SATELLITE COMMUNICATION SYSTEMS

Module 3

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**SATELLITE FREQUENCY BANDS**

- The frequencies are selected from bands that are most favorable in terms of interference effects.
- Frequencies distributed by **International Telecommunications Union (ITU)**
- broadcast regulations controlled by **World Administrative Radio Conference (WARC)**.

- **The basic objective** of these agencies are:
  - to allocate particular frequency bands for different satellite services
  - to provide international regulations in the areas of maximum radiation levels from space
  - coordination with terrestrial systems
  - the use of specific satellite locations in a given orbit.

- Use of frequencies has been separated into **military and nonmilitary**

- services have been designated as
  - fixed-point (between ground stations located at fixed points on Earth),
  - broadcast (wide-area coverage)
  - mobile (aircraft, ships, land vehicles).
• early satellite technology was developed for UHF, C-band, and X-band.

**Problem:**
- inadequate b/w Interference
- serious orbital congestion

**Advantages** of higher K-band and V-band frequencies
- more spectral bandwidth
- negligible terrestrial interference
- closer orbital spacing
- ability to modulate more information

eg: A carrier at 30 GHz can carry 5 times the information of a C-band carrier.
Uplink and downlink frequencies
<table>
<thead>
<tr>
<th>Band</th>
<th>Downlink, GHz</th>
<th>Uplink, GHz</th>
<th>Bandwidth, MHz</th>
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A satellite comm. network consists of a number of earth stations interconnected via a satellite. The radio links are designed to deliver messages at the destination with acceptable fidelity.

Factors for link design:
- operational frequency
- propagation effects
- acceptable spacecraft/ground terminal complexity (hence cost)
- effects of noise and regulatory requirements.

The source-to-destination path can be partitioned as:
- the earth station-satellite link or uplink
- the satellite path
- the satellite-earth station link or downlink.
SATELLITE LINK
A basic element in a satellite communication link is the **antenna**.

**Antenna basics:**

The power is received / transmitted by an antenna in the desired direction via **main lobe**

some energy is also received / transmitted in unwanted directions through the **side lobes**.

Power transmitted through the side lobes can cause interference in other radio systems and in turn may receive interfering signals.

The half-power beam width, $\psi_{hp}$, depends on the aperture distribution, antenna diameter and operating frequency

$$\psi_{hp} = \frac{N\lambda}{D}$$

where $N$ is a constant dependent on aperture distribution

- $N \approx 58$ for uniform distribution
- $N \approx 70$ for tapered distribution

$D$ and $\lambda$ are antenna diameter and operational wavelength
• The **radiation intensity**, $P(\theta, \varnothing)$ in the direction $(\theta, \varnothing)$ is defined as the power radiated from antenna per unit solid angle in that direction.

**Antenna directivity**, $D(\theta, \varnothing)$ is a measure of focusing property = $P(\theta, \varnothing)/P_{av}$

Where $\theta$ = elevation
$\varnothing$ = azimuth
$P_{av}$ = average radiation intensity = $Pr / 4\pi$
$Pr$ = total radiated power from an antenna.

In an antenna some power is lost due to energy spill-over, blockage of RF energy by sub-reflectors and supporting structures, manufacturing defects, ohmic and reflection losses.

**Such losses reduce the antenna gain and hence efficiency.**

The gain function, $G(\theta, \varnothing) = \eta D(\theta, \varnothing)$

Hence

$$G(\theta, \varnothing) = P(\theta, \varnothing) / (P_i/4\pi)$$

Where $P_i$ = power fed into an antenna.
$\eta = 1$ (lossless radiator)
isotropic radiator:

Pi /4π can be viewed as the radiation intensity produced by a lossless radiator (η =1) capable of transmitting uniformly in all directions, when fed with power Pi

\[ G = 4\pi \eta A / \lambda^2 \]

where A = aperture area of antenna
\[ \lambda = \text{wavelength of operational frequency} \]

\[ G = \eta \ 4\pi A / \lambda^2 \]

Where \( \eta \) = antenna efficiency
\[ \eta A = \text{the effective aperture of the antenna.} \]

Typical parabolic antennas, the value of \( \eta \) is between 50% and 70%.

For some types of horn antennas, the efficiency can be as high as 90%.
The polarization of an electromagnetic wave describes the orientation of the electric field vector in space.

