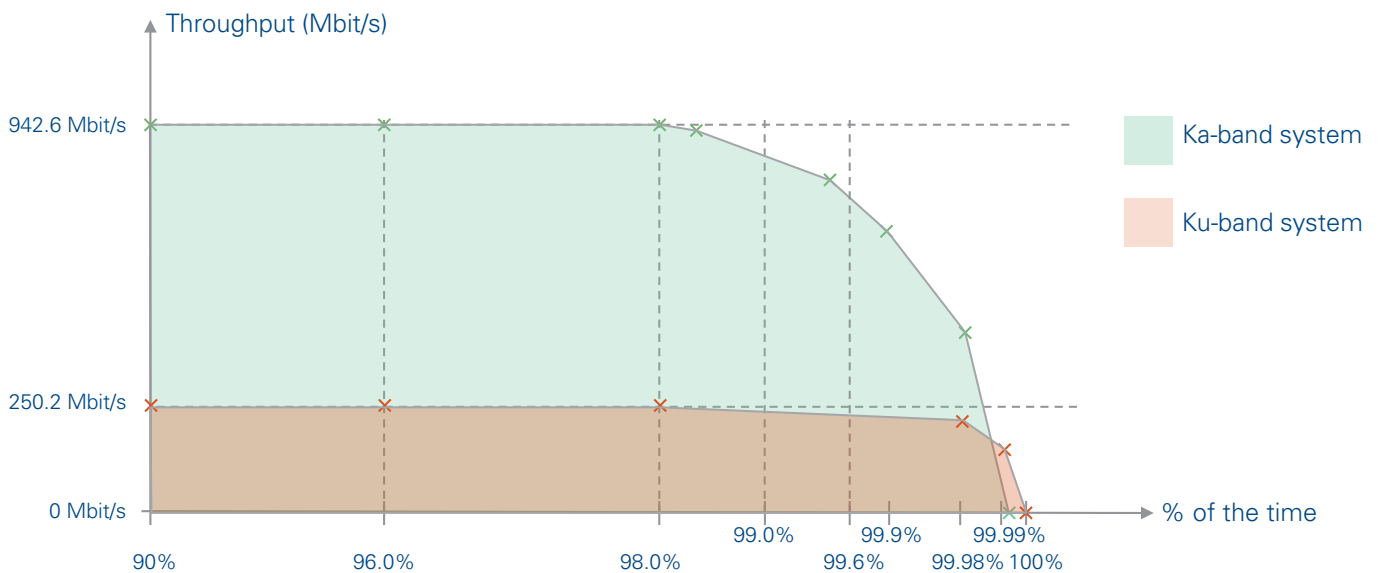
Source: Arthur D. Little analysis, Avanti Communications

Figure 14: C/N_0 comparison between Ka-band and Ku-band systems on the return link

Source: Arthur D. Little analysis, Avanti Communications

Figure 15: Throughput comparison between Ka-band and Ku-band systems on the return link
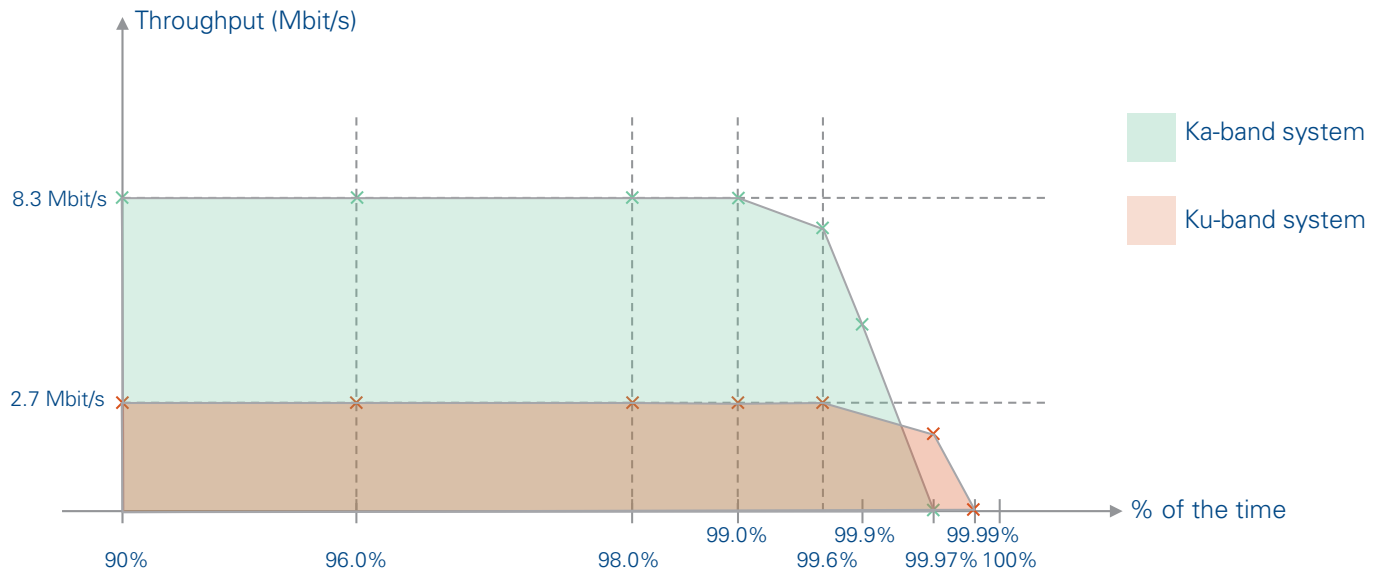
Source: Arthur D. Little analysis, Avanti Communications

