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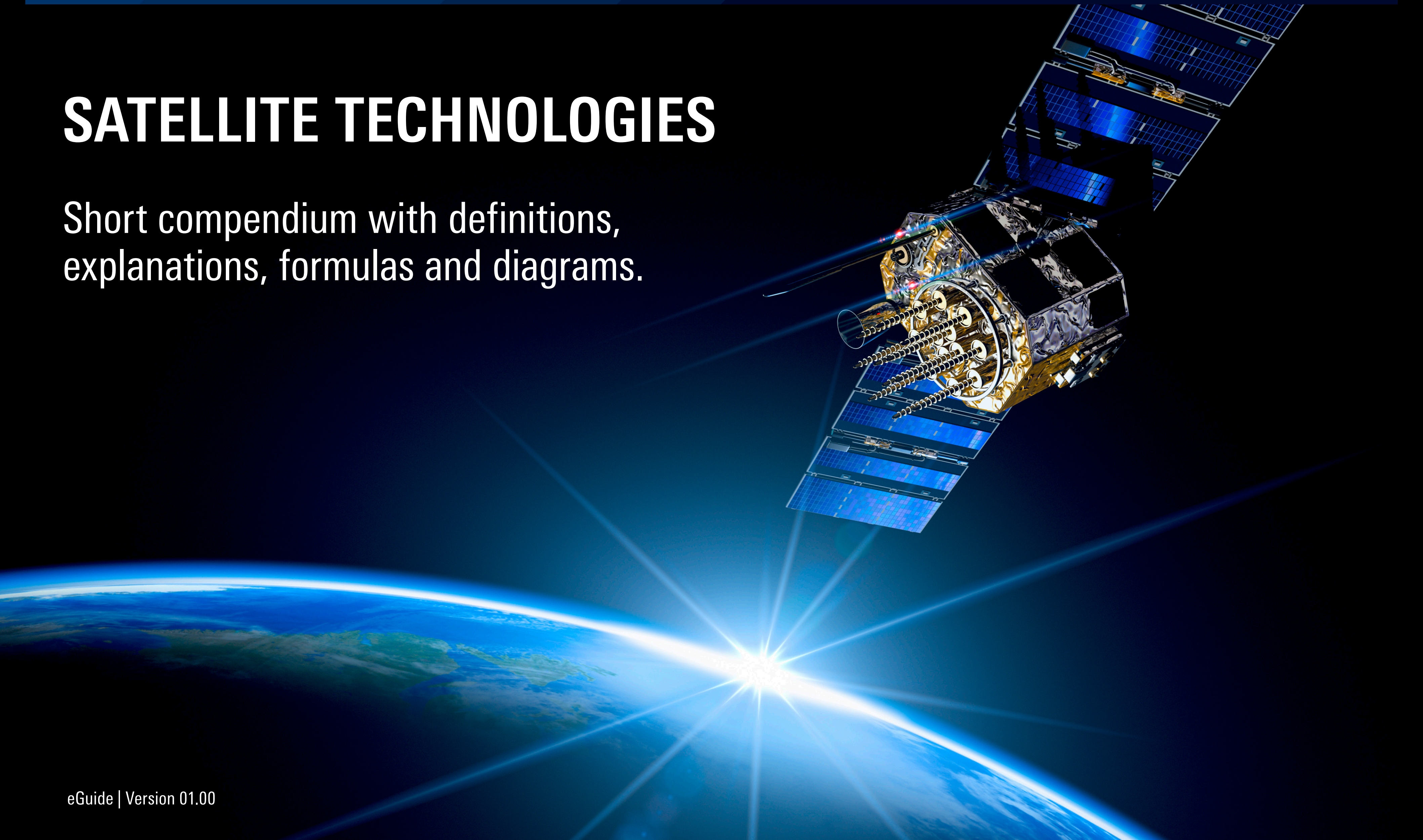
SATELLITE TECHNOLOGIES

Short compendium with definitions, explanations, formulas and diagrams.



eGuide | Version 01.00

This eGuide is a short compendium on the subject of satellite technology with definitions, explanations, formulas and diagrams.

Satellite technologies | eGuide

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Dr. Marco Krondorf studied information system technology at TU Dresden in Germany and graduated in 2005. In 2009, he received his PhD degree from TU Dresden. His research interests were mainly mobile multicarrier systems and the stochastic modeling of HF distortion effects.

In 2010, he co-founded the start-up INRADIOS. The company is specialized in the development of special-purpose satellite system technology for signal processing, signal monitoring and SATCOM system planning.

In 2017, INRADIOS was acquired by Rohde & Schwarz.

Since 2020, Marco Krondorf has been a full professor at Leipzig University of Applied Sciences (HTWK Leipzig) where he holds the chair for communications systems.

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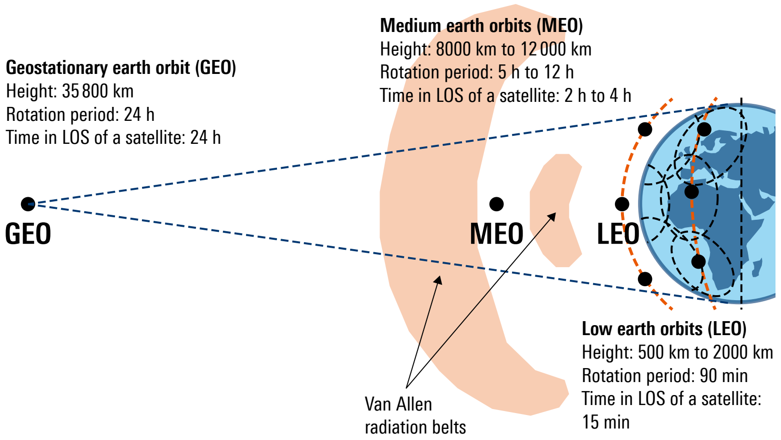
CONTENTS

SATELLITE OVERVIEW

Satellite orbits

Fig. 1: Overview of satellite orbits



Geostationary earth orbit (GEO)

Satellites are placed in an equatorial orbit at an altitude of 35 800 km above the earth's equator. In this orbit, spaceships co-rotate with the earth, i.e. the satellite position as seen from earth does not change. GEO SATCOM systems are often used for broadcast signal transmission.

Medium earth orbit (MEO)

Medium earth orbit covers a wide altitude range between LEO and GEO orbits. Spaceships in MEO typically support global navigation satellite systems (GNSS), communications as well as environmental and weather monitoring applications.

Low earth orbit (LEO)

Low earth orbit satellites are typically used for radar applications, environmental monitoring and communications. The new space industry has made LEO SATCOM affordable over the last decade, paving the way for satellite mega-constellations like Starlink or Amazon's Kuiper.

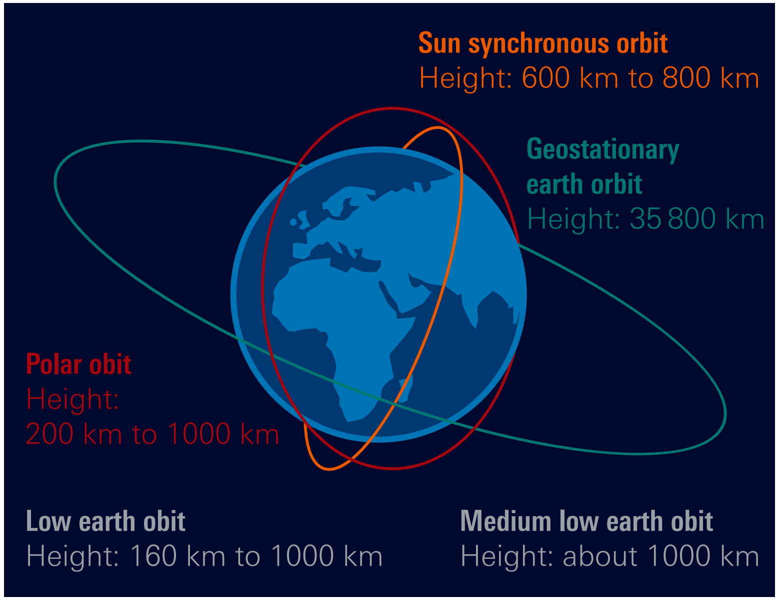
Polar orbit and sun synchronous orbit (SSO)

A polar orbit allows satellites to pass over the north and south poles. SATCOM systems in polar orbits usually provide global coverage. As a rule, polar orbits require a high inclination angle > 85° depending on the orbit altitude and beamwidth of the satellite antennas.

Larger launch vehicles are required to put satellites into a polar orbit compared to orbits with less inclination. This is because the launcher cannot utilize the earth's rotational velocity.

A special case of polar orbits is the solar synchronous orbit (SSO). SSO allows a spaceship to cross one specific location on earth at the same time every day. This is especially important for earth imaging since the solar exposition (sunlight angle) is always the same at the chosen location on earth.

Fig. 2: Polar orbit and sun synchronous orbits



Azimuth and elevation

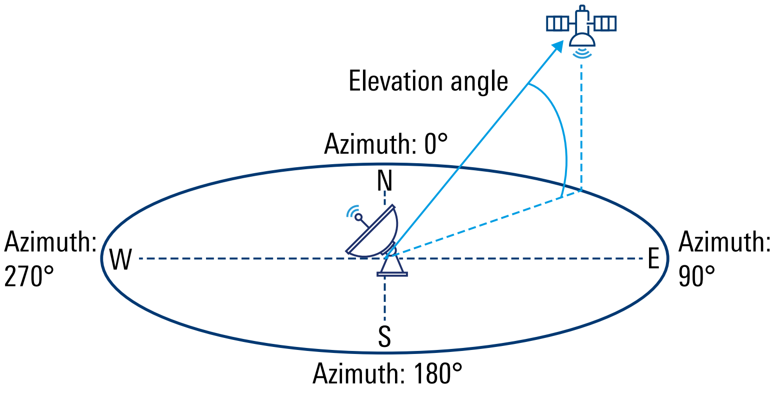
Geostationary earth orbit

Azimuth and elevation angle do not change over time.

Medium earth orbit and low earth orbit

Azimuth and elevation angles are time-varying during a satellite overflight.

Fig. 3: Azimuth and elevation angle



Satellite ground path

Field of view
The field of view (FOV) defines the area on the ground inside which the electromagnetic waves from the satellite can be detected/decoded. The FOV is typically measured in km in terms of an antenna swath width.

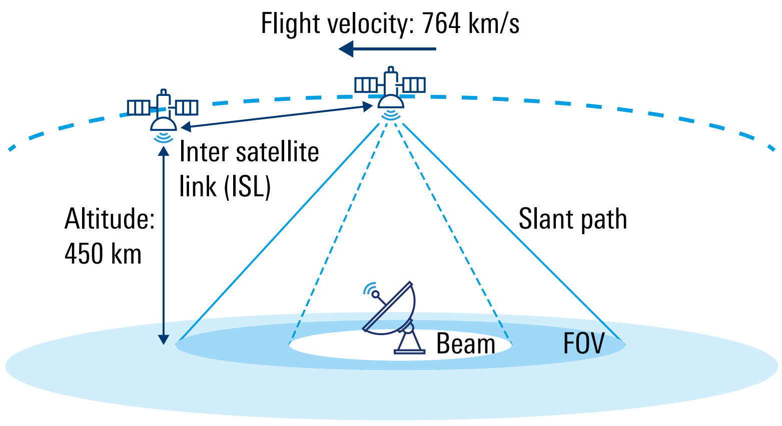
Overflight duration
The LEO/MEO overflight duration is defined as the time during which the electromagnetic waves from the satellite can be detected and decoded with the desired reliability and availability.

Nadir
The nadir is the direction from the satellite towards the earth's center. In practice, the nadir direction of a satellite is defined by the shortest path between the satellite and the earth's surface.

Satellite ground path
Trajectory on the ground defined by the satellite nadir direction as projected on the earth's surface. The satellite's ground path is therefore the path along which the satellite traverses the earth's surface.

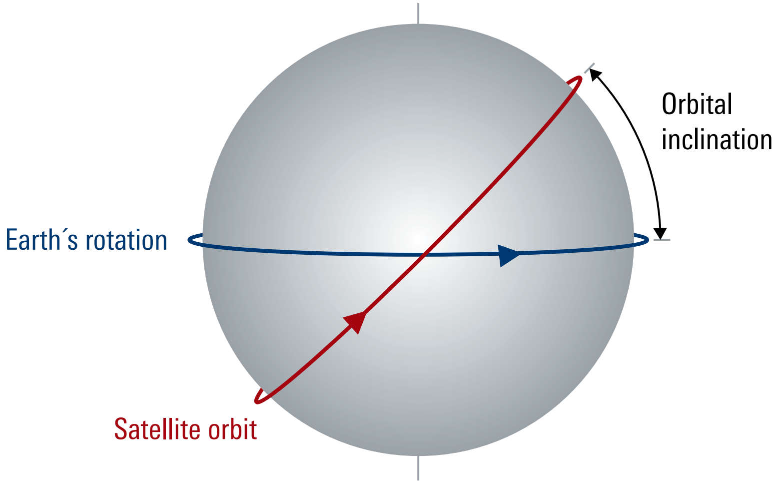
Slant path
Defines the worst-case distance between the edge of coverage (field of view) and the satellite. The slant path length is typically used for worst-case link budget calculations. The usable antenna beamwidth is less but almost equal to the field of view.

Fig. 4: Example of LEO satellite system at 450 km altitude



Satellite orbital inclination
Defines the angle between the earth's equatorial plane and the orbital plane.

Fig. 5: Satellite orbital inclination

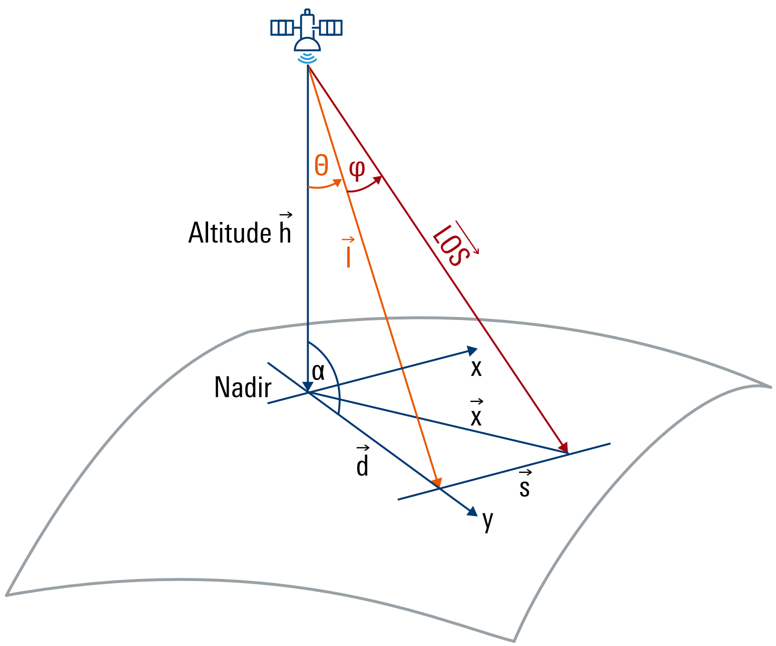


Altitude and line of sight

Altitude
Defines the distance between the earth's surface and the satellite in the nadir direction.

Line of sight (LOS)
The LOS path is the direct path between the satellite and ground terminal.

Fig. 6: Altitude and LOS path



Satellite categories
Satellites vary in size, weight and target orbit depending on their application and other factors. Conventional GEO satellites can be up to 7 m long and weigh more than 5000 kg. With their solar panels unfolded, these satellites can have lengths up to 50 m. For instance, the Inmarsat I6-F2 satellite has a length of 47 m, including the wingspan.

Satellites are usually classified according to their function, target orbit, size and weight. The following table provides an overview of different satellite types and payloads.

Table 1: Satellite categories

Class	Weight	Functions
Conventional satellites		
Heavy and large satellites	> 1000 kg	internet connectivity, TV broadcasting, weather forecasting, astronomical observations, defense and government applications
Medium satellites	500 kg to 1000 kg	navigation, internet connectivity, earth observation, scientific research, defense and government applications
Small satellites		
Mini satellites	300 kg to 500 kg	internet connectivity, remote sensing, earth observation, scientific research, defense and government applications
Super-micro satellites	100 kg to 300 kg	
Micro satellites	10 kg to 100 kg	
Nano satellites	1 kg to 10 kg	

LEO CubeSat architecture

CubeSat[1] is a class of nano satellites that use a standard size and form factor. The size of a CubeSat is specified in units (U) where 1 U measures 10 cm × 10 cm × 10 cm. The weight is about 1 kg per unit.

Fig. 7: CubeSat dimensions

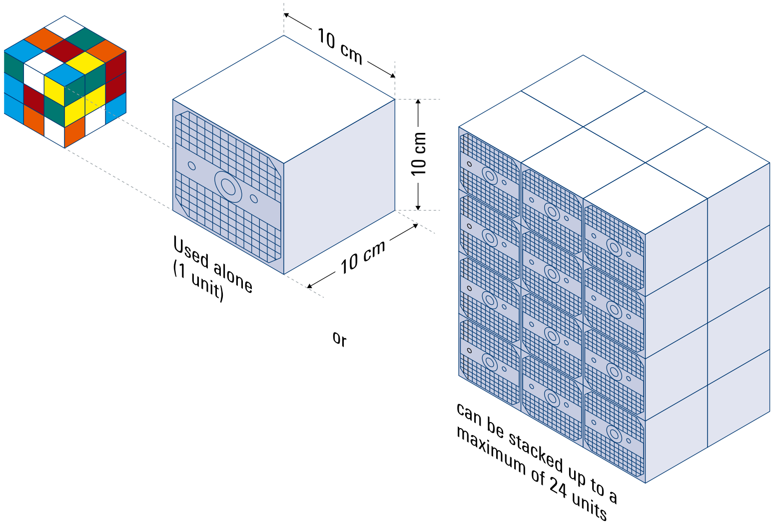


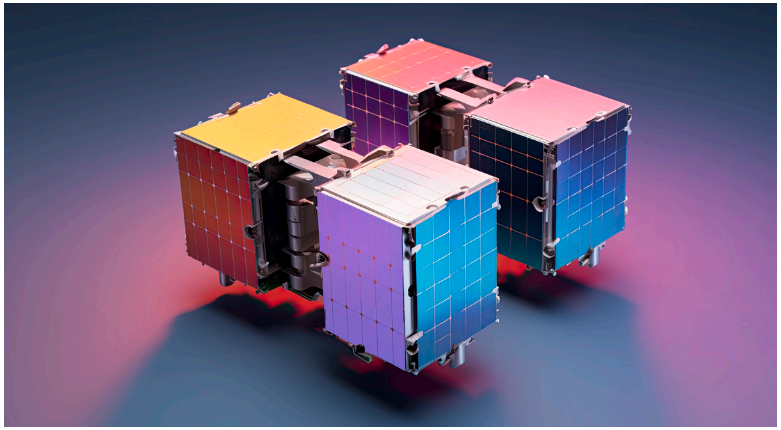
Table 2: CubeSat key specifications

Parameter	Values/range
Size ground plane	10 cm × 10 cm
Unit sizes	1 U, 2 U, 4 U, 8 U, 16 U, 24 U
Weight	approx. 1 kg per 1 U
Power	solar cells
Typical payloads	wireless communications, earth observations, antennas, science instruments

[1] The CubeSat specifications were developed in 1999 by Jordi Puig-Suari, professor at California Polytechnic State University (Cal Poly) and Bob Twiggs, professor at Stanford University Space Systems Development Laboratory.