A **linearly polarized** wave has an electric field vector oriented at a constant angle with respect to the horizontal or vertical axis, as it travels in space.

when the electric field vector is parallel to the horizon, it is **horizontally polarized**
when the electric field is vertical, the wave is **vertically polarized**.

The electric field vector of a **circularly polarized** wave describes a circle on a plane at right angles to the direction of propagation.

The rotation is clockwise for a **right-hand circularly polarized** wave and counter-clockwise for a **left-hand circularly polarized wave**
Dual Polarized antenna

Omni directional Antennas
Transmission equation

The transmission equation relates
the received RF signal power to the RF power transmitted, the transmission frequency, and the transmitter-to-receiver distance

for an isotropic radiator, the received power flux density at a distance D from the source is

$$P_{FD} = \frac{P_s}{4\pi D^2} \text{ W/ m}^2$$

Where $P_s$ = transmitted power from isotropic source
$4\pi D^2$ = surface area of a sphere of radius D.

When the isotropic antenna is replaced by an antenna of gain $G_s$, the $P_{FD}$ in the direction of antenna bore sight is increased by $G_s$.

$$P_{FD} = \frac{P_s G_s}{4\pi D^2} \text{ W/ m}^2$$
The product $P_s G_s$ is known as the **effective isotropic radiated power (EIRP)** of the transmitter.

Then,

$$P_{FD} = \frac{\text{EIRP}}{4\pi D^2} \ \text{W/m}^2$$

The expression for EIRP (in dB) is

$$\text{EIRP} = 10 \log (G_s) + 10 \log (P_s) \ \text{dBW}$$

The power flux density (in dB) is given by

$$P_{FD} = \text{EIRP} - 10 \log (4\pi D^2) \ \text{dBW/m}^2$$

The carrier power $C$ received at the destination with an antenna of area $A_d \ \text{m}^2$

$$C = P_{FD} A_d \ \text{watts}$$

In practice some power is lost in the antenna, hence

$$C = \eta A_d P_{FD} \ \text{watts}$$

Where $\eta$ is the efficiency of the antenna.
In terms of commonly used parameters of a communication link

\[ A_d = G_d \lambda^2 / 4 \pi \eta \]

Substituting for \( A_d \) and \( P_{FD} \), we obtain

\[ C = P_s G_s G_d [\lambda / 4\pi D]^2 \]

\[ \text{------------------- 1} \]

Again, expressing logarithmically

\[ C = P_s (dB) + G_s (dB) + G_d (dB) - 20 \log [4\pi D / \lambda] \]

\[ \text{------------------- 2} \]

The term \( 20 \log [4\pi D / \lambda] \) is known as the free space path loss.

*These equations are transmission equations.*
Typical Satellite Link
Noise Considerations

Noise introduces a fundamental limit on the capacity and performance of any communication system.

A. Thermal noise

All active devices used in a communication system introduce thermal noise.

The mean square voltage of noise,

$$e^2_n (t) = 4kTB_nR \text{ (volt)}^2$$

where $k$ = Boltzmann’s constant
$T$ = absolute temperature of resistance
$B_n$ = measurement bandwidth
$R$ = resistance.

Maximum power $p_n$, is transferred when a load is matched to the noise generator,

$$P_n = \frac{e^2_n (t)}{4R} = KTB_n \text{ watt.}$$
Thermal Noise

- Electrons in conductors *vibrate* because of their non-zero temperature.
- The vibrations cause small *voltages* across the conductor terminals.
Sources of Thermal Noise

Physical Temp of Line = $T_L$

Sky Temp $\sim$50 -150o K

Ground Temp $\sim$300o K

Temp of Receiver $T_R$

Physical Temp of Antenna $T_{AP}$

Temp of Receiver $T_R$
**Noise figure**

It is the ratio of the signal-to-noise power ratio at the input to the output

\[ F = \frac{P_i / N_i}{P_0 / N_0} \]

\[ = \frac{N_0}{GkT_iB_n} \]

Where \( P_i \) = available input signal power

\( N_i \) = available input noise power  =  \( kT_iB_n \)

\( T_i \) = ambient temperature in Kelvin

\( P_0 \) = available output signal power = \( GP_i \)

\( N_0 \) = available o/p noise power in a noise-free amp.

\[ = GkT_iB_n \]

\( G \) = average power gain over the specified frequency band.