Figure 16: Compared throughput of links using Ka-band and Ku-band frequencies

RETURN DIRECTION	Ka-band			Ku-band		
Location	Link availability [%]	Typical throughput per carrier [Mbit/s]	Average throughput per carrier, taking in account link availability [Mbit/s]	Link availability [%]	Typical throughput per carrier [Mbit/s]	Average throughput per carrier, taking in account link availability [Mbit/s]
Toulouse, France	99.97%	8.344	8.328	99.99%	2.731	2.731
Abuja, Nigeria	99.88%	8.344	8.280	99.99%	2.731	2.730
Cape Town, South Africa	99.98%	8.344	8.334	99.99%	2.731	2.731
Brent Field, North Sea	99.97%	8.344	8.326	99.99%	2.731	2.731
Lochinver, UK	99.97%	8.344	8.329	99.99%	2.731	2.731
In Amenas, Algeria	99.99%	8.344	8.343	99.99%	2.731	2.731
London, UK	99.97%	8.344	8.332	99.99%	2.731	2.731

FORWARD DIRECTION	Ka-band			Ku-band		
Location	Link availability [%]	Typical throughput per carrier [Mbit/s]	Average throughput per carrier, taking in account link availability [Mbit/s]	Link availability [%]	Typical throughput per carrier [Mbit/s]	Average throughput per carrier, taking in account link availability [Mbit/s]
Toulouse, France	99.99%	942.561	941.075	99.99%	250.228	250.087
Abuja, Nigeria	99.98%	942.561	939.533	99.99%	250.228	250.070
Cape Town, South Africa	99.99%	982.041	978.422	99.99%	250.228	250.168
Brent Field, North Sea	99.99%	942.561	940.214	99.99%	250.228	249.771
Lochinver, UK	99.99%	942.561	940.373	99.99%	250.228	249.996
In Amenas, Algeria	99.99%	982.041	981.705	99.99%	250.228	250.222
London, UK	99.99%	942.561	941.481	99.99%	250.228	250.135

Source: Arthur D. Little analysis, Avanti Communications

On the most sensitive link (the return link) and during fair weather conditions (clear sky) which occur 95% of the time, the Ka-band systems are able to deliver higher throughput than Ku-band systems in all locations (for a given percentage of transponder bandwidth).

For more than 99.9% of the time in the majority of customer locations, the Ka-band systems will be able to provide a better throughput than an equivalent Ku-band system. We can therefore conclude that for the majority of customer locations, the conditions offsetting the otherwise higher efficiency of a Ka-band system are occurring for less than 0.1% of the time. For example, in Brent Field, North Sea (as presented in Figure 15), the Ka-band system will provide a lower throughput for only 0.04% of the time. This slightly reduces the average throughput obtained per carrier on the Ka-band system compared to the typical throughput, but by looking at Figure 16, it is clear to see that the average throughput obtained is still much larger for the Ka-band system compared to the Ku-band system (for a given percentage of transponder bandwidth). This conclusion is even more valid when looking at the forward link, where it can be seen that on average the Ka-band link delivers approximately 700 Mbit/s more than the Ku-band link.

2.7   Mitigating techniques offset the atmospheric losses on Ka-band frequencies

Overall the improvement in C/N_0 derived from using the higher frequency bands outweighs any disadvantages from atmospheric losses and system noise, for almost all of the time, in the majority of customer use locations. This confers spectral performance advantage to higher frequency Ka systems in many locations, except where frequent extreme weather events are

experienced. Even in that case, additional mitigating strategies (such as the use of Uplink Power Control, Adaptive Coding and Modulation, and Diverse Gateway Sites) are routine to improve the link performance and make the situation effectively transparent to the end user.