CubeSats are very cost-efficient and versatile, often coming with commercial off-the-shelf (COTS) components for their electronics and structure. Originally used for technology demonstrations, the CubeSat industry has grown quickly in recent years. The miniature satellites are used in various missions, e.g. remote sensing, wireless communications, research and education, emission monitoring and earth observation payloads for LEO orbits.

Fig. 8: LEO SATCOM CubeSat example



Satellite frequency bands

The following table shows the frequency bands for various satellite services and applications. The nomenclature used to name the frequency bands differs between the ITU, IEEE and NATO.

For a detailed list of worldwide frequency bands and applications, see the poster "Worldwide spectrum allocations" (PD 3683.9492.82)

Table 3: Satellite frequency bands and applications

Frequency bands			Application and services	
ITU	IEEE	NATO	Space	Ground
VHF band: 30 MHz to 300 MHz	**VHF band:** 50 MHz to 300 MHz	**A band:** 0 Hz to 250 MHz	satellite uplinks	broadcast, milcom
UHF band: 300 MHz to 3000 MHz	**UHF band:** 300 MHz to 1000 MHz **L band:** 1 GHz to 2 GHz **S band:** 2 GHz to 3 GHz	**B band:** 250 MHz to 500 MHz, **C band:** 500 MHz to 1000 MHz	mobile satellite services, satellite navigation services	broadcast communications
SHF band: 3 GHz to 30 GHz	**S band:** 3 GHz to 4 GHz **C band:** 4 GHz to 8 GHz **X band:** 8 GHz to 12 GHz **Ku band:** 12 GHz to 18 GHz **K band:** 18 GHz to 27 GHz **Ka band:** 26.6 GHz to 30 GHz	**F band:** 3 GHz to 4 GHz **G band:** 4 GHz to 6 GHz **H band:** 6 GHz to 8 GHz **I band:** 8 GHz to 10 GHz **J band:** 10 GHz to 20 GHz **K band:** 20 GHz to 30 GHz	fixed satellite services, broadcast satellite services, satellite uplinks and downlinks	weather radar, imaging radar, air traffic control
EHF band: 30 GHz to 300 GHz	**Ka band:** 30 GHz to 40 GHz **Q band:** 33 GHz to 50 GHz **V band:** 40 GHz to 75 GHz **E band:** 71 GHz to 86 GHz **W band:** 75 GHz to 110 GHz **D band:** 110 GHz to 170 GHz	**K band:** 30 GHz to 40 GHz **L band:** 40 GHz to 60 GHz **M band:** 60 GHz to 100 GHz **N band:** 100 GHz to 200 GHz	inter-satellite links, military survivable SATCOM	microwave data links, active denial system

Satellite services and use cases

Today, it is impossible to imagine many areas without satellite communications or navigation services. These services enable a wide range of applications in the private, public and industrial sectors.

The following table provides an overview of satellite services and selected use cases.

Table 4: Satellite services and use cases

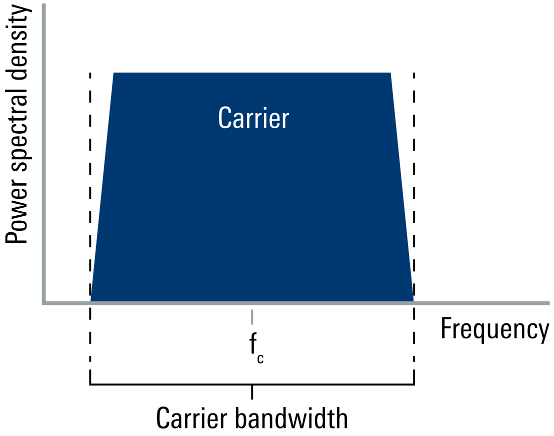
SATCOM and navigation services	Selected use cases
Geostationary earth orbit (GEO)	
▶ TV and radio broadcasting ▶ Broadband connectivity (IP trunking) ▶ High-speed backhaul	▶ Satellite TV ▶ Broadband internet connectivity at sea and in remote areas ▶ Inflight Wi-Fi ▶ Water management or early pest detection in agriculture ▶ Shipment tracking in transport and logistics ▶ Secure communications for government agencies ▶ UAV control ▶ Emergency response and aid, e.g. to establish connectivity in earthquake affected areas
Medium earth orbit (MEO)	
▶ Global navigation satellite systems (GNSS) ▶ Broadband connectivity (low latency) ▶ High-speed backhaul ▶ Satellite telephony	▶ Satellite navigation on land, air and sea ▶ Low-latency, high-bandwidth internet connectivity ▶ Satellite phone
Low earth orbit (LEO)	
▶ Broadband connectivity (low latency) ▶ Direct to cell (non-terrestrial networks) ▶ Internet of things (IoT)	▶ Internet of things (IoT) for industry, agriculture and logistics ▶ Broadband internet connectivity at sea and in remote areas ▶ Secure communications for government agencies ▶ UAV control ▶ Emergency response and aid, e.g. to establish connectivity in earthquake affected areas ▶ Telecommunications and 5G broadband
High earth orbit (HEO)	
Broadcast and communications services for the Arctic above 60N latitude	Aircraft and maritime connectivity for latitudes above the polar circle

SATELLITE COMMUNICATIONS

RF spectrum and carrier bandwidth

Carrier: Radio frequency communications signal, mixed to a center frequency f_c. The carrier occupies an amount of spectrum due to its own bandwidth.

Fig. 9: Power spectral density (PSD) of a carrier signal



Channel: Frequency band inside a transponder. All carrier signals inside a transponder channel are amplified by the same high-power amplifier. All carriers in a given transponder channel are received by the same uplink antenna and use the same downlink antenna.

Carrier frequency: Center frequency of a given carrier.

Carrier bandwidth $B_{carrier}$**:** Amount of spectrum occupied by a carrier. The carrier bandwidth is proportional to the carrier symbol rate B_{sym} according to the following formula:

$$B_{carrier} = B_{sym}(1 + r)$$

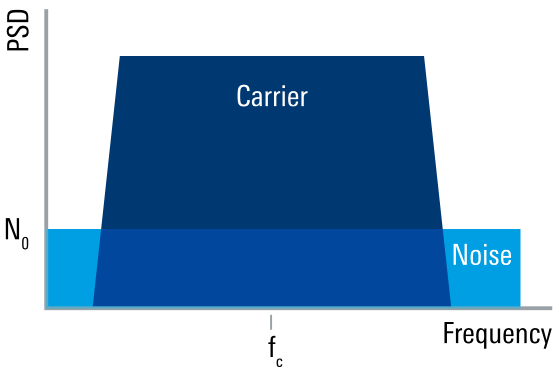
where r denotes the carrier's rolloff factor.

Rolloff factor: Width of the carrier band transition from signal band to stopband. The rolloff factor is typically between 10 % (r = 0.1) and 30 % (r = 0.3).

Transponder bandwidth: Aggregated bandwidth of all transponder channels.

Noise floor: Power spectral density of additive noise inside the transponder channel band. The shape of the noise power spectral density is assumed to be frequency flat. The noise power spectral density is often abbreviated with N_0.

Fig. 10: Power spectral density of a carrier signal and noise



DOCON frequency: Frequency generated inside a transparent satellite transponder to realize a frequency shift from the uplink frequency to the downlink frequency.

Power equivalent bandwidth (PEB): The resource allocation of a particular SATCOM carrier is measured in bandwidth consumption and power consumption. The bandwidth consumption is typically expressed in percent relative to the transponder (channel) bandwidth. The power consumption, however, is typically expressed in PEB (in MHz) according to the following formula:

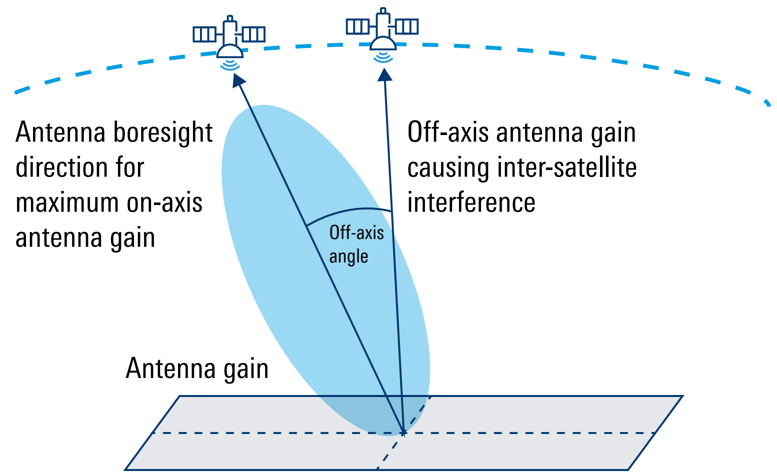
$$PEB = B_{channel} \cdot \left(\frac{P_{carrier}}{P_{channel}}\right)$$

$P_{carrier}$ Carrier power consumption
$P_{channel}$ Available transponder HPA output power

Adjacent satellite interference (ASI)

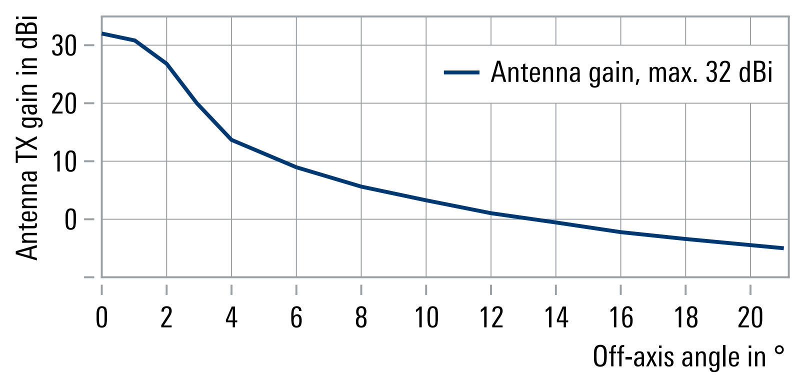
Inter-satellite interference: International regulations define power flux density limits for adjacent satellite systems. One regulation defines the off-axis power flux density in a given frequency band. The off-axis emissions are influenced by the antenna diagram of the transmitting ground station:

Fig. 11: Adjacent satellite interference



If the actual antenna diagram for a particular ground station is unknown, the ITU offers numerous antenna gain models to be used for interference calculations. For example, the antenna diagram model in line with ITU-R S1428-1:

Fig. 12: Antenna TX gain versus off-axis angle in line with ITU-R Rec. S.1428-1



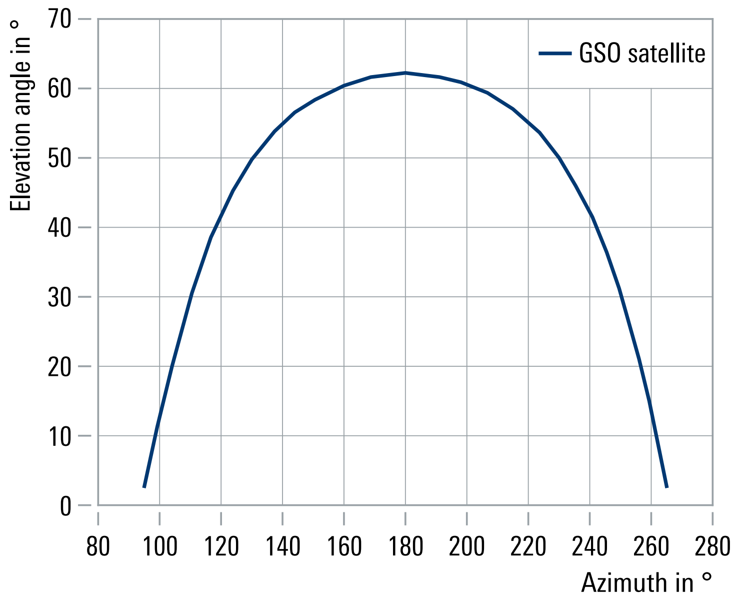
Power flux density (PFD): The power flux density depends on the effective isotropic radiated power and the distance between the transmitter and receiver. For GSO satellite systems, the off-axis PFD can be calculated by:

$$PFD = \frac{P_{HPA} \cdot L_{Feed} \cdot G_{off-axis}}{\pi \cdot 36000000^2} \quad in \ \frac{W}{m^2}$$

P_{HPA}	High-power amplifier output power
L_{Feed}	Antenna feeder loss
$G_{off\text{-}axis}$	Off-axis antenna gain. Using on-axis antenna gain would allow computation of the PFD on the desired satellite.

The impact and criticality of the off-axis emissions are also dependent on the location of the transmitting ground station. This is because the R&S®shape of the GSO (as seen from the ground station) varies with the geographic latitude of the station.

Fig. 13: Elevation angle of a GSO satellite versus latitude (azimuth) of the ground station



Multiplexing and multiple access methods

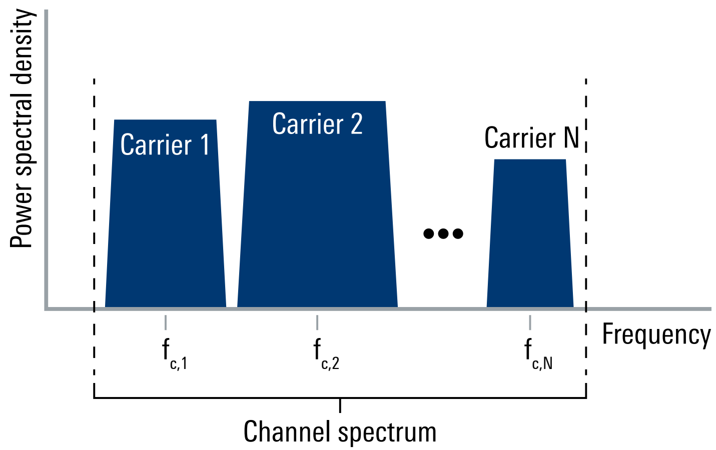
Frequency division multiple access (FDMA)

Multiple independent data streams are individually assigned to carriers. The carriers are separated in the frequency domain in order to minimize inter-carrier-interference. Each of the frequency division multiplexing (FDM) carriers thus uses a different center frequency and bandwidth.

In order to minimize inter-carrier-interference, a guard band is used between adjacent carriers. Typically, the FDM carriers are also referred to as subcarriers. In traditional FDM, each data stream is statically assigned to a single carrier (i.e. to a single center frequency and bandwidth). Hence, multiple independent users each use a separate carrier.

If the FDM user-to-carrier assignments are implemented dynamically, FDM turns into FDMA. Here, the frequency allocation (center frequency and bandwidth) is handled dynamically, i.e. time-varying depending on the multi-user traffic load.

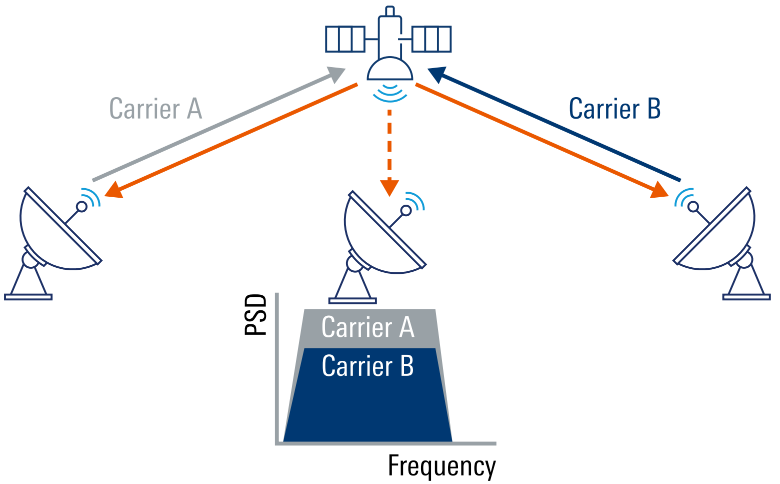
Fig. 14: Frequency division multiplexing spectrum



Paired carrier multiple access (PCMA)
In PCMA systems, the classic SCPC topology is made highly spectrum efficient. The two carriers are assigned equal baud rates and are set such that they fully overlap in the frequency domain. This halves the spectrum consumption compared to conventional SCPC setups. PCMA requires specialized digital modem technology in order to separate both overlapping carriers in the hub station and the remote terminal.

PCMA is widely used for IP trunking and very small aperture terminal (VSAT) applications. There exist several synonyms such as carrier-in-carrier or double-talk.

Fig. 15: Carrier-in-carrier multiple access scenario and spectrum

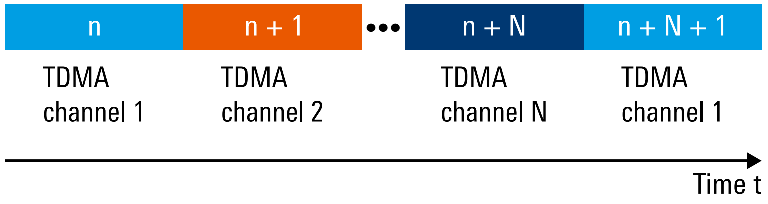


Time division multiple access (TDMA)
Multiple independent data streams are individually assigned to timeslots of a given carrier. The time division multiplexing (TDM) slots are separated in the time domain in order to avoid inter-slot interference. Each of the TDM slots is thus assigned to a single data stream/user.

In order to minimize inter-slot interference, a guard interval is used between adjacent slots. Typically, the TDM slots are also referred to as TDM channels. In traditional TDM, each data stream is statically assigned to a single slot with a predetermined duration and signal bandwidth. Hence, multiple independent users each use a separate non-overlapping timeslot.

If TDM multi-user slot assignment is implemented dynamically, TDM turns into TDMA. Here, the timeslot allocation (slot duration, slot order) is handled dynamically, i.e. time-varying depending on the multi-user traffic load.

Fig. 16: TDMA channels



Telemetry, tracking and command (TT&C)

Telemetry, tracking and command (TT&C) is a critical subsystem of satellites that ensures their proper functioning.

Table 5: TT&C in overview

Description	TT&C bands
Telemetry	
Downlinking of status information, health and performance data from the satellite to the ground station	S band (2 GHz to 4 GHz), X band (8 GHz to 12 GHz) BPSK, QPSK, ACM
Tracking	
Tracking of the precise satellite location and distance to earth using radio signals from the satellites	S band (2 GHz to 4 GHz) X band (8 GHz to 12 GHz)
Command	
Uplink commands from the ground station to the satellite to control various functions, such as adjusting orbits and configuring subsystems	S band (2 GHz to 4 GHz)

TT&C can also cover links between separate spacecraft, such as inter-satellite links for sharing data and cooperating.