An actual amplifier adds noise, \( \Delta N \)

Therefore,

\[ F = \frac{1 + \Delta N}{GkT_iB_n} \]
Noise Temperature

The noise temperature of an amplifier is defined as the temp, $T_e$, of a resistance which provides the same noise power at the output of an ideal amplifier as that given by an actual amplifier which has its input terminated at a noise-free resistance (i.e. $T_i = 0$).

$$F = (1 + \frac{T_e}{T_i})$$

When the ambient temperature is 290K

$$F = 1 + \frac{T_e}{290}$$

Or

$$T_e = 290 \left(F - 1\right)$$
noise temperature of a lossy networks

The loss factor \( L = \frac{P_i}{P_0} \)

The noise at the output of the attenuator is

\[
P_0 = (kT_iB_n / L )+ P_a
\]

where the first term is the attenuated input noise power, the second the noise introduced by the attenuator.

the equivalent noise temperature of the attenuator can be expressed as

\[
T_e = T_i \left(1 - \frac{1}{L}\right)
\]

when \( T_i = 290 \) K

\[
T_e = 290 \left(1 - \frac{1}{L}\right)
\]

Noise figure and noise temperature of networks in series

\[
T_e = \frac{T_1 + T_2}{G_1} + \frac{T_3}{(G_1G_2)} + \ldots + \frac{T_n}{(G_1G_2 \ldots G_{n-1})}
\]

Where \( T_n \) is the effective noise temperature

\( G_n \) the gain of the nth stage.

\[
F_n = \frac{F_1 + (F_2 - 1)}{G_1} + \ldots + \frac{(F_n - 1)}{(G_1G_2 \ldots G_n)}
\]

Where \( F_n \) is the noise temperature of the nth stage amplifier.
Antenna noise temperature

The antenna noise temperature is a measure of the noise entering a receiver via the antenna.

\[ T_a = \frac{1}{4\pi} \int \int G(\theta, \phi) \ T_b(\theta, \phi) \ d\Omega \]

Where \( d\Omega \) is an element solid angle subtended by a source at the antenna.

\[ G(\theta, \phi) \] - gain function of the antenna in the direction \( \theta, \phi \)

\[ T_b(\theta, \phi) \] - brightness temperature in the direction \( \theta, \phi \)

\( \theta, \phi \) - elevation and the azimuth angle of the antenna.

The average cosmic noise power decreases with frequency (negligible above 1000 MHz).

The noise temperature of the Sun depends on the frequency. The average noise temperature can be approximated as \( 12000f^{-0.75} \) K.

The average brightness temperature of the Moon is between 200 and 300 K.

For large antennas the noise introduced by rain attenuation dominates all other types of noise (above \( \sim 10\)GHz.)
System noise temperature
The system noise temperature is the summation of all noise components

\[ T_s = \left( \frac{T_A}{L} \right) + T_i \left( 1 - \frac{1}{L} \right) + T_r \]

Where
- \( T_i = \) ambient noise temperatures (assumed to be 290K)
- \( T_r = \) effective noise temperature of the receiver
Intermodulation noise

A major source of noise in a satellites communication system
It is generated by non-linearities in the high power amplifier stages

Two types of non-linearities exist
- amplitude non-linearity which causes AM-AM conversion,
- phase non-linearity which causes AM-PM conversion.

FDMA scheme used is particularly susceptible to this noise because many carriers use the transponder simultaneously
Interference

Sources of interference in a satellite communication system may be classified as *intra-system* and *inter-system*.

Intra-system interference

Caused by coupling of orthogonally polarized signals in a dual-polarized system. Occurs in earth station, satellite antenna, and feed systems. It is caused during propagation through rain and ice. Minimized by using well-designed earth station and spacecraft antennas.

Also occurs when the filters used for isolating adjacent satellites channels do not have sufficient roll-off characteristic. This can be minimized by using adequate guard bands and using well-designed channel separation filters. Also occurs while signals travelling via multiple paths in satellites.
**Inter-system interference**

**Interference** may occur between

- a satellite system and terrestrial systems
- or between two satellite networks whenever the same frequencies are shared.