Ka-band Broadband Satellite Systems can take advantage of a combination of the following Fade Mitigation Techniques. These techniques support and improve different links in the overall communication.

Thus potential users of future HTS systems should take into account the higher overall spectral efficiency of Ka-band systems, and consider carefully the relevance of driving parameters relative to their actual use case and deployment site.

Figure 17:   Mitigating techniques used to offset the atmospheric losses

Technique	Description	Improvement on			
		Forward link		Return link	
		Up	Down	Up	Down
Larger antennas at gateways	The gateways use large antennas (typically 9.2m). This means that the power received and transmitted by the gateway is increased.	✓			✓
Powerful amplifiers	The gateways use high-power amplifiers that can supply the antenna with large amounts of power.	✓			
Uplink Power Control (UPC)	The intent of the uplink power control is to maintain a constant level of uplink flux density as received by the satellite. Gateway uplink power control methods have been developed that strive to maintain a constant uplink power level when the feeder link is exposed to weather events as received by the satellite. Beacon signals are transmitted from the satellite and received by the ground earth station. The gateway uplink power control system then analyses the received beacon signals and increases the transmitter power to effectively compensate for the increased Ka-band attenuation caused by the rain event. The dynamic range at the gateway could be up to 10 dB. Up link power control is also considered at the User Terminal side, but because of power limitation of the amplifier, the dynamic range is much less, about 3 dB. Also it is difficult to measure how much rain attenuation there is on the link and the command is sent by the gateway through signalling.	✓		✓	
End-to-end Power Control (EEPC)	With conventional transparent repeaters, the overall link budget (C/No) total is a combination of up and down link budgets. In the case of one carrier per transponder and thanks to the dependency of the downlink budget with the uplink budget, the adjustment of output power of the transmitting earth station (Gateway) can be used to mitigate impairments occurring on either or both uplink and downlink. EEPC aims at keeping a constant margin on the overall link budget. As for UPC, transmitter power is increased to counteract fade or decreased when more favourable propagation conditions are recovered to limit interference and optimise satellite capacity.	✓	✓		
Automatic level control (ALC)	With ALC, the gain of the channel amplifier of the satellite repeater is adjusted depending on the level of the uplink signal going through the amplifier. This ensure that same amount of power is downlinked to the Earth, regardless of the amount of atmospheric loss on the uplink (Satellite EIRP is kept constant), and therefore the downlink budget (C/No)down -and the power received on ground- remains the same. It should be noted that this does not entirely negate the effect of atmospheric loss experienced on the uplink as the overall link budget is impaired by the reduction of the uplink budget (C/No)up.		✓		
Adaptive Coding And Modulation (ACM)	With digital communications, the use of channel coding allows a reduction of the required energy per bit (or symbol) to obtain a given error rate. Adaptive Coding consists in implementing a variable coding rate matched to impairments originating from propagation conditions. Higher system capacity for a given bandwidth can be achieved using high order modulation schemes that provide a large spectral efficiency at the expense of an increasing value of energy per bit. As Adaptive Coding, the aim of Adaptive Modulation is to use a modulation scheme requiring less energy per bit when the links suffers from fading. However, this translates into a reduction of the spectral efficiency. Almost all of today's satellite systems use ACM. For a given available link budget, the terminal will be transmitting data using a certain modulation and coding (MODCOD) scheme. The systems will attempt to transmit using the most efficient MODCOD, which whilst resulting in the greatest throughput, requires a given minimum energy per bit and therefore specific C/N0. When atmospheric losses increase and the specific C/N0 can no longer be achieved, the system will decide to transmit using a more robust but less spectrally efficient MODCOD, thus 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 used both on the forward link by gateway and on the return link by the user terminal. Terminals in the same beam will use different MODCOD, because large rain fades tend to be highly localized in space.	✓		✓	
Dynamic Rate Adaptation (DRA)	The symbol rate of each terminal is adaptively tuned to meet the current link situation determined by channel conditions changes. The goal of adaptation is to give each terminal the highest possible Symbol Rate that the link may support, while preserving operating margin enough to compensate short term fluctuations. The rate is matched to propagation condition: nominal rates are used under clear sky conditions, whereas reduction is introduced according to fade levels. Differently from UPC which aims at restoring the Carrier-to-Noise Ratio (C/No) through an increase of the ground station transmitted power, Adaptive Coding and Modulation as well as Dynamic Rate Reduction allow a decrease in the required C/No while maintaining the link performance in terms of BER.				
Diverse gateway sites	The objective of diversity is to re-route information in the network in order to avoid impairments due to an atmospheric perturbation. Gateway diversity takes advantage of the fact that two fades experienced by two GWs separated by a distance higher than the size of a convective rain cell (at least 10 km), are statistically independent. The gateway in better conditions is used and the information is routed to the original destination through a separated terrestrial network. The technique requires the replication of the gateway, and therefore increases the cost of the earth segment. It may not be necessary to double the total number of gateways of the satellite system by considering a smart redundancy approach where a number of gateways are inter-connected with terrestrial links to form an agile routing of feeder link data. In the event of a gateway experiencing outage or reduced capacity, some or all user traffic can be re-directed terrestrially to any one or several of the remaining gateways, as long as the gateways are within the feeder link coverage.	✓			✓