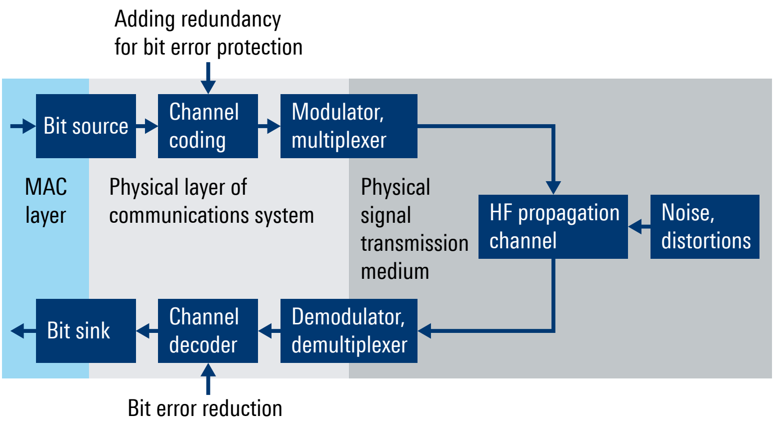
Satellite modems

Digital modulator and demodulator

Modem technology: A SATCOM modem transforms an input bit stream into a radio frequency carrier signal. The transformation of binary data (bits) into an analog radio frequency signal is known as modulation. The inverse operation at the receiver is known as demodulation.

SATCOM modems generate carrier signals at center frequencies in the L band, i.e. from 1.0 GHz to 2.0 GHz. These L band carriers are then upconverted to higher frequencies by the ground station equipment.

Fig. 17: Physical layer of a SATCOM system



Channel coding with forward error correction

The forward error correction (FEC) adds redundancy bits to the payload bit stream. Redundancy is used to enable the FEC decoder at the receiver to reduce bit errors after signal demodulation. The number of information bits that are FEC encoded is defined as k. The result is a code word of length n with $n, k \in \mathbb{N}$ and $k \leq n$. The code rate r is defined as $r = k / n$.

The lower the code rate, the greater the bit error protection and the greater the bit overhead used for error protection.

Example of systematic block code with $r = k / n$

Fig. 18: Code word with redundancy for bit error protection

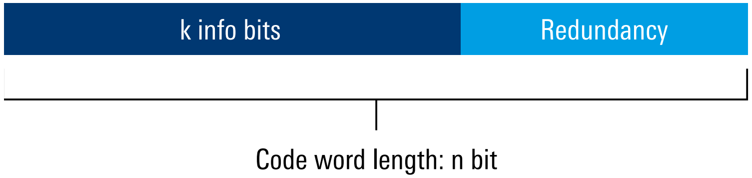


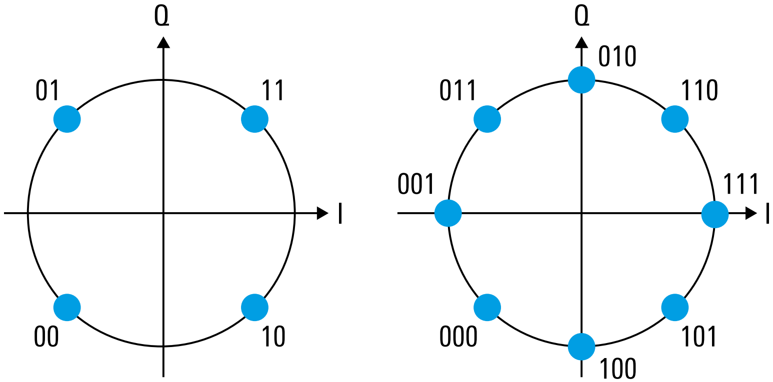
Table 6: Acronyms for modern FEC technology

Acronym	Term	Usage
LDPC	low density parity check codes	DVB-S2X, VSAT
TPC	turbo product codes	VSAT
PC	polar codes	5G, LEO systems

Digital modulation

Digital modulation used in SATCOM: Digital modulation uses complex valued symbols. The discrete set of symbols is called an alphabet. The alphabet size is M. Each symbol carries ld(M) bits. The following figure shows two exemplary modulation alphabets (constellations).

Fig. 19: Constellation diagrams



Left: quadrature phase shift keying (QPSK) with M = 4
Right: eight-phase shift keying (8PSK) with M = 8

Symbol duration T_{sym}: Time duration to transmit one symbol.

Symbol rate B_{sym}: Inverse of T_{sym}; The term baud rate is used synonymously. The carrier bandwidth directly depends on B_{sym}.

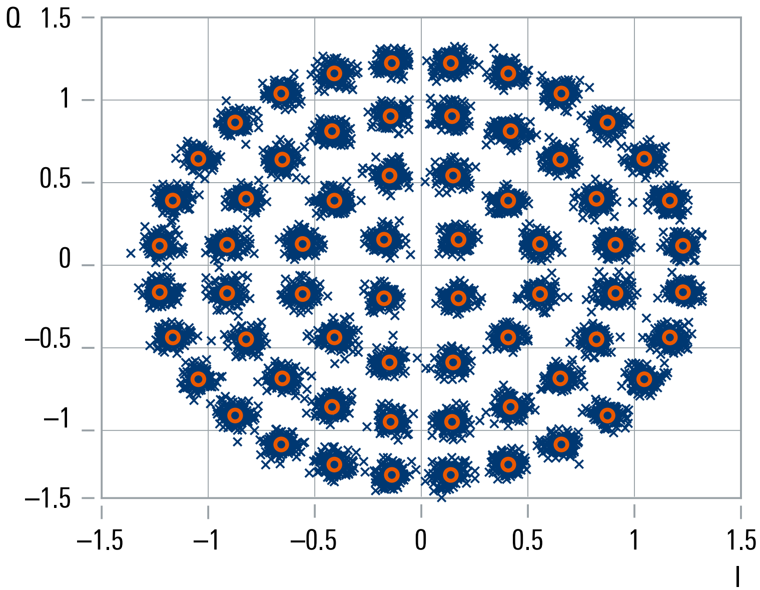
Spectral efficiency S: In practice, spectral efficiency is expressed in units of bit/s/Hz according to the formula:

$S = r \cdot \mathrm{ld}(M)$ in bit/s/Hz

High throughput SATCOM applications can use higher order modulation types such as 32APSK or even 64APSK.

The following figure shows an example of a 64APSK constellation received at SNR = 25 dB.

Fig. 20: Constellation diagram 64APSK



As a general rule, the higher the modulation order (M value), the higher the bit/symbol error rate at a given SNR value.

Table 7: Modulation versus spectral efficiency and SNR range

Modulation	Spectral efficiency	SNR range (E_s/N_0)
QPSK	2 bit/symbol	1 dB to 4 dB
8PSK	3 bit/symbol	5 dB to 8 dB
16APSK	4 bit/symbol	9 dB to 11 dB
32APSK	5 bit/symbol	12 dB to 15 dB
64APSK	6 bit/symbol	15 dB to 19 dB
128APSK	7 bit/symbol	19 dB to 24 dB

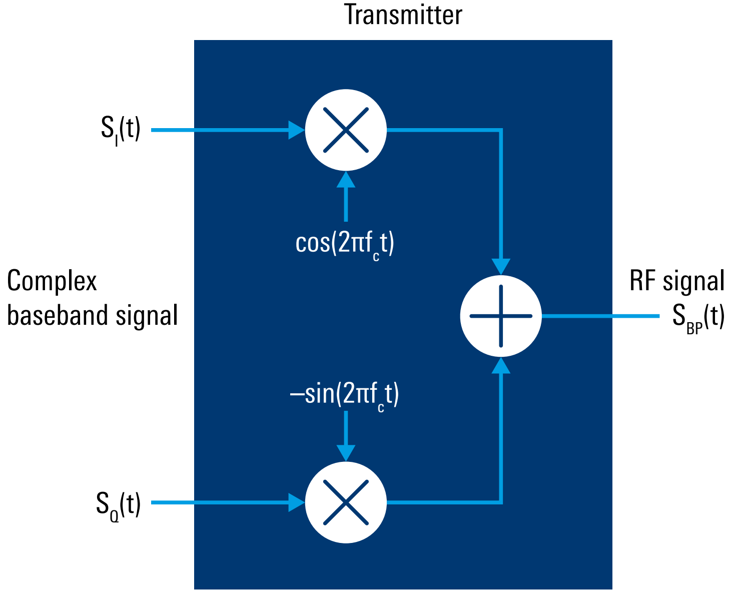
Table 8: Modulation for various satellite services

Standard	Modulation
DVB-S2	single carrier linear modulation M-PSK, M-APSK
DVB-S2X	FEC and MODCOD extensions of DVB-S2, up to 256APSK defined
OneWeb	LTE like OFDM (downlink) and OFDMA (uplink)
DVB-RCS2	burst traffic MF-TDMA uplink waveform used for VSAT return links (uplink)
Kuiper	TDMA, FDMA with LDPC FEC
Starlink	OFDM proprietary

Signal up- and downconversion

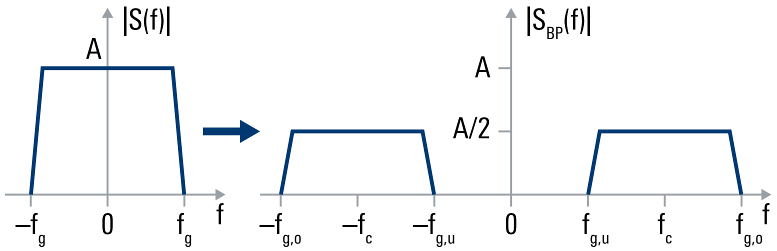
Signal upconversion: Satellite modems use I/Q mixers to upconvert a complex-valued baseband signal to the L band. The L band output signal is a real-valued signal. The complex baseband signal is also referred to as the I/Q signal. Here, I (in-phase) and Q (quadrature phase) represent the real and imaginary parts.

Fig. 21: Upconverter (transmitter) for complex baseband signal to intermediate frequency



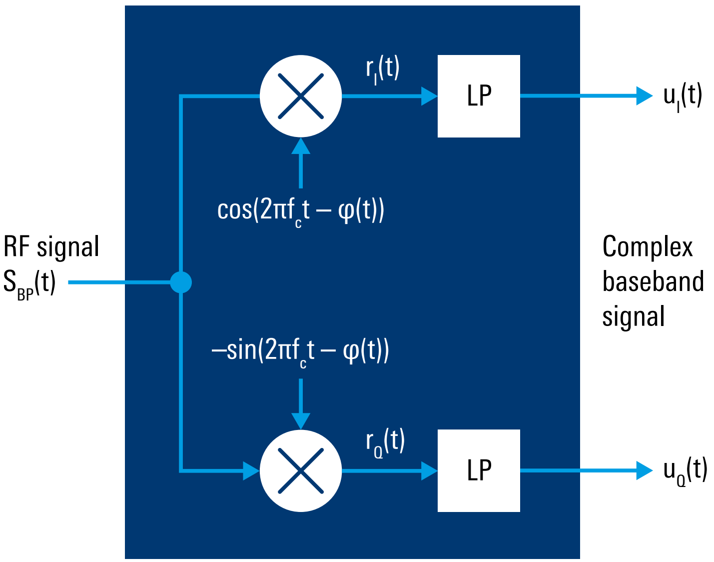
The mixing carrier frequency is internally generated by phase-locked loop (PLL) frequency generators. Typically, the PLL oscillator clocks can be stabilized by an external GPS PPM input signal.

Fig. 22: Upconversion of a complex baseband signal to an intermediate frequency f_c



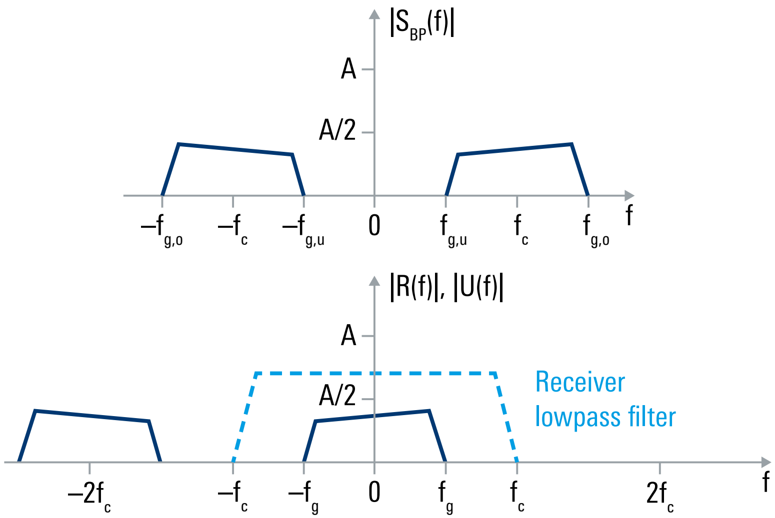
Signal downconversion: Satellite modems use I/Q mixers to upconvert a complex-valued baseband signal to the L band. The receiver applies the inverse frequency downconversion operation to yield a complex baseband signal from an incoming RF carrier.

Fig. 23: Downconverter (receiver) for intermediate frequency signals to the complex baseband



Receiver lowpass filter: The receiver lowpass filter is used to eliminate radio frequency image signals of the received carrier signal. It also applies anti-aliasing before ADC.

Fig. 24: Downconversion from an intermediate frequency to the complex baseband



MODCOD

Definition of MODCOD: The combination of the modulation alphabet (constellation) and FEC rate is known as MODCOD. Each MODCOD is thus associated with a given spectral efficiency. Moreover, each MODCOD has a target SNR at which the MODCOD can be received quasi error-free. The following table gives an example as defined in the DVB-S2 standard.

Table 9: DVB-S2 short codes MODCOD table

MODCOD	Constellation size M	Code rate r	Spectral efficiency S in bit/s/Hz	Target SNR in dB
QPSK 1/4	4	0.25	0.50	–3.5
QPSK 1/3	4	0.33	0.66	–1.2
QPSK 2/5	4	0.40	0.80	–0.2
QPSK 1/2	4	0.50	1.00	0.5
QPSK 2/3	4	0.66	1.32	3.3
QPSK 3/4	4	0.75	1.50	4.3
QPSK 4/5	4	0.80	1.60	4.8
QPSK 5/6	4	0.83	1.66	5.4
QPSK 8/9	4	0.89	1.78	6.4
8PSK 2/3	8	0.66	1.98	6.9
8PSK 3/4	8	0.75	2.25	8.2
8PSK 4/5	8	0.80	2.40	9.0
8PSK 5/6	8	0.83	2.49	9.7
16APSK 3/4	16	0.75	3.00	10.6
16APSK 4/5	16	0.80	3.20	11.3
16APSK 5/6	16	0.83	3.32	12.0
32APSK 3/4	32	0.75	3.75	13.2
32APSK 4/5	32	0.8	4.00	14.1
32APSK 5/6	32	0.83	4.15	14.8

Signal-to-noise ratio

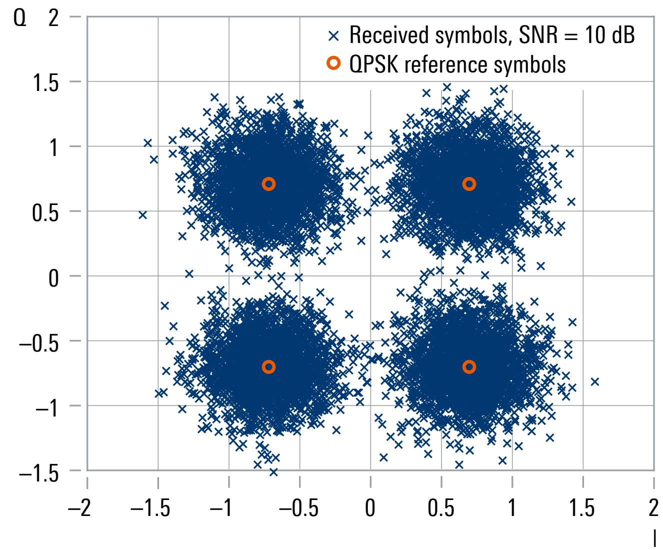
Signal-to-noise ratio (SNR): The SNR measures the power ratio of the useful received data signal and the additive noise:

$$z(t) = d(t) + n(t)$$

$d(t)$ denotes the received data signal of power σ_D^2 and the additive noise signal $n(t)$ exhibits the power σ_N^2. The SNR is typically calculated on a logarithmic scale.

In the receiver, the additive noise widens the constellation, which can potentially lead to symbol/bit errors.

Fig. 25: QPSK constellation with additive noise



Meanings:

- Carrier-to-noise ratio (CNR)
- Energy per symbol to noise power spectral density (E_s/N_0)

SATCOM link budget

The aim of a link budget calculation is to evaluate the resulting carrier-to-noise ratio at the receiver. In a geostationary transparent SATCOM system, three independent and dominant noise sources exist, all of which need to be considered in the final CNR equation:

$$CNR = \frac{1}{\frac{1}{\gamma_{UL}} + \frac{1}{\gamma_{Intermod}} + \frac{1}{\gamma_{DL}}}$$

The variables γ_{UL} and γ_{DL} denote the CNR in the uplink and downlink, respectively. The variable $\gamma_{Intermod}$ denotes the carrier-to-intermodulation ratio, which measures the amount of nonlinear signal distortion within the satellite transponder HPA.

In LEO communications, the signal is either received/decoded in the satellite receiver or the ground station receiver. Hence, LEO communications requires two link budgets for the uplink and the downlink.

In both cases, intermodulation originates from the terminal HPA (uplink) or the satellite HPA (downlink):

Uplink:

$$CNR = \frac{1}{\frac{1}{\gamma_{UL}} + \frac{1}{\gamma_{Intermod,Term}}}$$

Downlink:

$$CNR = \frac{1}{\frac{1}{\gamma_{Intermod,Sat}} + \frac{1}{\gamma_{DL}}}$$

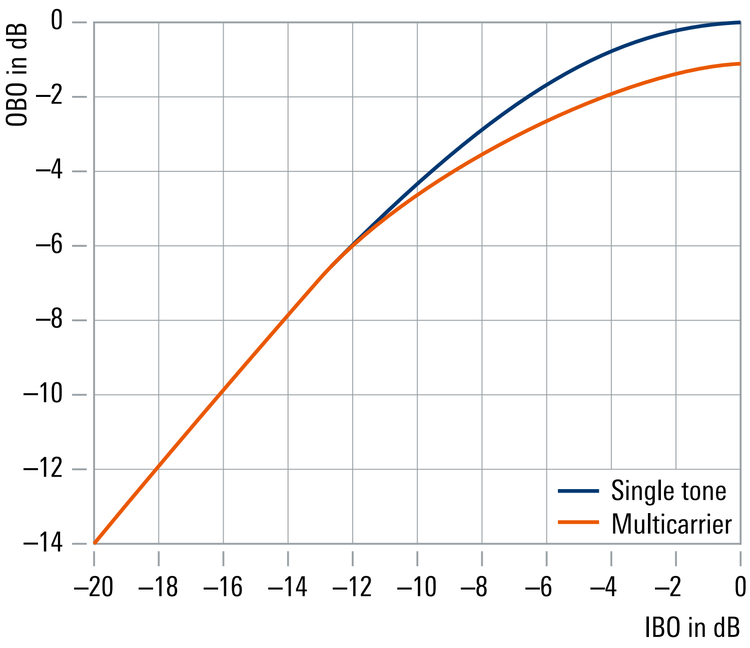
High power amplifiers (HPA)

SATCOM HPAs are characterized by their gain, which is the ratio between input power P_{in} and HPA output power P_{out}. The maximum HPA output saturation power $P_{out,max}$ depends on the input power $P_{in,max}$. Hence, we can define the so-called input power back-off (IBO) and the output power back-off (OBO). Both determine the operating point of the HPA.

$$IBO = 10\log_{10}\left(\frac{P_{in}}{P_{in,max}}\right), \quad OBO = 10\log_{10}\left(\frac{P_{out}}{P_{out,max}}\right)$$

Close to saturation (OBO = 0 dB), the HPA becomes nonlinear. As a result, the gain degrades (gain compression). Note that this behavior differs depending on the signal type that is amplified.