The **procedures** to reduce intersystem interference involve

- the use of sharing constraints
- frequency coordination
- the use of regional or global pre-assigned plans.

**Sharing constraints** impose limits on

- transmission levels from terrestrial transmitters
- earth stations and satellites in certain bands
- services for which sharing is permitted.
Coordination involves
permitting coexistence of 2 networks sharing the same frequencies
mutual agreement (avoiding high power transmissions in a specific
section of the band)
allowing for entry of a certain amount of interference.

The use of a plan involves
using worldwide /regional plans developed for certain services.
assigning an orbital position, frequency, bandwidth and satellite power
making efficient use of orbital locations and RF spectrum.

The maximum single entry noise from external sources is limited to 4-6%.

A total interference noise budget of 20% is a reasonable compromise for most
purposes.
Link Parameters’ Impact on Service Quality

Service Quality = BER

\[ \text{Service Quality} = \frac{C}{N} \]

\( \text{Uplink EIRP} \quad \text{EIRP}_{\text{up}} \)
\( \text{Uplink Pattern Advantage} \quad \beta_{\text{up}} \)
\( \text{Transponder Gain Step} \quad \beta_{\text{down}} \)
\( \text{Downlink Pattern Advantage} \)
\( \text{Receive Antenna Gain} \quad G_{\text{rx}} \)

\( \text{Free Space Losses} \quad L_{\text{up}}, L_{\text{down}} \)
\( \text{Waveguide Losses} \quad L_{\text{wg}} \)
\( \text{Atmospheric Losses} \)
\( \text{Rain Attenuation} \)
\( \text{Tracking Errors} \)

\( \text{E/S Intermodulation} \quad C/T_{\text{hpalm}} \)
\( \text{Uplink Thermal Noise} \quad C/T_{\text{up}} \)
\( \text{Downlink Thermal Noise} \quad C/T_{\text{down}} \)
\( \text{Transponder Intermodulation} \quad C/T_{\text{imsat}} \)
\( \text{Co-Channel Interference} \quad C/T_{\text{co}} \)
**Link design**

The parameters affecting the link design may be categorized as:
- **Earth station related**
  - Satellite propagation channel

**Earth station related**

**Geographical location** provides an estimate of:
- rain fades,
- satellite look angle,
- satellite EIRP in the direction of the earth station
- earth station-satellite path loss.

**Transmit antenna gain** and **transmitted power** provide:
- the earth station EIRP.

**Receive antenna gain** and **System noise temperature** is:
- related to the sensitivity of the earth station.

**Intermodulation noise** affects the total carrier-to-noise ratio.

**Equipment characteristics** (cross-polar discrimination, filter characteristics)
- dictate the additional link margins.
Satellite related

Location of satellite - coverage region and earth station look angle.

Transmit antenna gain and radiation pattern provide the EIRP and coverage area.

Receive antenna gain and radiation pattern are related to the sensitivity and coverage area.

Transmitted power is related to the satellite EIRP.

Transponder gain and noise characteristics are related to EIRP and G / T.

Intermodulation noise affects the total carrier-to-noise power at the earth station receiver.

Transponder type (transparent /regenerative) affects the system noise budget.
Channel related

Operating frequency is related to path loss and link margin.

Modulation and coding characteristics govern the required carrier-to-noise ratio.

Propagation characteristics govern the link margin and the choice of modulation and coding.

Inter-system noise affects the system noise budget.
**Total carrier-to-noise ratio**

The carrier-to-noise ratio at the demodulator input is a function of the uplink and downlink EIRP, the noise introduced in the earth station receiver, the satellite link, and the amount of interference.

The total noise $N_T$ at the receiver is the summation of noise from all sources:

$$N_T = N_U + N_D + N_I + N_i$$

Where $N_U$ = uplink noise, measured at the satellite
$N_D$ = downlink noise, measured at the receiving earth station
$N_I$ = intermodulation noise in the satellite link
$N_i$ = sum of uplink and downlink interference noise.

The total carrier-to-noise ratio is then

$$C / N_T = C / (N_U + N_D + N_I + N_i)$$
Total carrier-to-noise ratio (regenerative transponder)

In a regenerative transponder, each part of the link is separate from the others.