Source: Arthur D. Little analysis, Avanti Communications

3. Key conclusions

We derive four main conclusions from this detailed review and technical assessment of HTS systems.

3.1 Satellite technology will remain crucial for connectivity

Despite the steady growth in terrestrial networks, there remain locations all over the world where secure, resilient and configurable transmission links of sufficient capacity at diverse customer locations can only be provided through satellite links. Furthermore, satellites provide useful distinct capabilities, including broadcast capabilities, and a useful alternative connection path for fully resilient supply of connectivity services.

The potential to upgrade ground segment infrastructure, the accelerated build and launch times and the fact that beams can be steered and thus redeployed to other areas allows satellite providers to respond to changing client requirements, hot zones of demand and shifts in the balance of supply via other routes and technologies.

3.2 Future HTS systems will impact the satellite communication industry

HTS systems have transformed the satellite communications industry in recent years by enabling much higher capacities at more affordable costs, which in the consumer and business segments for example are similar to the capacities and costs provided by DSL lines.

Several further HTS programs are underway for launch in the coming years. These future HTS systems will further extend footprints, significantly increase the total capacity available and accelerate the trend towards more affordable and higher capacity to effectively and efficiently meet the demand for satellite data transmission.

3.3 New bands (Ka) yield further capacity and performance

Two typical frequency bands are available for HTS systems, i.e. the Ku-band (lower) and Ka-band (higher). The size of the Ka-band, and the relative availability of spectrum within it make it a key contributor to future supply.

Overall the improvement in C/N_o derived from using the higher frequency bands outweighs any disadvantages from atmospheric losses and system noise for almost all of the time, in the majority of customer use locations. This confers spectral performance advantage to higher frequency Ka systems in many locations, except in scattered locations where frequent extreme weather events are experienced. Even in that case, additional mitigating strategies (such as Uplink Power Control, Adaptive Coding and Modulation, and Diverse Gateway Sites) are routinely used to improve the link performance and make the situation effectively transparent to the end user.
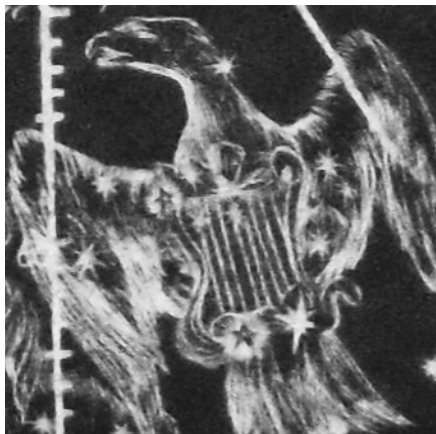
Thus potential users of future HTS systems should take into account the higher overall spectral efficiency of Ka-band systems, and the general higher performance of this frequency band for most of the time and consider carefully the relevance of driving parameters relative to their actual use case and deployment site.

In addition, the combination of larger availability of spectrum in the Ka-band and the narrower beams enables satellite operators to propose more capacity at these frequencies, for a generally more competitive price.

3.4 Impact for users

If the choices available – in terms of geographic footprint, performance, and cost – are many, it is increasingly important for users to carefully consider their actual use case requirements. Here the Ka-band frequencies have multiple advantages over the Ku-band for high-capacity systems, in many deployment scenarios considered.

Satellite communications remains one of the most technically advanced industries, leveraging the very latest technology to continually increase the capabilities, capacity and performance delivered to its customers, where and when they need it.

Contacts

Arthur D. Little

Arthur D. Little has been at the forefront of innovation since 1886. We are an acknowledged thought leader in linking strategy, innovation and transformation in technology-intensive and converging industries. We navigate our clients through changing business ecosystems to uncover new growth opportunities. We enable our clients to build innovation capabilities and transform their organization.

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