Fig. 26: Traveling wave tube amplifier (TWTA) output power back-off as a function of input power back-off



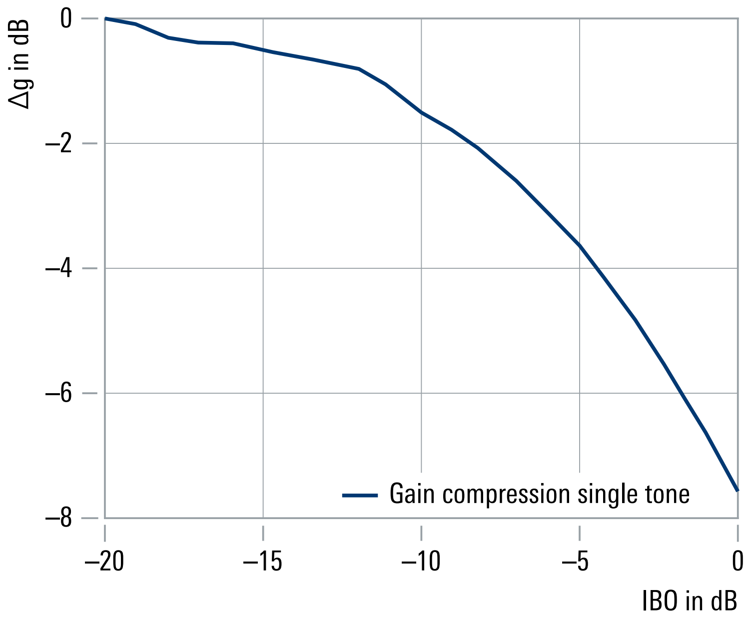
The OBO versus IBO defines all possible combinations of input and output power of a HPA. At $P_{out,max}/P_{in,max}$, the HPA becomes saturated. Any further increase in input power will no longer lead to higher output power.

The saturation shape of the OBO versus IBO chart has a significant impact on the HPA gain g:

$$g = \frac{P_{out}}{P_{in}}$$

Amplifier saturation reduces the HPA gain close to saturation, which we refer to as gain compression.

Fig. 27: TWTA gain compression (single tone) as a function of input power back-off



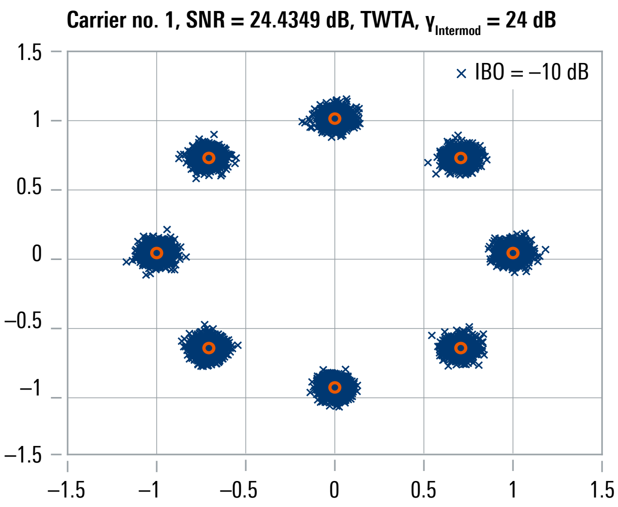
Amplifier distortion becomes dominant close to amplifier saturation. The so-called intermodulation distortion adds an additional noise signal to the transponder output. The intermodulation noise power density is measured as IM_0 in dBW/Hz. The corresponding carrier-to-intermodulation ratio can be calculated as follows:

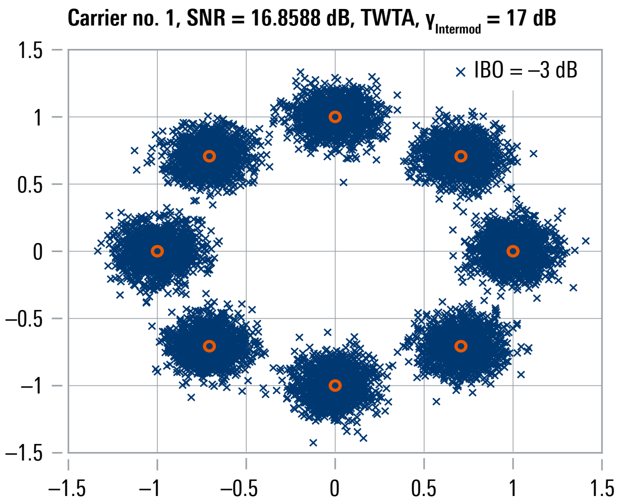
$$\gamma_{Intermod} = P_{out,car} - 10log_{10}(IM_0 \cdot B)$$

$\gamma_{Intermod}$ Carrier-to-intermodulation ratio
$P_{out,car}$ Carrier HPA output power
B Carrier bandwidth

The traveling wave tube amplifier (TWTA) intermodulation degradation depends on the IBO.

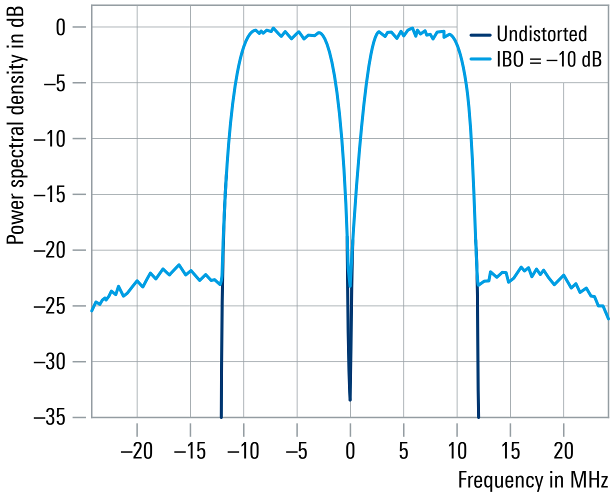
Fig. 28: TWTA intermodulation degradation as a function of input power back-off (IBO)

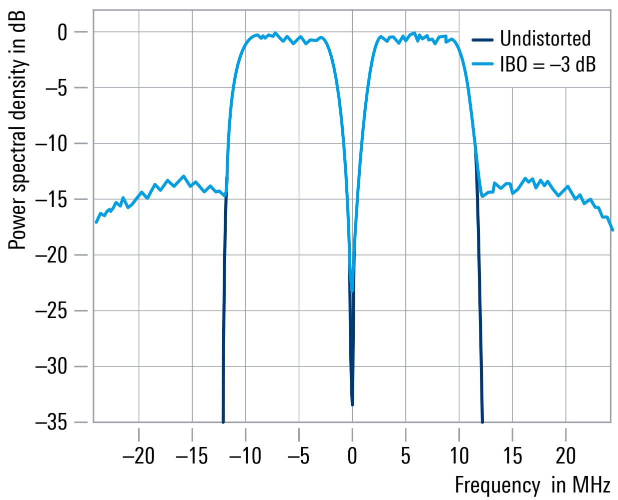




Amplifier saturation generates out-of-band spectral emissions. The power spectral density of these emissions is typically on the order of IM_0 and is thus dependent on the IBO and OBO. The following examples demonstrate out-of-band emissions for a TWTA in a two-carrier scenario.

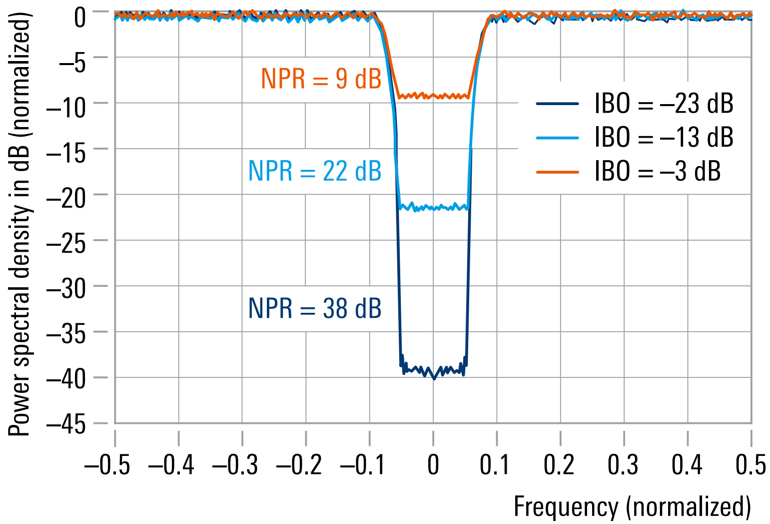
Fig. 29: TWTA out-of-band emissions as a function of different IBOs





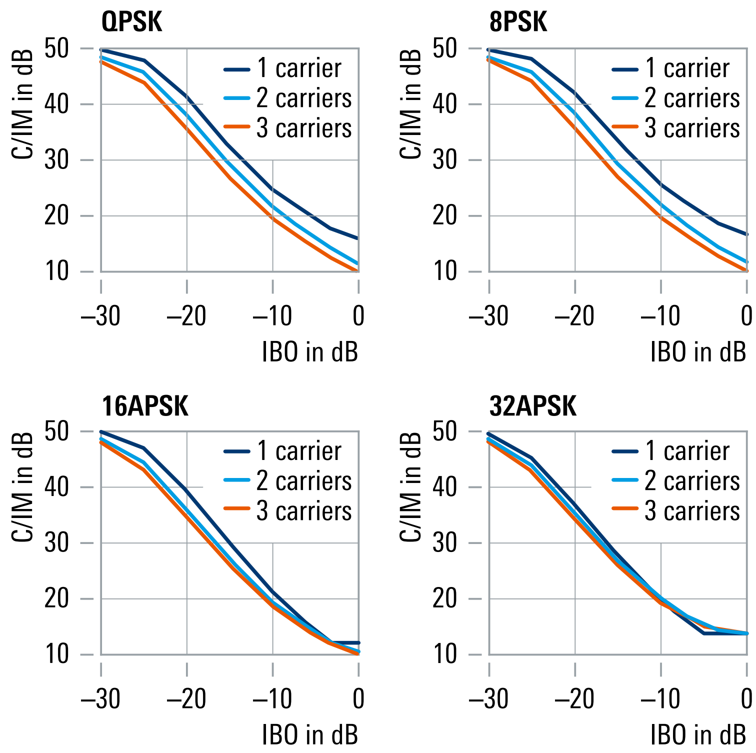
Communications amplifiers exhibit different IM_0 depending on the input power back-off. Since IM_0 needs to be included in the link budget analysis, IM_0 can be determined by measuring the noise power ratio (NPR) of an amplifier. A wideband signal with notch is amplified where the NPR denotes the dB difference between the intermodulation power spectral density inside the notch and outside the notch.

Fig. 30: Noise power ratio (NPR) as a function of input power back-off (IBO)



Amplifier saturation becomes worse in multicarrier scenarios. It also depends on the modulation format that is used. The following figures show how the carrier to intermodulation ratio (C/IM) depends on the modulation format, the IBO and the number of carriers that are simultaneously amplified. The C/IM quantifies the amount of in-band noise that originates from nonlinear power amplifier (PA) signal distortion.

Fig. 31: C/IM as a function of input power back-off and modulation formats



Solid-state power amplifiers

Gallium nitride (GaN) semiconductor technology has the potential to supply space-qualified and robust solid-state power amplifiers (SSPA) for radio frequencies with high power. GaN based SSPAs are increasingly used in space communications systems due to their efficiency, reliability and radiation resistance. These advantages make GaN a preferred choice for satellite communications and other space based applications.

Requirements and limitations for satellite communications systems

Need for more bandwidth

- As satellite communications grows, there is demand for increased bandwidth to handle additional data transmissions.
- Our connected world requires more data for applications like 4K/8K video, autonomous vehicles, 5G and the internet of things (IoT).
- Scientific research (such as earth sciences) also relies on a high volume of data transmissions from space based sensors.

Limits of existing technology (TWTA)

- Current geostationary satellite data transmissions use traveling wave tube amplifiers (TWTA).
- TWTAs have limitations including frequency restrictions (degradation above 50 GHz), large size, high weight and high-voltage power requirements.
- These characteristics are not favorable for space satellites.

Solid-state mmWave amplifiers with GaN technology

- GaN technology addresses the limitations of TWTAs.
- GaN based SSPAs offer:
  - **High power density:** GaN technology allows higher output power density.
  - **Efficiency:** GaN SSPAs convert more input power into RF output power.
  - **Reliability:** GaN technology is radiation-resistant, crucial for space applications.
  - **Compact size:** GaN technology amplifiers are smaller and lighter.
  - **Wideband operation:** GaN technology facilitates wider bandwidth and smaller antennas.

In summary, GaN technology is a game changer for space-qualified SSPAs, enabling efficient, reliable and high-power communications systems in space.

Receiver noise temperature

The noise factor F is a measure of the degradation of the signal-to-noise ratio of a system component. The noise factor is defined as the ratio of the input SNR γ_{in} and the component output SNR γ_{out}:

$$F = \frac{\gamma_{out}}{\gamma_{in}}$$

The noise figure is the noise factor converted to dB. The following figure illustrates how the internal noise of an electronic component with gain G generates extra noise power that ultimately degrades the output SNR.

Fig. 32: Receiver noise model

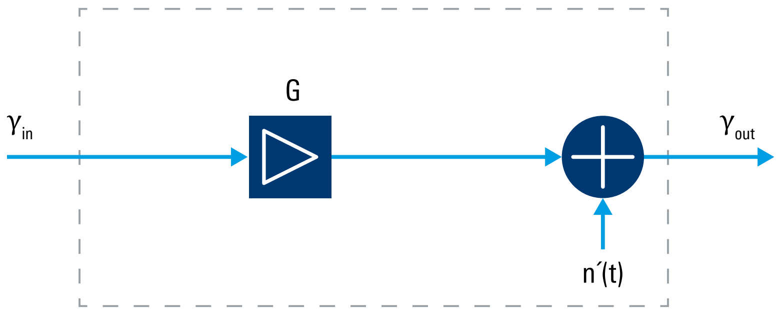
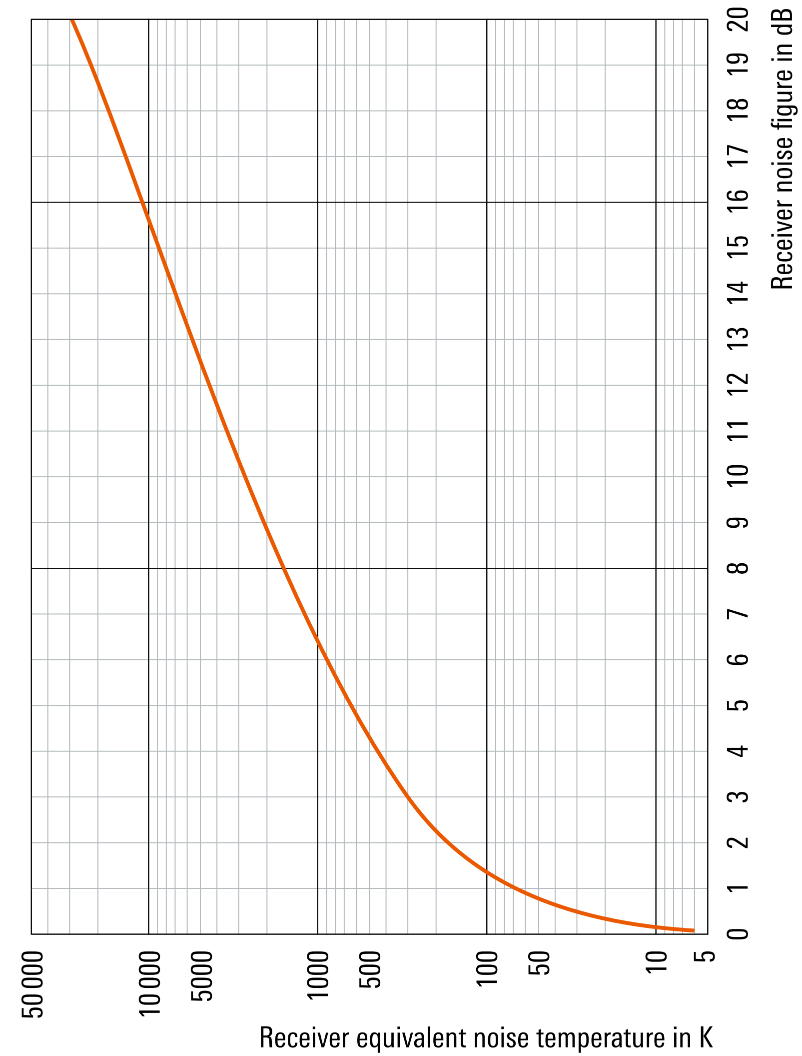


Fig. 33: Receiver noise figure as a function of receiver equivalent noise temperature



The noise power can be interpreted as an equivalent noise temperature T with the following equation:

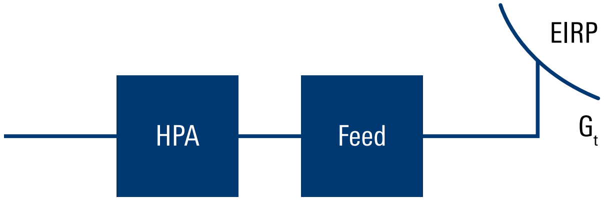
$$\sigma_N^2 = k \cdot T \cdot B$$

Here, k is the Boltzmann constant and B denotes the signal bandwidth. The noise temperature is the temperature of a hypothetical resistor at the input to an ideal noise-free device that would generate the same output noise power per unit bandwidth. For a given noise factor, it can be calculated as follows:

$$T_{noise} = 290\ \mathrm{K} \cdot (F - 1)$$

Uplink EIRP and receive power
The uplink signal is generated with an RF carrier signal that is amplified by an HPA. The HPA output signal is fed to the antenna using the feeder link (waveguide).

Fig. 34: Satellite ground station transmit path



The antenna gain of a parabolic dish is given by:

$$G_t = \eta \frac{4\pi A}{c^2} f_c^2 \quad \text{with} \quad A = \frac{\pi}{4} D^2$$

A	Antenna size (aperture) in m²
f_c	Carrier frequency in Hz
D	Antenna diameter in m
c	Speed of light in m/s
η	Antenna efficiency, numeric value between 0 and 1
P_{HPA}	HPA output power in W (logarithmic in dBW)
L_{Feed}	Feeder loss
G_t	Antenna gain, numeric value in dBi

Note that the antenna gain is frequency dependent. A parabolic dish has a higher antenna gain (higher pointing accuracy) at higher frequencies.