The error probability $(P_e)_t$ is given as

$$(P_e)_t = (P_e)_u \left[ 1 - (P_e)_d \right] + (P_e)_d \left[ 1 - (P_e)_u \right]$$

$$\approx (P_e)_u + (P_e)_d$$

where $(P_e)_u$ is error probability in uplink

$(P_e)_d$ is error probability in downlink

Therefore, the overall error rate $BER_t$ is

$$BER_t = BER_u + BER_d$$
Received carrier power

In practice losses and link degradations must be considered.

Such degradations are compensated by transmitting additional power, termed link margin.

The main components considered in obtaining the downlink margin are:
- antenna tracking loss;
- atmospheric absorption;
- a statistical loss parameter due to hydrometers (mainly rain);
- a statistical loss parameter due to shadowing multipath when a mobile system is considered;
- a statistical loss parameter associated with scintillation;
- intra-and-inter-system interference;
- miscellaneous losses (wet random, equipment ageing, domodulator inefficiencies).
The transmission equation can be modified to

\[ C = P_e - L_p - L_m + G_d \] dB

Where

- \( C \) = received carrier power under worst-link conditions
- \( P_e \) = EIRP (dBW) [earth station or satellite]
- \( L_p \) = uplink path loss (dB)
- \( L_m \) = link loss under worst-link conditions
- \( G_d \) = destination antenna gain (dB) in the direction of the transmitter.

Uplink carrier-to-noise ratio

\[ \frac{C_u}{N_u} = (P_e - L_{pu} - L_{mu} + G_s) - 10 \log (kT_sB) \] dB

Or

\[ \frac{C_u}{N_u} = P_e - L_{pu} - L_{mu} + G_s - 10 \log (T_s) - 10 \log (kB) \] dB

The above equation can be rearranged as

\[ \frac{C_u}{N_u} = P_e - L_{pu} - L_{mu} + G_s / T_s - 10 \log (k) - 10 \log (B) \] dB

where

- \( P_e \) = earth station EIRP (dB)
- \( L_{pu} \) = uplink path loss (dB)
- \( L_{mu} \) = uplink loss under worst-link conditions (dB / K)
- \( G_s / T_s \) = G /T of the satellite in the direction of the earth station
- \( 10 \log (k) = -228.6 \) dBW/K.
The carrier-to-noise ratio expressed in per Hertz of bandwidth, is known as the carrier-to-noise power spectral density. The term $G_s / T_s$ is the figure of merit for measuring the receiver sensitivity.

**Downlink carrier-to-noise ratio**

$$C_d / N_d = P_s - L_{pd} - L_{md} + G_e / T_e - 10 \log (k) - 10 \log (B) \text{ dB}$$

where $P_s = \text{EIRP from satellite in the direction of the earth station}$

$L_{pd} = \text{downlink path loss}$

$L_{md} = \text{downlink loss under worst-link conditions}$

$G_e / T_e = G/T$ of destination earth station.

**Satellite path**

The noise in the link is dominated by

- the noise power introduced by the receiver
- the intermodulation noise introduced by the final stages of the amplifier.

The satellite EIRP is obtained as

$$P_s = C_i + G \text{ dBW}$$

Where $C_i = \text{received carrier level (dBW) at the satellite}$

$P_s = \text{satellite EIRP (dBW)}$

$G = \text{satellite gain (dB)}$

$G = Gr + GT + Gt$

$Gr = \text{receive antenna gain}$

$GT = \text{transponder gain}$

$Gt = \text{transmit antenna gain}$
Link design considerations

Applications may be
- the choice of satellite communications may be obvious /
- a satellite system may be favored in a complementary role.

In a satellite system implementation
- basic satellite system model is developed
- is refined further
- a business plan developed.

The most important aspect is
- the arrangement of capital to finance the project
- completion of applicable clearance and licenses.

The system is implemented

A mechanism is set to ensure reliable service and guarantee continuity.

Overall performance is monitored to ascertain its future viability and upgrades.
In a ‘no-risk’ approach
- leasing of transponders from operational satellites
- eliminating all risk & complexity of owning & operating a satellite.

Another planning approach
- include a certain degree of risk by opting for some innovation.