Effective radiated power (ERP) is the effective radio signal power that is used by the transmit antenna:

$$P_t = P_{HPA} \cdot L_{Feed}$$

Effective isotropic radiated power (EIRP) is the radiated power that accounts for antenna directivity in a certain direction:

$$P_{EIRP} = P_t \cdot G_t$$

Satellite receive power can be calculated logarithmically as follows:

$$P_r = P_t + G_t + L_{UL} + G_r$$

P_r	Receive power at satellite RX antenna in W (logarithmic in dBW)
P_t	Carrier transmit power (ERP) in W (logarithmic in dBW)
G_t	TX antenna gain in dBi
L_{UL}	Uplink path loss (uplink signal attenuation) in dB
G_r	Satellite RX antenna gain in dBi

Uplink signal attenuation consists of different effects:

$$L_{UL} = FSPL + L_{Rain} + L_{Cloud} + L_{Gas} + L_{Scint}$$

$FSPL$	Free space path loss in dB
L_{Rain}	Signal attenuation due to rain in dB
L_{Cloud}	Signal attenuation due to clouds in dB
L_{Gas}	Signal attenuation due to gas absorption in dB
L_{Scint}	Scintillation signal attenuation in dB

Free space path loss (FSPL) is the loss between two isotropic radiators in free space, expressed as a power ratio between the transmitted power P_{TX} and the received power P_{RX}. It increases with the square of distance between the antennas because radio waves spread out by the inverse square law, and decreases with the square of the wavelength λ of the radio waves:

$$FSPL = \frac{P_{TX}}{P_{RX}} = \left(\frac{4\pi R}{\lambda}\right)^2$$

P_{TX}	Transmitted power
P_{RX}	Received power
R	Range
λ	Wavelength

Uplink CNR and G/T link budget

A link budget is an accounting of all power gains and losses between transmitter and receiver.

The uplink CNR γ_{UL} can be calculated as follows:

$$\gamma_{UL} = \frac{P_t \cdot G_t \cdot L_{UL} \cdot G_r}{k \cdot T_{sat} \cdot B} = \underbrace{\underbrace{P_t \cdot G_t \cdot L_{UL} \cdot \frac{G_r}{T_{sat}} \cdot \frac{1}{k}}_{C/N_0} \cdot \frac{1}{B}}_{C/N}$$

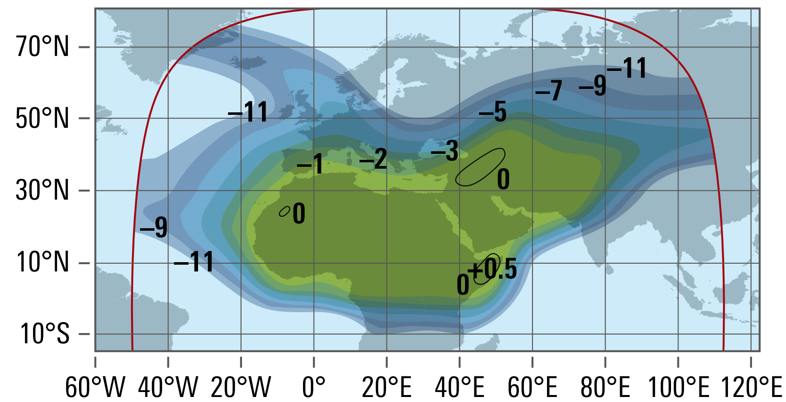
k	Boltzmann constant 1.380649 · 10^{-23} in Ws/K
B	Carrier bandwidth in Hz
T_{sat}	Satellite receiver noise temperature in K

Link budgets are typically calculated on a logarithmic scale:

$$\gamma_{UL} = P_t + G_t + L_{UL} + \frac{G_r}{T_{sat}} - 10log_{10}(k) - 10log_{10}(B)$$

The satellite receiver noise temperature is typically unknown to operators. For the sake of link budget calculations, satellite operators publish satellite G/T values for each transponder. Since the satellite RX antenna gain depends on the direction of signal reception, the G/T value is direction dependent as well. Satellite operators publish G/T contour maps that allow accurate link budget calculation.

Fig. 35: G/T contour map



Downlink CNR and EIRP

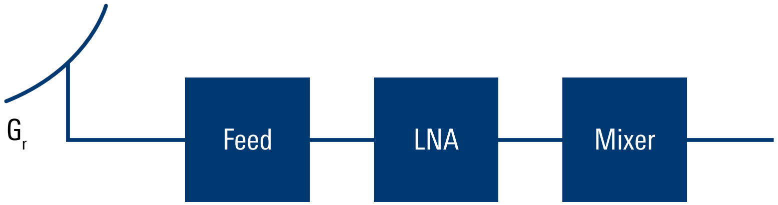
The satellite downlink link budget can be calculated using the same equations as the uplink. The downlink link budget calculation aims at deriving the downlink CNR γ_{DL} at the ground station receiver:

$$\gamma_{DL} = P_{t,sat} + G_{t,sat} + L_{DL} + \frac{G_r}{T_{system}}$$

$P_{t,sat}$	Carrier satellite ERP in W (logarithmic in dBW)
$G_{t,sat}$	Satellite TX antenna gain in dBi
L_{DL}	Downlink path loss, signal attenuation due to free space path loss and atmospheric effects in dB
G_r/T_{system}	G/T value of receiving ground station in dB/K
k	Boltzmann constant 1.380649 · 10^{-23} in Ws/K
B	Carrier bandwidth in Hz

The ground station G/T value can be derived if the noise temperature of the receiver is known. The ground station receiver noise temperature is mainly determined by the feed, LNA and frequency downconverter.

Fig. 36: Ground station receiver (outdoor unit)

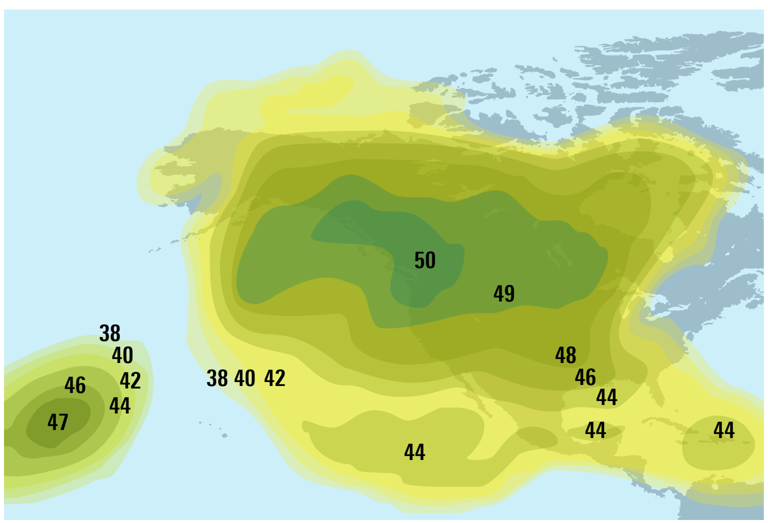


The satellite downlink EIRP can be calculated by:

$$EIRP = P_{t,sat} + G_{t,sat}$$

For commercial GSO satellite systems, the EIRP is direction dependent. Note that satellite operators publish EIRP gain contour maps from which the sum EIRP (for all transponder carriers) can be seen.

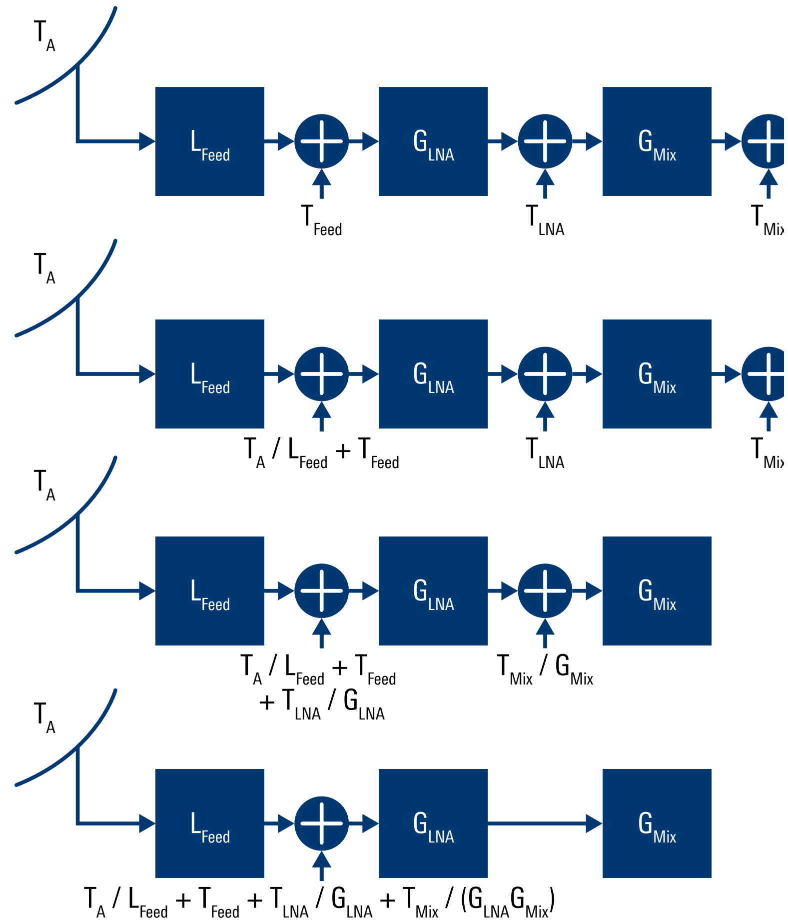
Fig. 37: EIRP gain contour maps (Telstar 5)



Downlink G/T

Satellite receiver G/T can be calculated by using the individual noise temperatures of the receiver components.

Fig. 38: Receiver G/T calculation based on the individual noise temperatures



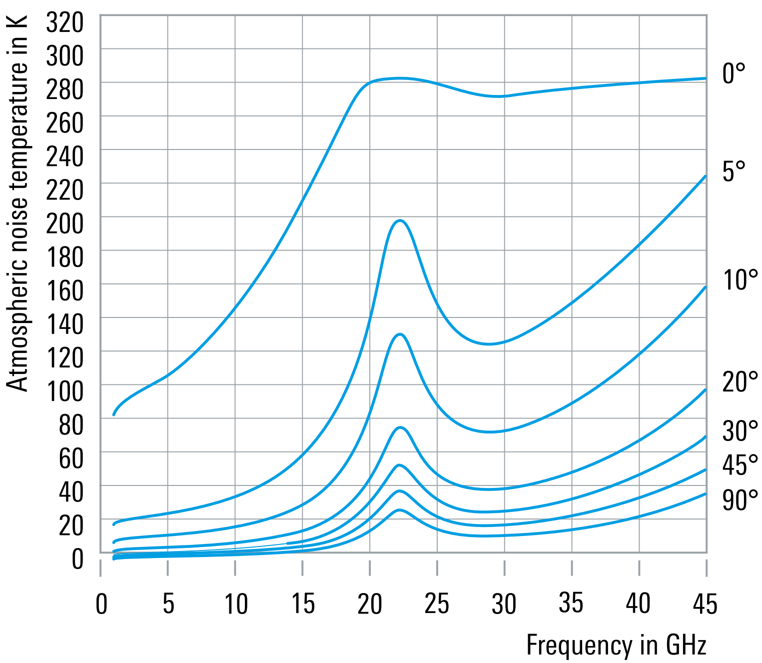
Satellite receiver G/T can be calculated using the following equation where T_A is the antenna temperature in Kelvin:

$$\frac{G}{T} = \frac{G_r L_{Feed}}{\frac{T_A}{L_{Feed}} + T_{Feed} + \frac{T_{LNA}}{G_{LNA}} + \frac{T_{Mix}}{G_{LNA} G_{Mix}}}$$

T_A is the antenna temperature during rain. $T_{A,Sky}$ is the clear sky antenna temperature. During a downlink rain event with loss L_{Rain}, the antenna temperature is increased as follows:

$$T_A = T_{A,Sky}/L_{Rain} + 275\left(1 - 1/L_{Rain}\right) \text{ in K}$$

Fig. 39: Atmospheric noise temperature as a function of frequency



Here, we see the atmospheric noise temperature as a function of frequency for a clear atmosphere at various elevation angles. A median level of water vapor density (atmospheric humidity = 7.5 g/m^3) is assumed. At a zero degree elevation angle, the noise temperature reaches 280 K at 20 GHz.

Atmospheric effects

Attenuation

SATCOM atmospheric attenuations are a collection of statistical models that are centrally published by the ITU. The ITU provides public access to the latest data sets.

Table 10: The main ITU recommendations in relation to attenuation factors

Attenuation factor	ITU recommendation
Rain rate	ITU-R Rec. P 837-7
Rainfall height	ITU-R Rec. P 839-4
Specific attenuation due to rain	ITU-R Rec. P 838-3, P.1511-2
Rain attenuation, frequency scaling, scintillation	ITU-R Rec. P 618-13, P.453-14
Gas attenuation	ITU-R P Rec. 676-12, P.835-6, P.836-6, P.1510-1, P.1511-2
Cloud attenuation	ITU-R Rec. P 840-4, P.840-7, P.840-8
Surface temperature	ITU-R Rec. P.1510
Earth station height above sea level	ITU-R Rec. P.1511

Atmospheric attenuation depends on:

- Satellite orbit position and ground station location
- Carrier frequency
- Average carrier availability for a typical year
- Antenna type

The following example shows the differences in SATCOM atmospheric attenuation on the downlink at different locations in different frequency bands.

Fig. 40: Positions of satellite ground stations in Germany

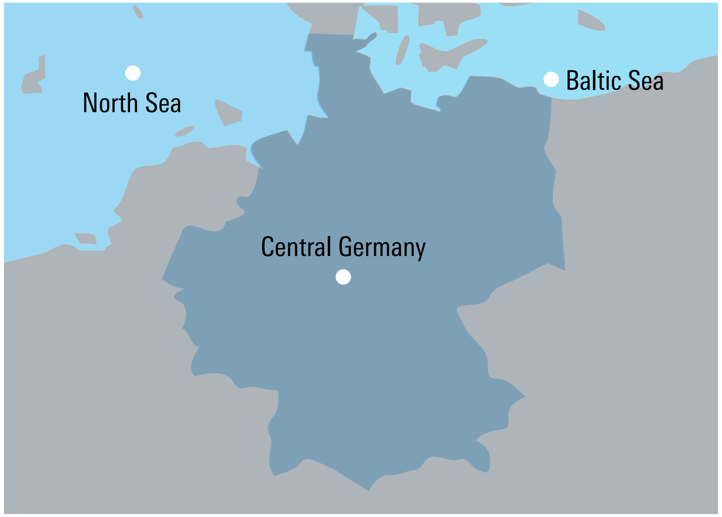


Table 11: Atmospheric attenuation at 18 GHz, availability 99.5 % (average year)

	Central Germany	North Sea	Baltic Sea
Scintillation	0.3 dB	0.4 dB	0.4 dB
Rain	1.9 dB	1.8 dB	1.6 dB
Gas	0.3 dB	0.4 dB	0.4 dB
Cloud	0.8 dB	1.0 dB	0.9 dB

Table 12: Atmospheric attenuation at 28 GHz, availability 99.5 % (average year)

	Central Germany	North Sea	Baltic Sea
Scintillation	0.4 dB	0.5 dB	0.5 dB
Rain	4.5 dB	4.0 dB	3.8 dB
Gas	0.5 dB	0.7 dB	0.6 dB
Cloud	1.7 dB	2.3 dB	2.0 dB

Fig. 41: Direct measurement of atmospheric attenuation with a radiometer

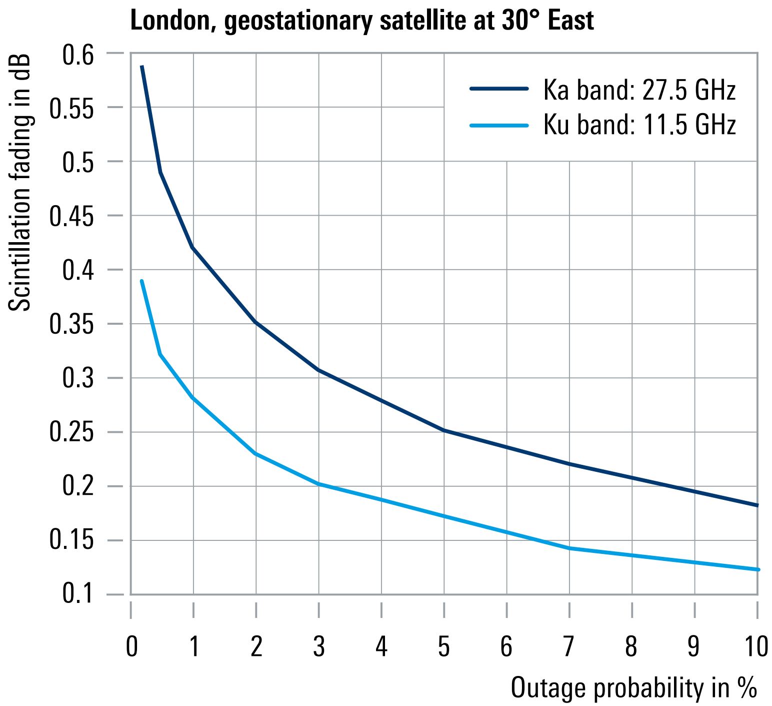
Microwave radiometers provide precise real-time data on attenuation and path delay with synchronized steering of the beams (according to the main antenna system). With a suitable choice of a multi-channel meteorological radiometer, such data is available at any desired frequency in the full spectral range from 1 GHz to 400 GHz.

For more information regarding radiometers, visit the Radiometer Physics website.

Scintillation

Scintillation is one of the lesser known attenuation effects in SATCOM systems. Scintillation describes the time-varying refraction index effect due to atmospheric turbulence. The major effect of scintillation is a sort of random signal attenuation, which effectively generates a channel fading effect. The scintillation fading effect requires additional power margins in the link budget. These additional power margins should be selected such that the desired signal availability can be maintained. The following figure shows the scintillation fading versus outage probability. Both curves illustrate the required power margins in order to achieve a given carrier availability for the Ka and Ku bands.

Fig. 42: Scintillation fading in dB as a function of outage probability in percent

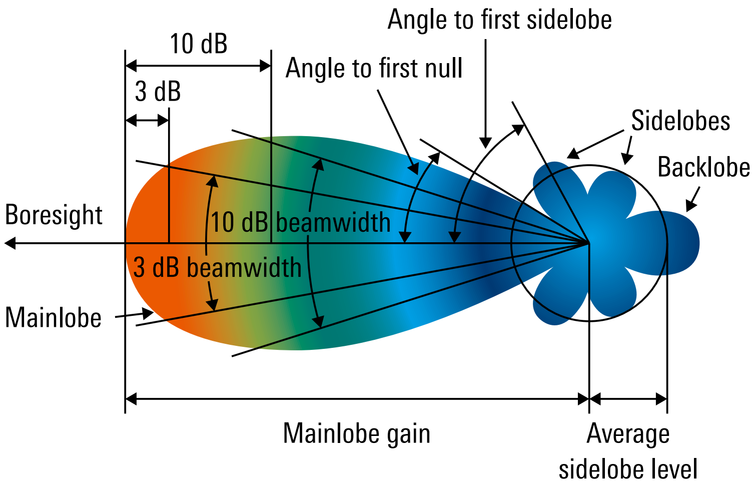


ANTENNAS AND WAVEGUIDES

Antenna pattern

Antenna pattern is a term for the angular dependence of the strength of the radio waves from the antenna source.

Fig. 43: Antenna gain in terms of direction



The **boresight** is the direction in which the antenna points. This is usually the direction of maximum gain when no electronic swiveling take place.

The **mainlobe** is the primary or maximum gain beam of the antenna. The mainlobe has both a vertical and a horizontal shape that can be the same (symmetrical) or different (asymmetrical). The power at this point is defined as 0 dB. All other values are relative to this point.

Antennas also have beams other than a mainlobe:

- The **backlobe** points in the opposite direction from the mainlobe.
- The **sidelobes** point in a different direction.
- **Grating lobe** is the term for a very strong sidelobe in the antenna pattern. It may have approximately the same size as the mainlobe. Grating lobes sometimes occur with phased array antennas depending on the steering direction (and also with ultrasound probes used in sonography).

Fig. 44: Parabolic dish radiation pattern

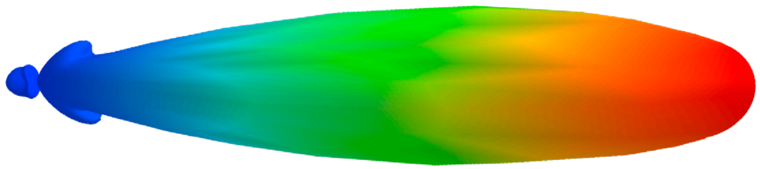
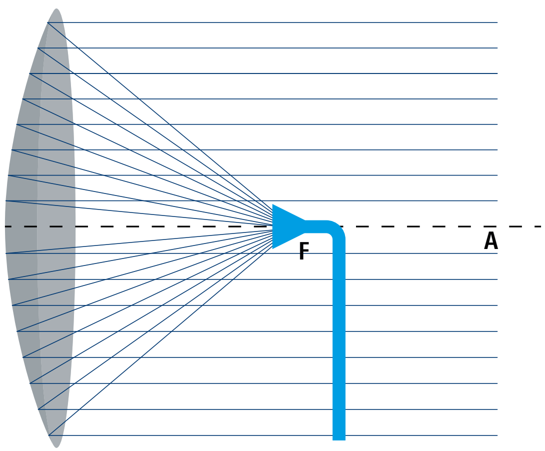


Fig. 45: Principles of operation for a parabolic antenna



Advantages of directional antennas:
- Low cost
- Highly directional
- Greater gain compared to phased array (typically)
- Low/no processing

Disadvantages of directional antennas:
- Mechanical steering required
- Slow change of beam direction
- Single beam
- Insensitive outside of main lobe
  (can also be considered as an advantage)

Signal and antenna polarization

Fig. 46: Vertical and horizontal polarization

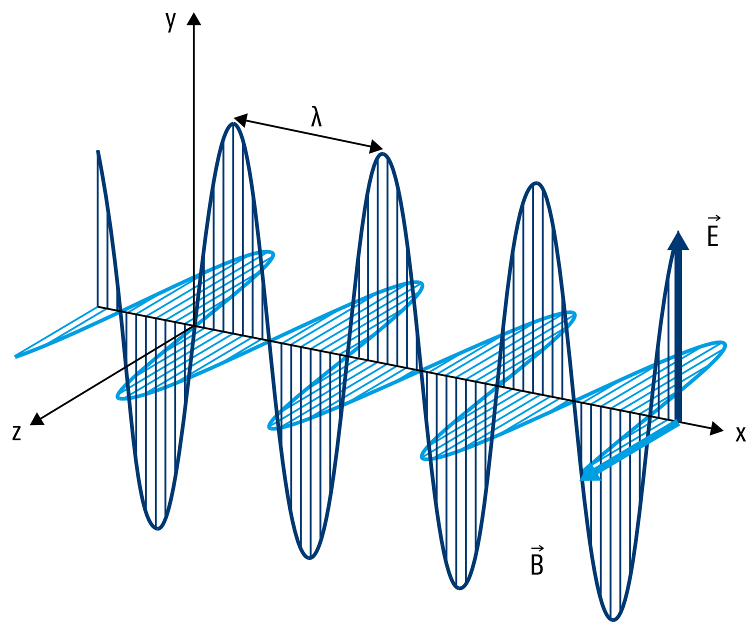


Fig. 47: Circular polarization

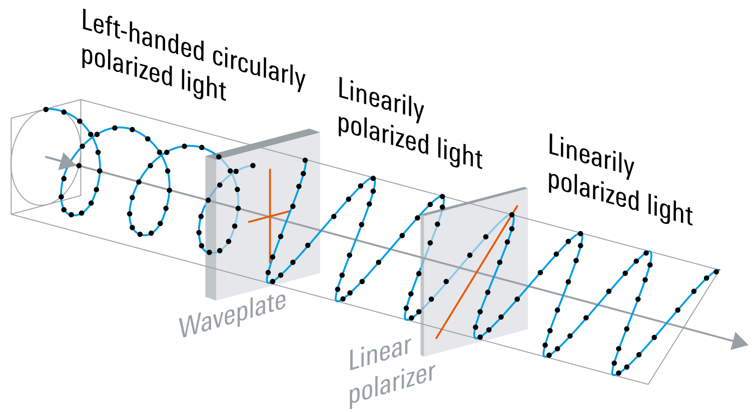


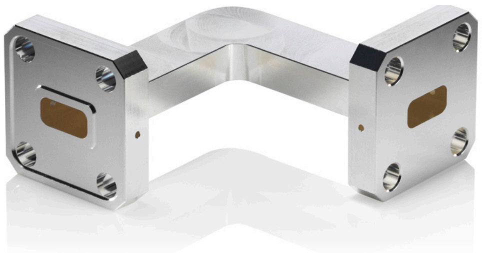
Table 13: Polarization and system design

Polarization	Degrees of freedom	Impact on system design
Linear polarization	Horizontal (H) Vertical (V)	Antenna/feed need to be angle matched to the polarization planes in order to prevent polarization crosstalk
Circular polarization	Right-hand side (RHS)	Good RHS versus LHS decoupling from 20 dB to 30 dB
	Left-hand side (LHS)	Can be received with linear polarized antenna with 3 dB gain loss

Waveguide and polarization

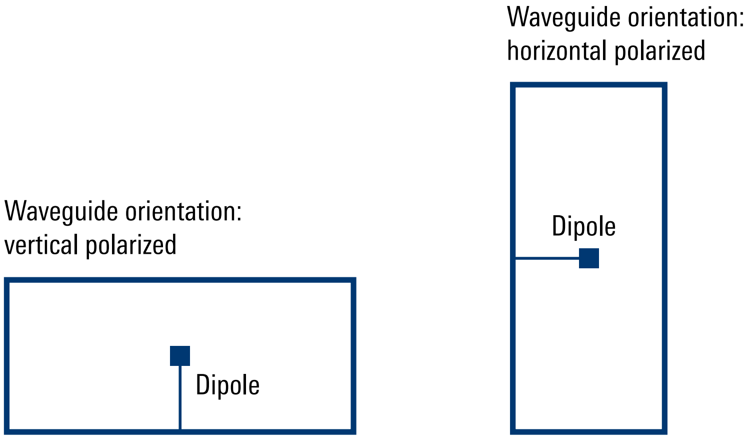
SATCOM ground stations typically use antenna feeds to connect the RF signal from the antenna to the receiver and from the transmitter to the antenna. Typically, an RF waveguide is used as the antenna feed. The waveguide consists of a rectangular shaped metal block.

Fig. 48: Image of a waveguide



Inside the waveguide, a quarter-wave dipole is used to convert the electrical signal into a radio wave. The dipole position inside the waveguide determines whether the antenna is horizontally or vertically polarized.

Fig. 49: Waveguide polarizations



Waveguide types are subject to international standardization as listed below:

EIA (US standard/ RG number)	RCSC (UK standard)	Band	Inner dimensions A side	Inner dimensions B side	Standard frequency width	Upper frequency limit
WR229	WG11A		58.166 mm	29.083 mm	3.30 GHz to 4.90 GHz	5.154 GHz
WR112/ RG51	WG15		28.499 mm	12.624 mm	7.05 GHz to 10.00 GHz	10.519 GHz
WR90/ RG52	WG16	X	22.860 mm	10.160 mm	8.20 GHz to 12.4 GHz	13.114 GHz
WR75	WG17		19.050 mm	9.525 mm	10.0 GHz to 15.0 GHz	15.737 GHz
WR51	WG19		12.954 mm	6.477 mm	15.0 GHz to 22.0 GHz	23.143 GHz
WR34	WG21		8.636 mm	4.318 mm	22.0 GHz to 33.0 GHz	34.714 GHz
WR28/ RG96	WG22	Ka	7.112 mm	3.556 mm	26.5 GHz to 40.0 GHz	42.153 GHz

Antenna systems

Parabolic antennas

Fig. 50: Stationary dish

Parabolic dish-shaped reflector antenna. Typically used in GEO SATCOM systems. Antenna gain depends on dish size (aperture). Large antennas require accurate pointing towards the satellite.

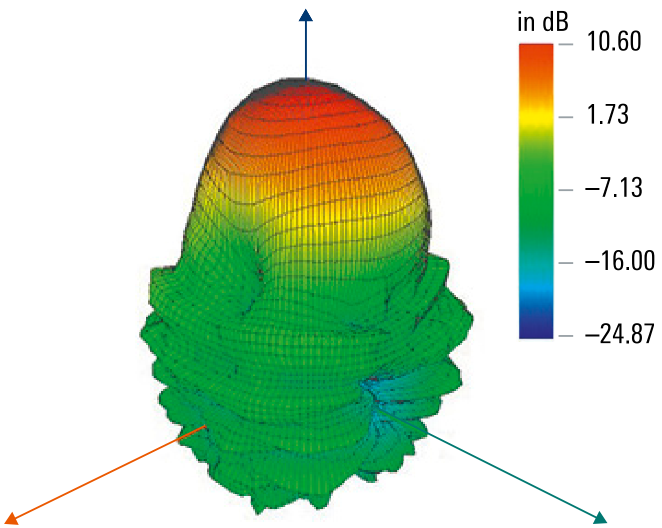
Fig. 51: VSAT antenna for SATCOM applications

VSAT antenna with fully automated tracking for stable satellite internet at sea (with kind permission of EPAK GmbH)

Mechanically tracked very small aperture terminals are used in maritime or vehicular SATCOM on the move (SOTM) applications. They are typically protected against environmental and weather effects by a radome. The radome is transparent to radio waves and imposes a negligible extra signal attenuation on the SATCOM carrier.

Electronically steerable antennas (ESA)
Phased array antennas are electronically steerable antennas consisting of multiple single antenna elements that are combined to form one large array. Each antenna element signal is individually phased shifted such that the antenna is sensitized to a desired spatial direction of signal arrival.

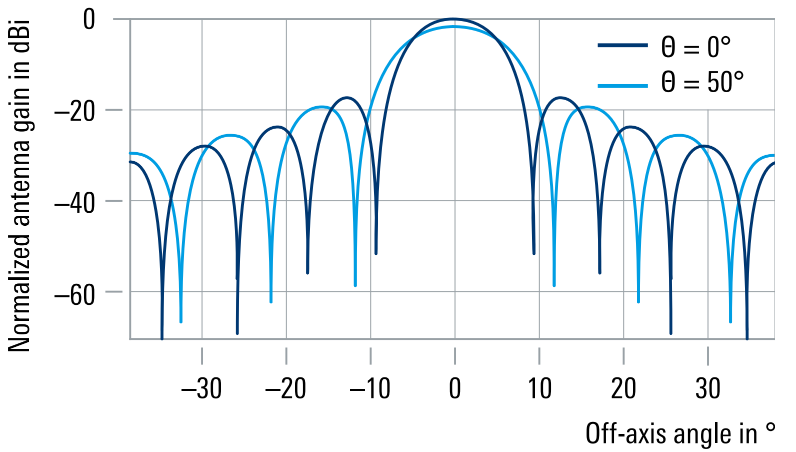
Fig. 52: Electronically steerable antenna (ESA)



Phased array antennas come in a flat antenna panel without any mechanical elements. Since no active mechanical elements are required, the antennas are typically more robust in harsh environments than mechanically steerable antennas. Phased array antennas can also be implemented with a semi-mechanical design using a combination of mechanical and electronic steering.

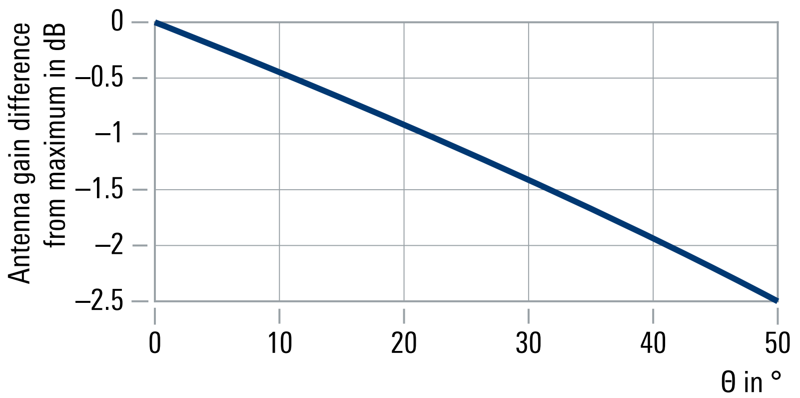
Phased array antennas exhibit a scan loss. The scan loss causes degradation of the on-axis antenna gain with increasing scanning angle. The scanning angle θ denotes the steering angle of the antenna. Scan loss also widens the antenna diagram as depicted below.

Fig. 53: Effect of gain loss and antenna lobe widening versus off-axis angle in ESA



In practice, the scanning loss of phased array antennas is measured in dB difference towards the maximum antenna gain at θ = 0° as depicted below.

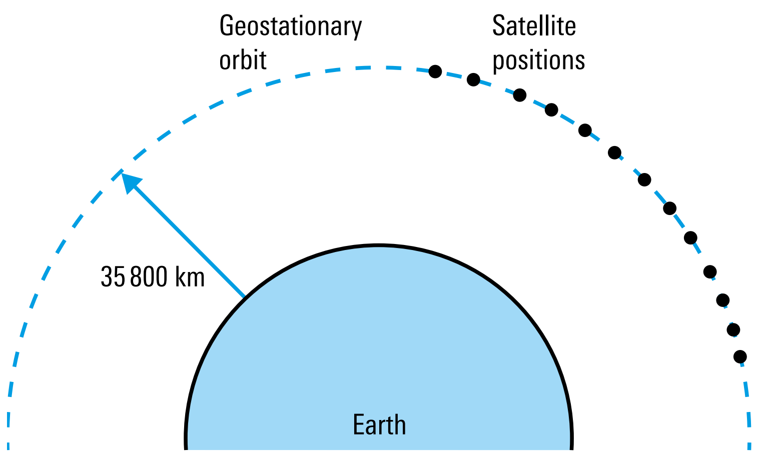
Fig. 54: Effect of scan loss in phased array antennas



GEOSTATIONARY SYSTEMS

GEO constellations

Fig. 55: Geostationary orbit



GSO orientation is parallel to earth´s equatorial plane

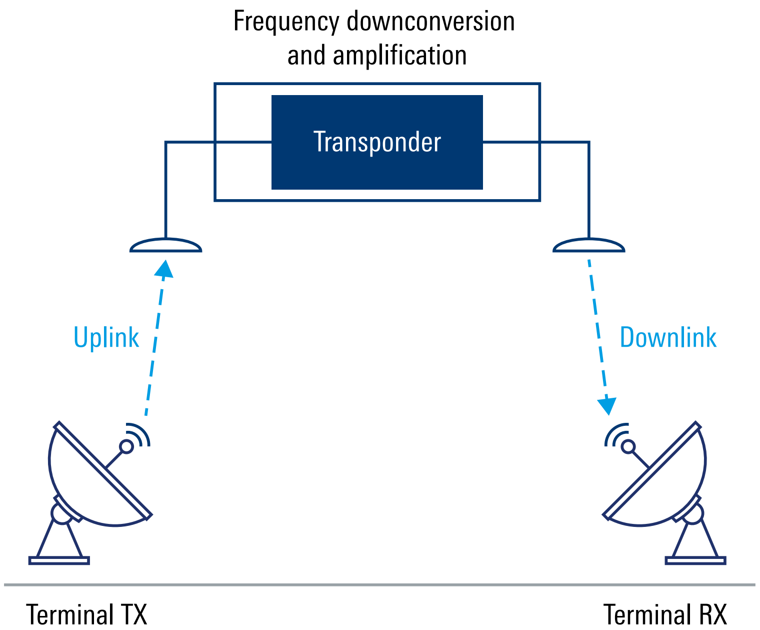
- The angular velocity of a geostationary orbit (GSO) is the same as the earth’s rotation. As a result, each orbit position in GSO exhibits constant azimuth and elevation angles when seen from earth.
- Geostationary satellite systems offer a large coverage area (up to global coverage).
- GSO orbital positions are occupied by some hundred complex high-power satellites with a long lifetime (approx. 15 years).
- Constant satellite position in GSO allows the use of stationary antennas without the need for antenna tracking.
- High signal attenuation due to 35 800 km orbit height
- High propagation delay (240 ms for uplink and downlink)

Table 14: Earth coverage definitions (INTELSAT)

Beam	Definition
Global beam	coverage of earth in view; small EIRP requires large earth station antennas
Hemi beam	coverage of earth in view with two beams, higher EIRP than global beam
Wide beam	partial earth coverage, e.g. Europe, Middle East, North Africa
Zone beam	coverage of earth in view with four beams, higher EIRP than hemi beam
Spot beam	steerable antenna for VSAT or high data rate applications

Transponder types

Fig. 56: Geostationary satellite transponder definition

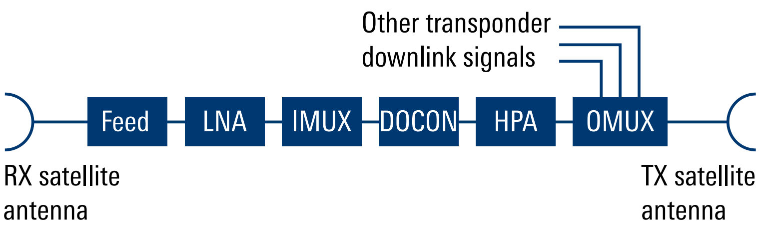


- Geostationary satellite transponders typically act as transparent bent-pipe systems.
- Carrier uplink and downlink frequencies are different. The transponder performs a carrier frequency downconversion of the received uplink signal before it is transmitted back to earth.
- Transparent mode: Satellite transponder amplifies uplink signal and transmits the signal back to earth.
- Digital transparent mode: Uplink signal is digitized in the satellite transponder and sent back to earth.
- Regenerative mode: Uplink signal is received and decoded by satellite, uplink bit errors are corrected in satellite receiver, refreshed signal is sent back to earth.