Advantages:
  - such as increased satellite lifetime
  - improvement in system capacity
  - resulting in reduction in cost/circuit,

INTELSAT has always included a significant amount of innovation in each generation of spacecraft

- maximizing the use of frequency
- vastly increasing the circuits offered.
VSAT link design example

- Very small aperture terminals
- small and inexpensive terminals
- mounted directly on customer’s premises
- direct communication between a central point and large number of remote points via a central hub
- fixed terminals hence considered to be a fixed satellite service.

Choice of frequencies

- VSAT network frequencies are chosen in the FSS band
- C(6/4 GHz), Ku (14/11 GHz) and Ka (30/20 GHz) bands
- small terminals hence sensitivity (i.e. G/T) is low
- Spread spectrum is used in C-band (sharing constraints are severe)
- Ku band very popular for VSAT applications.
  - sharing problem is less severe at the Ku band
- VSAT antenna sizes are smaller
Availability of link
- The factor affecting link availability in the Ku and Ka band is **rain fade**.
  - mitigated by providing a suitable link margin
  - channel coding (redundant bits are added)
  - Advanced techniques are emerging
    - use of regenerative transponders
    - non-geostationary constellations
    - very narrow spot beams

Channel quality
- any comm. n/w should provide an signal at acceptable quality to the user.
  - The parameter for specifying signal quality is
    - signal-to-noise ratio for analog signals
    - bit error rate for digital signals.
- VSATs are generally used for carrying digital signals.
- BPSK or QPSK modulation schemes with FEC using Viterbi or sequential decoding technique are often used.
Noise sources
- include thermal noise in the front-ends of satellite and station receivers
- intermodulation noise in the satellite transponder

Adjacent satellite interference
- Adjacent satellites sharing the same band contribute interference.
- they depends on
  . the EIRP and antenna pattern of the satellites
  . terminals sharing the band.

Cross-polar coupling
- occurs at earth station antennas, satellite i/p and o/p antenna
- induced in the atmosphere by rain and ice.
- Antennas can provide cross-polar isolation of the order of 25-30 dB.
- net effect is the sum of individual components of XPlt

\[(XPlt)^{-1} = ((XPI1)^{-1} + (XPI2)^{-1} + \ldots \ldots \ldots (XPIN)^{-1}
\]
Where XPI is expressed as the ratio number (not as decibel)
XPI (ratio) = 10XPI(db)/10
Adjacent channel interference
- depends on the guard band between adjacent carriers sharing the same transponder.

- two components of adjacent channel interference - uplink and downlink.
- uplink component is dependent on spectral overlap between carriers
- downlink component is by spectral spread occurring in the satellite transponder as a result of non-linearity.
- typical value of total adjacent carrier interference is of the order of <75 dB.

Adjacent transponder interference
- Interference can arise from carriers occupying adjacent transponders.
- In the uplink, if adjacent transponders is within the wanted VSAT carrier b/w.
- minimized by imposing a constraint on out-of-band transmissions

- In the downlink, spectral spreading of carriers in the adjacent transponder caused by transponder non-linearity
- Magnitude of this interference is >100 dB below the VSAT carrier.
Interference from terrestrial systems
- this problem in the Ku band is minimized by allocating a secondary status to terrestrial transmissions in a specific part of the band reserved for VSAT application.

Numerical example

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<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uplink frequency</td>
<td>14.5 GHz</td>
</tr>
<tr>
<td>Maximum hub earth station EIRP</td>
<td>55 dBW</td>
</tr>
<tr>
<td>Fade margin</td>
<td>6 dB</td>
</tr>
<tr>
<td>Total carrier-to-interference noise density ratio</td>
<td>70dB</td>
</tr>
<tr>
<td>Access</td>
<td>TDM</td>
</tr>
<tr>
<td>Modulation</td>
<td>BPSK</td>
</tr>
<tr>
<td>Coding</td>
<td>½ FEC Convolution Code</td>
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<tr>
<td>Space segment satellite location</td>
<td>700E</td>
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<tr>
<td>Elevation angle at edge of coverage</td>
<td>50</td>
</tr>
<tr>
<td>Satellite G/T</td>
<td>0 dB/K</td>
</tr>
<tr>
<td>EIRP/VSAT carrier</td>
<td>20 dBW</td>
</tr>
<tr>
<td>Transponder carrier-to-IM noise power density ratio</td>
<td>70dB</td>
</tr>
</tbody>
</table>
| Type of transponder                            | transparent
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