Transparent GEO transponder

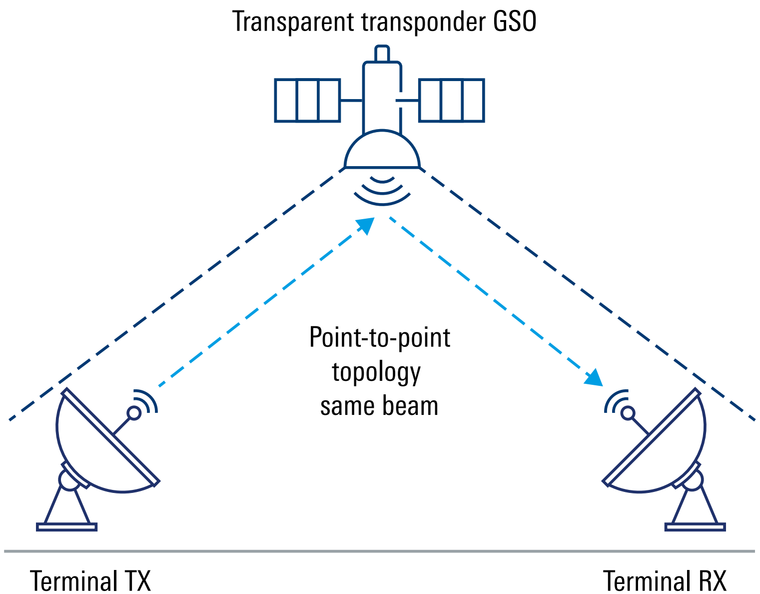
- **Feed:** RF waveguide between antenna and transponder circuitry
- **LNA:** Low-noise power amplifier, amplifies incoming uplink signal with low noise figure and almost no signal distortion
- **IMUX:** Input multiplexer, RF filter to extract transponder channel band from entire received uplink signal
- **DOCON:** Downconversion, frequency shift from uplink frequency down to downlink frequency, involves frequency synthesizer and mixer
- **HPA:** High power amplifier, signal amplification of entire transponder signal
- **OMUX:** Output multiplexer to send different downlink signals to one antenna, involves RF filters to minimize inter-channel interference

Fig. 57: Geostationary transponder building blocks



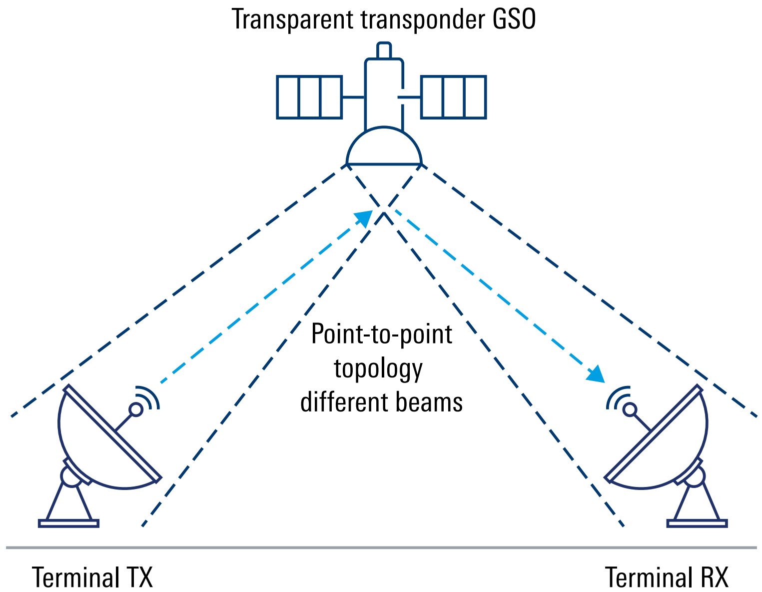
Geostationary system topologies

Fig. 58: Geostationary point-to-point topology



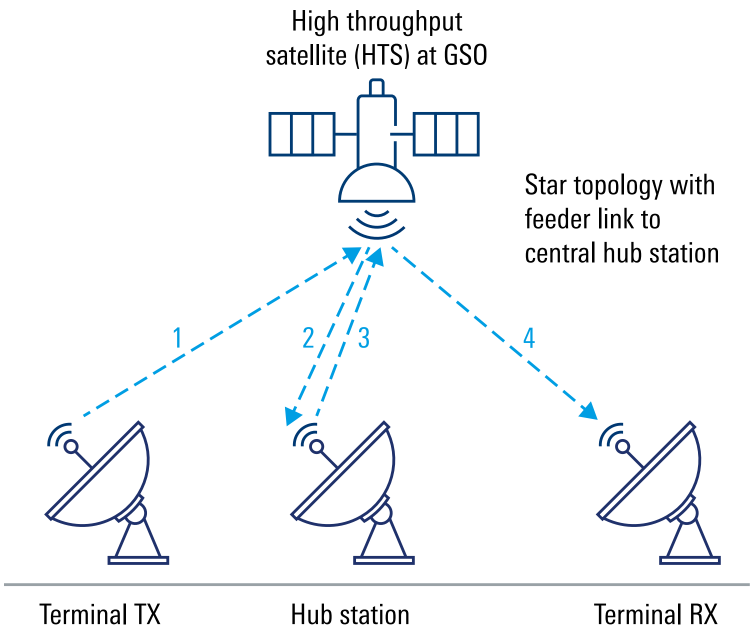
Point-to-point topologies are typically used in GEO systems for IP trunking applications.

Fig. 59: Geostationary point-to-point topology using different beams



Point-to-point topologies can be set up in the same satellite antenna beam. Alternatively, certain GEO transponder channels allow use of different beams for the uplink and downlink.

Fig. 60: Geostationary high throughput satellite using central hub station

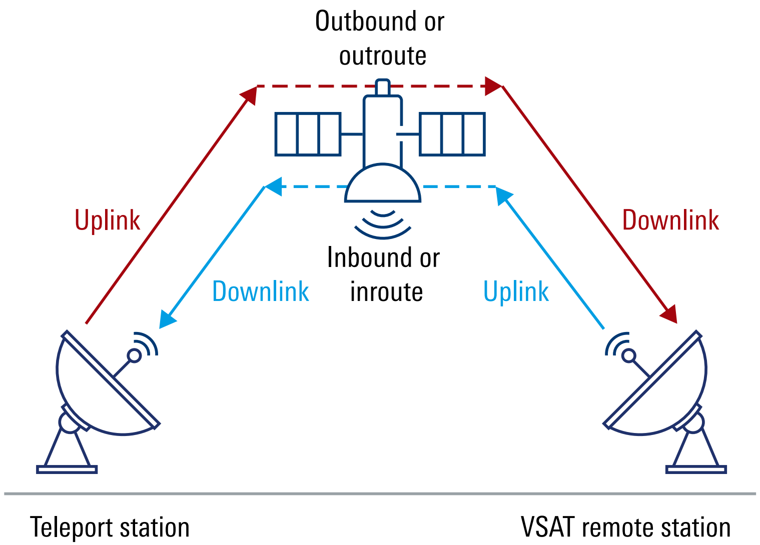


Digital high throughput satellites (HTS) are often used for VSAT systems where the user traffic is routed to a central hub station via a feeder link.

Single carrier per channel (SCPC)

The SCPC mode is typically used to establish a bidirectional data link over a GEO satellite. For the inbound and outbound traffic, individual FDM carriers are used.

Fig. 61: Geostationary SCPC setup used for IP trunking



GEO SCPC satellite communications typically uses ground station infrastructure with large-scale stationary dishes. Such ground stations are typically called teleport stations. The teleport station provides internet access for the remote station over GEO satellites. Hence, SCPC provides internet access to VSAT remote stations over a worldwide coverage area.

Fig. 62: Teleport antenna site

Very small aperture terminal (VSAT) systems

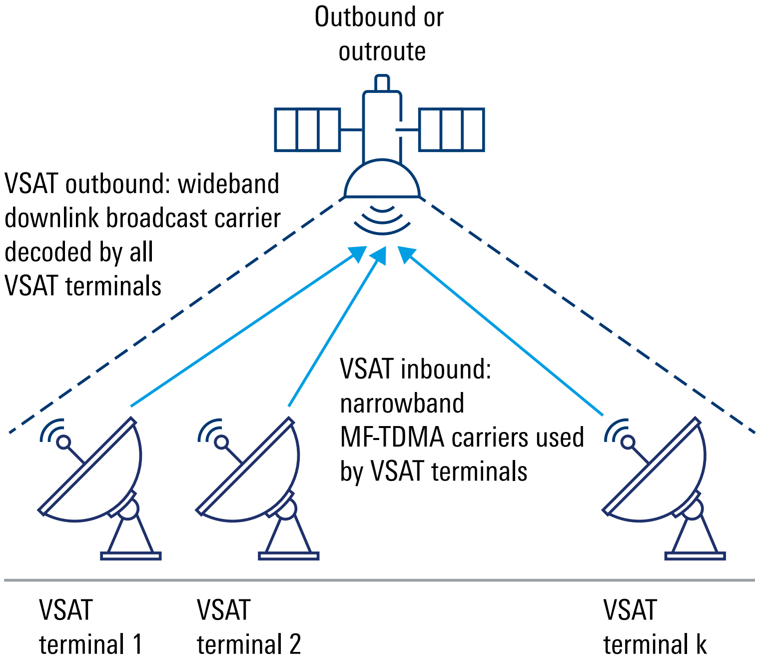
Various VSAT applications build TDMA based meshed networks using a wideband outbound carrier and narrowband inbound carriers.

The narrowband inbound carriers can use the same spectrum as the outbound carrier (carrier-in-carrier technology).

The outbound signal is defined from the VSAT hub station to the remote carriers. Typically, a wideband DVB-S2 carrier is used where the information for each VSAT terminal is multiplexed into the broadband outbound data stream.

The inbound signal is formed by narrowband TDMA carriers that are set by the VSAT terminals. Hence, the VSAT hub uses a wideband multicarrier receiver to simultaneously demodulate each of the incoming TDMA VSAT carriers.

Fig. 63: Geostationary VSAT topology

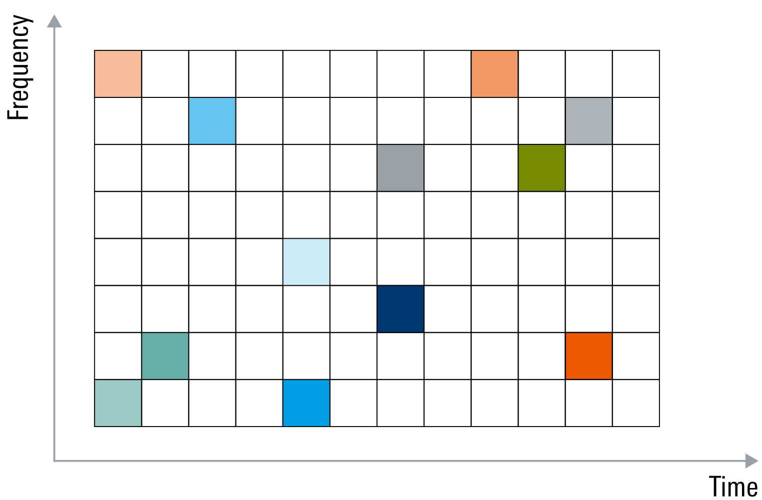


VSAT system medium access

Modern VSAT systems apply dynamic timeslot and subcarrier allocations to each of the terminals. At regular time intervals, the VSAT hub station defines a burst time plan that is propagated by the outbound carrier to all remotes. The burst time plan assigns timeslot and frequency resources to VSAT terminals and defines the modulation and FEC rate of the inbound carriers.

The combination of timeslot and subcarrier allocations is known as multi-frequency time division multiple access (MF-TDMA). The timeslot and subcarrier assignment is updated regularly depending on the traffic demand (data rate requirements) of the corresponding VSAT remote stations.

Fig. 64: Burst time plan for multi-user scheduling



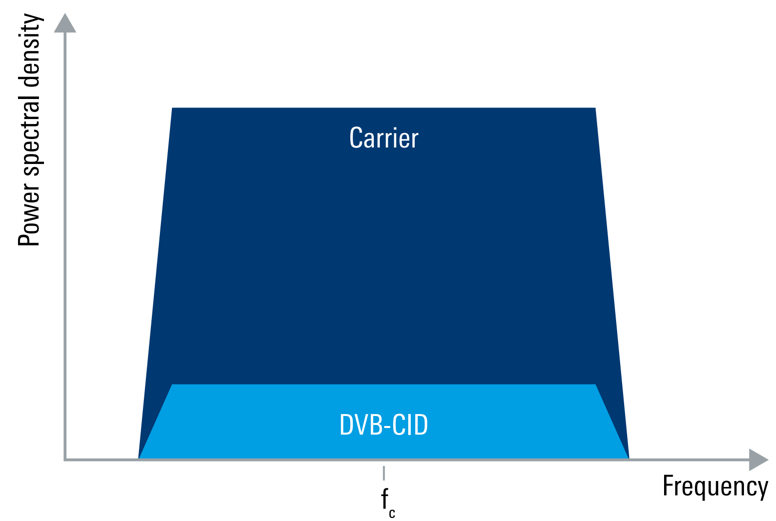
DVB-CID

Modern satellite communications must deal with signal interference, i.e. such interference needs to be efficiently avoided. The Digital Video Broadcasting organization has specified a carrier ID (CID) that identifies the host carrier, effectively reducing interference between satellite signals, e.g. DVB-S2X.

Additional DVB-CID receivers handle CID signals, i.e. they are detected and then demodulated. The CID-specific "global unique ID", the GPS coordinates and the telephone number of the carrier operator are extracted. The global unique ID allows users to identify their satellite signal source precisely.

Since DVB-CID signals are transmitted inside the payload carrier signal (overlay direct sequence spread spectrum technique), they are difficult to monitor. R&S®GSACSM communication system monitoring can efficiently demodulate and decode DVB-CID signals.

Fig. 65: DVB-CID spread signal spectrum



Fixed satellite service (FSS) transmitter setup

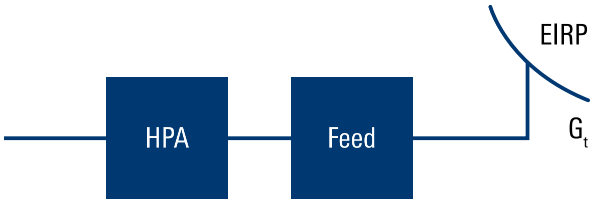
Modem: Performs modulation of digital input data stream (bits) to a SATCOM carrier. The carrier symbol rate and L band center frequency can be parameterized by the modem user interface. The SATCOM modem typically provides a wide range of digital modulation formats and FEC.

BUC: A block upconverter translates the L band analog input carrier delivered by the SATCOM modem to the desired frequency band (e.g. C band, Ka band, Ku band).

HPA: A high power amplifier boosts the BUC output signal by a given gain factor. The HPA signal is directly sent to the antenna feed.

Feed: Connection of antenna and HPA output, waveguide of received RF signal. The feed is frequency dependent. Multiband feeds can be used to simultaneously receive satellite signals on multiple bands.

Fig. 66: SATCOM transmitter frontend



Fixed satellite service (FSS) receiver setup

Feed: Connection of antenna and LNA, waveguide of received RF signal. The feed is frequency dependent. Multiband feeds can be used to simultaneously receive satellite signals on multiple bands.

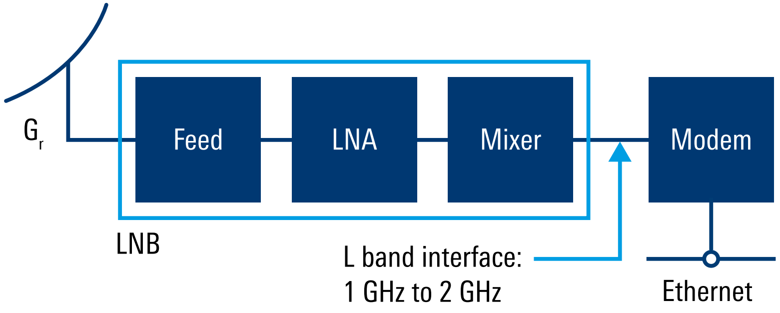
LNA: Low-noise amplifier used in receiver to increase RX signal power prior to analog and digital receiver signal processing.

Mixer: Converts the receiver input signal center frequency down to L band (1 GHz to 2 GHz).

LNB: Low-noise block downconverter combines feed, LNA and mixer (frequency downconversion) into one building block.

Modem: Performs RX signal demodulation. Modem input is the received SATCOM carrier, downconverted to L band. The modem digital output interface is typically an RJ-45 plug (Ethernet).

Fig. 67: SATCOM receiver components



High throughput satellites (HTS)

New type of GEO communications satellites that offer high data transmission capacity by using:

Digital transparent payloads: Each received signal is digitized to allow adaptive signal decomposition and flexible downlink antenna routing.

Flexible multispot beam technology: The uplink and downlink antennas are designed to allow focusing of multiple antenna beams such that they only cover areas of less than 1000 km diameter on the ground. This allows reuse of frequency resources in multiple beams, which greatly increases the spectral efficiency of the entire SATCOM system.

Fig. 68: Geostationary HTS payload building blocks

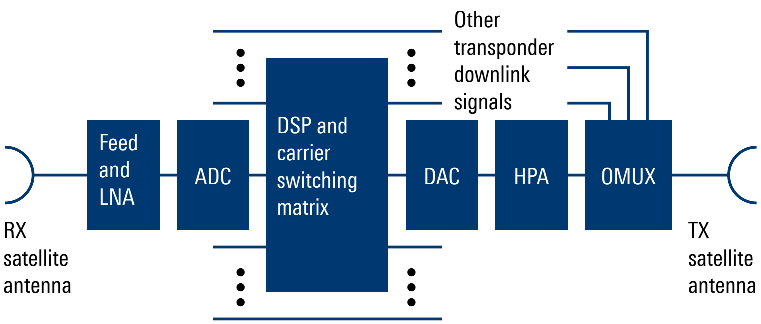
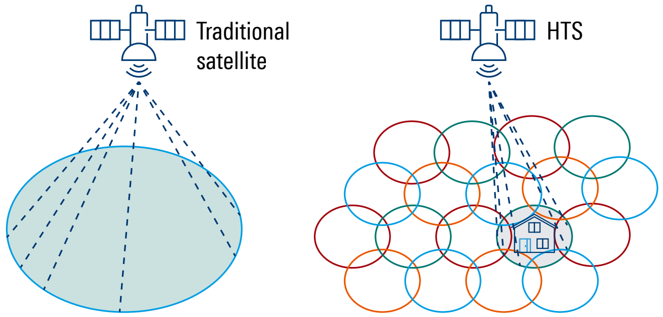


Fig. 69: Cellular coverage and beam steering



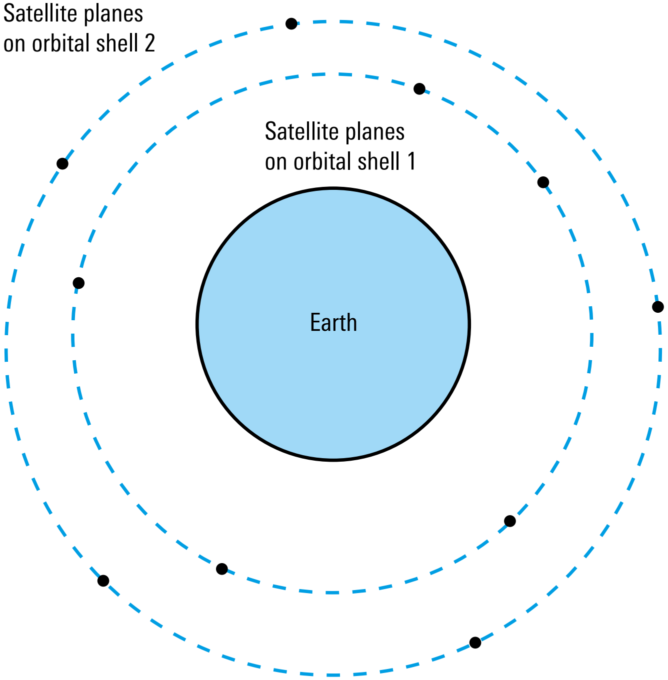
Left: Traditional GEO wide beam coverage with single beam antennas
Right: Multiple small-sized beams forming a cellular grid on ground

LEO SATELLITE SYSTEMS

LEO constellations

LEO constellations are often formed by Walker-Delta designs. Per orbital shell, multiple orbital planes of the same altitude and inclination are used. Satellites on the same orbital shell have the same altitude, but are coordinated such that collisions never occur between orbital planes.

Fig. 70: LEO SATCOM: satellite planes on orbital shells

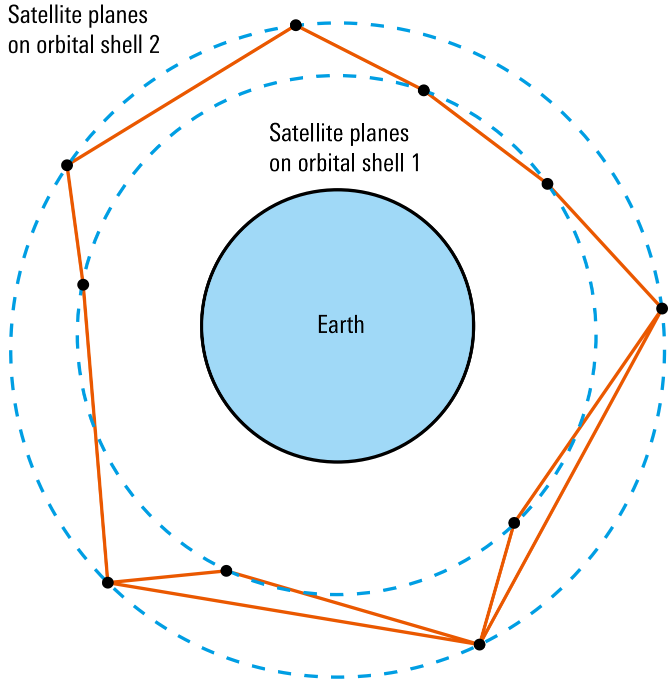


LEO constellations ISL

Inter-satellite links (ISL) are used for data routing through LEO constellations. ISL links are either implemented as microwave links or via laser terminals. Modern laser communications terminals (LCT) allow gigabit traffic to multiple network nodes.

Microwave inter-satellite links are more cost-efficient, but they have a limited data rate and are subject to mutual ISL interference. LCT ISL links do not suffer from interference due to the good focus of the laser beam.

Fig. 71: ISL for LEO SATCOM

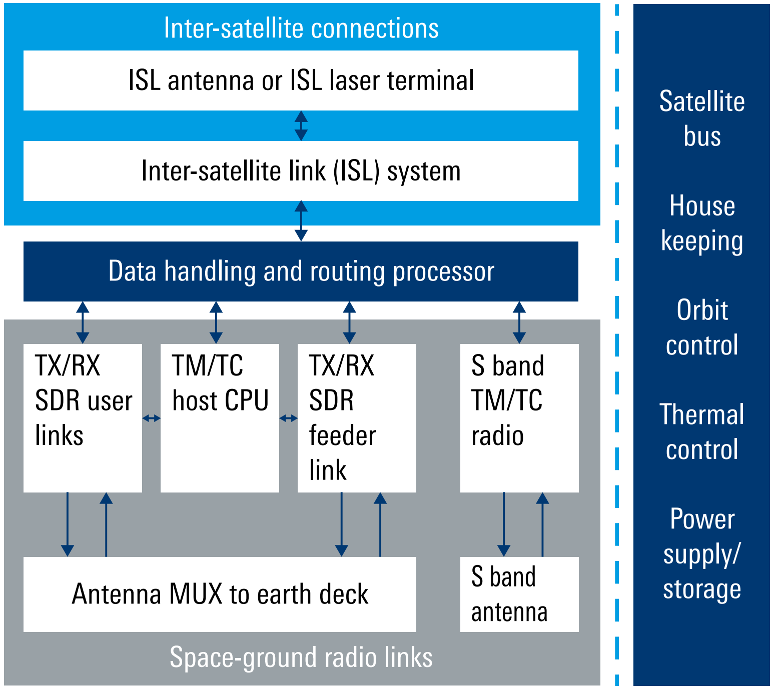


LEO payload architectures

A LEO satellite payload typically consists of four parts:

- Space-ground communications digital payload
- Inter-satellite communications terminal
- Data handling and routing system
- Satellite bus infrastructure subsystems

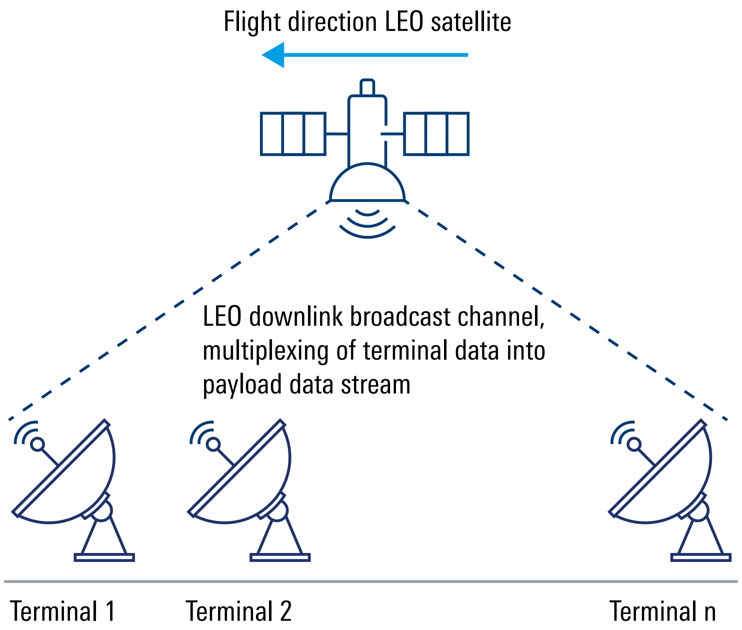
Fig. 72: LEO satellite payload structure



Downlink broadcast channel

All ground station receivers receive and decode the downlink signal. Information for each ground station terminal is multiplexed into the downlink data stream.

Fig. 73: LEO SATCOM downlink concept

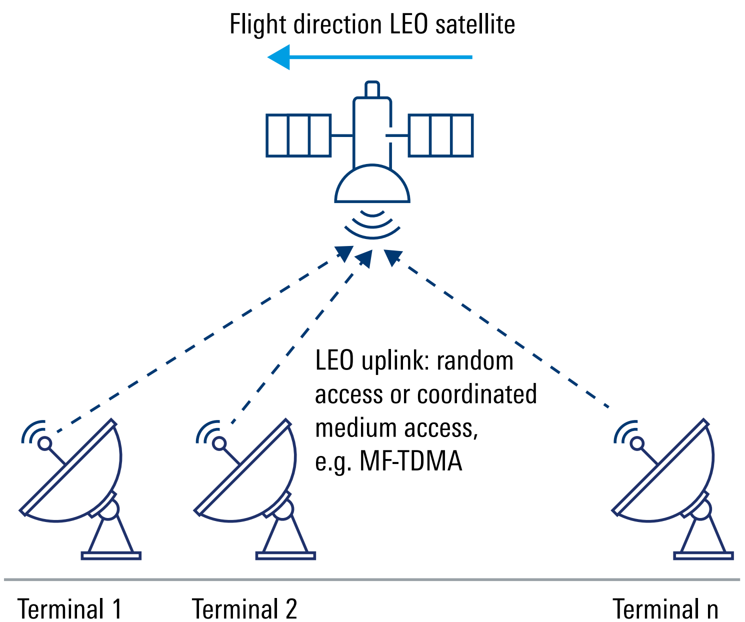


Since the LEO orbit position is time-varying, the LEO ground station receivers need to continuously track the antenna pointing towards the LEO overflight pass. Typical LEO overflight time durations differ depending on the orbit height. Typical values range from two minutes to six minutes.

Uplink channel

All ground station terminals use orthogonal uplink signals to prevent signal collisions at the satellite receiver. The LEO receiver is able to simultaneously demodulate and decode each of the different uplink signals. Typically, MF-TDMA is used to realize multi-user orthogonality in the LEO uplink.

Fig. 74: LEO SATCOM MF-TDMA uplink concept

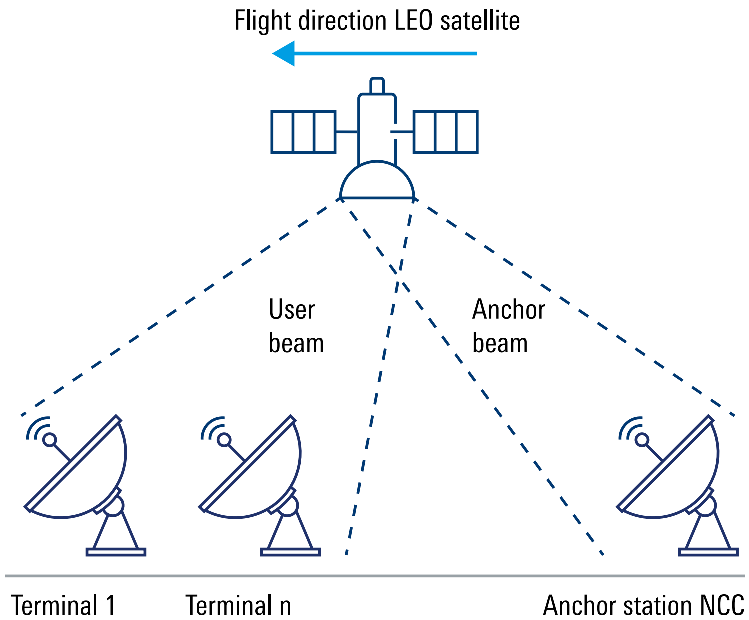


In order to maximize the data throughput for each LEO terminal, the satellite constantly measures the uplink CNR. Depending on the measured CNR, the MODCOD and symbol rate for each uplink carrier are adapted (adaptive coding and modulation (ACM)).

System control

LEO system user management and radio resource allocation are implemented in a central anchor station. This anchor station is often referred to as the network control center (NCC) or network control station (NCS).

Fig. 75: LEO SATCOM over centralized NCC over anchor beam



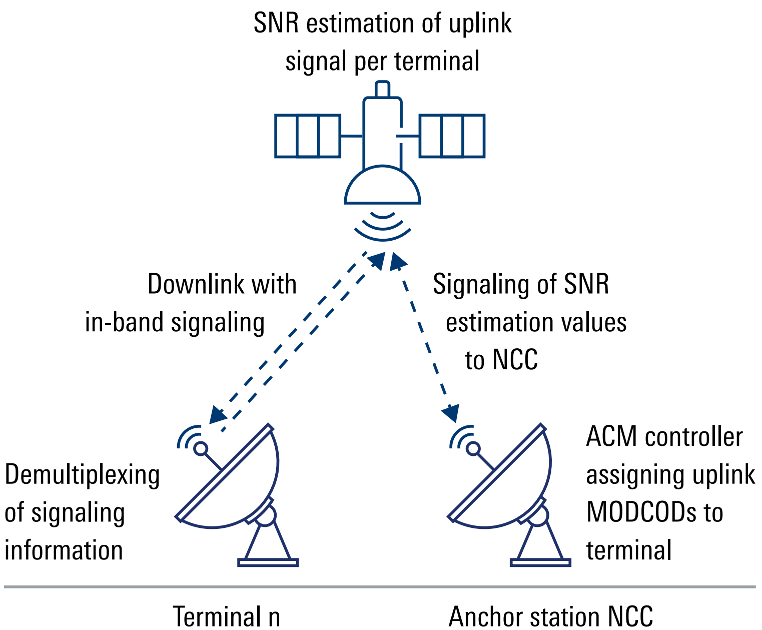
Typically, the anchor station uses a separate communications link to/from the LEO satellite. In some cases, even a separate antenna is used to realize the anchor beam data transfer. The anchor beam typically implements the telemetry and telecommand (TM&TC) link that is crucial for LEO operation.

It is possible to update the LEO firmware over the TM&TC link.

Adaptive coding and modulation (ACM)

In order to maximize the data throughput, the modulation and coding scheme (MODCOD) needs to be assigned in a terminal-specific manner. MODCOD selection is handled such that the total data rate of all terminals is maximized. Therefore, the uplink SNR for each terminal is constantly monitored in the LEO satellite receiver. The SNR values are fed to the NCC where the MODCOD selection is implemented for all terminals within the satellite coverage.

Fig. 76: LEO SATCOM ACM infrastructure



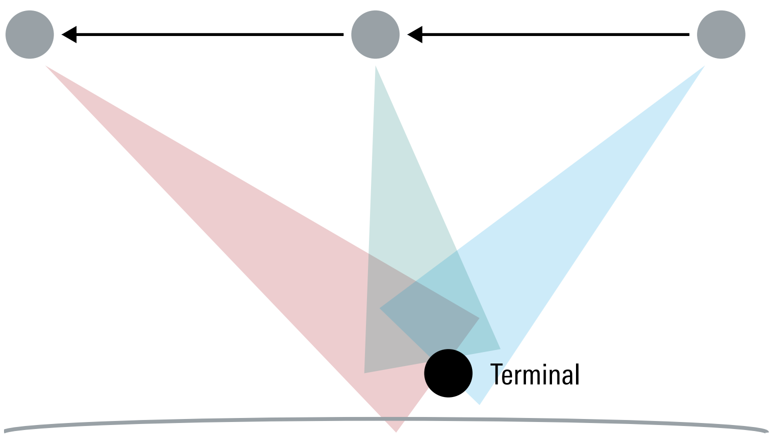
LEO SATCOM ACM follows these steps:

- Measurement of uplink SNR for each terminal
- Signaling of SNR information to NCC
- MODCOD selection in NCC
- Signaling of MODCOD selection back to LEO
- Signaling of MODCOD selection by downlink broadcast carrier to all terminals

Time-varying radio wave propagation conditions

Contemporary LEO satellite systems use phased array beamforming antennas for proper beam tracking towards the ground terminals. During the LEO overflight, the LEO antenna beam needs to be accurately pointed towards the terminals at all times (and vice versa).

Fig. 77: LEO satellite communications over time-varying channels



The time during which wireless data communications is possible between a satellite and terminal is known as the contact time duration. It ranges from three minutes to six minutes, depending on the orbit height. LEO radio wave propagation is heavily influenced by the Doppler effect.

Doppler effect

The Doppler effect originates from relative motion between the LEO satellite and the ground terminal. The Doppler frequency shift $f_{Doppler}$ increases or decreases the receiver carrier frequency f_c. It needs to be compensated at the radio receiver before carrier demodulation can be performed:

$$f_c' = f_c + f_{Doppler}$$

Given v_0 as the LEO satellite orbital velocity, the Doppler shift can be calculated as (non-relativistic):

$$f_{Doppler} = f_c \frac{v_0}{c} \cdot \cos\alpha$$

Here, α represents the angle between the velocity vectors of the satellite and the ground terminal. In addition to a carrier frequency shift, the Doppler effect introduces a symbol clock timing error as follows:

$$\Delta T_{Sym} = \frac{f_{Doppler}}{f_c} T_{Sym}$$

The symbol clock timing error ΔT_{Sym} denotes the signal time dilation that expands or compresses the data symbols at the receiver.

Since the Doppler effect is time-varying, we introduce the Doppler rate $r_{Doppler}$ in Hz/s as follows:

$$r_{Doppler} = \frac{df_{Doppler}}{dt}$$

Table 15: Doppler effect in different LEO systems

Orbit height (altitude) in km	Carrier frequency in MHz	Average $f_{Doppler}$ in kHz	Maximum $f_{Doppler}$ in kHz	Average $r_{Doppler}$ in Hz/s
300	450	6	9	68
300	850	11	17	128
300	1500	20	30	226
300	3500	48	72	528
300	5500	75	113	830
300	10000	137	206	1508
300	12000	164	247	1809
300	20000	274	412	3017
300	27000	371	557	4072
500	450	5	8	62
500	850	10	15	117
500	1500	18	26	206
500	3500	41	61	481
500	5500	64	97	756
500	10000	117	176	1374
500	12000	141	211	1649
500	20000	234	351	2748
500	27000	316	474	3709
700	450	4	7	55
700	850	8	13	104
700	1500	15	22	184
700	3500	35	52	429
700	5500	54	82	674
700	10000	99	148	1225
700	12000	119	178	1471
700	20000	198	297	2452
700	27000	267	400	3310
1000	450	3	5	45
1000	850	7	10	86
1000	1500	12	17	151
1000	3500	27	40	353
1000	5500	42	64	555
1000	10000	77	116	1009
1000	12000	92	139	1210
1000	20000	154	231	2017
1000	27000	208	312	2723

Fig. 78: LEO SATCOM overflight ground track example

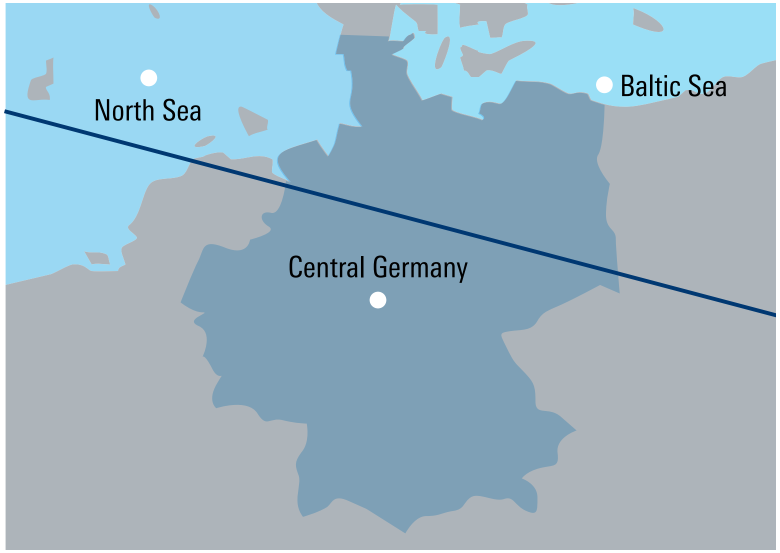


Fig. 79: LEO SATCOM overflight Doppler frequency shift example

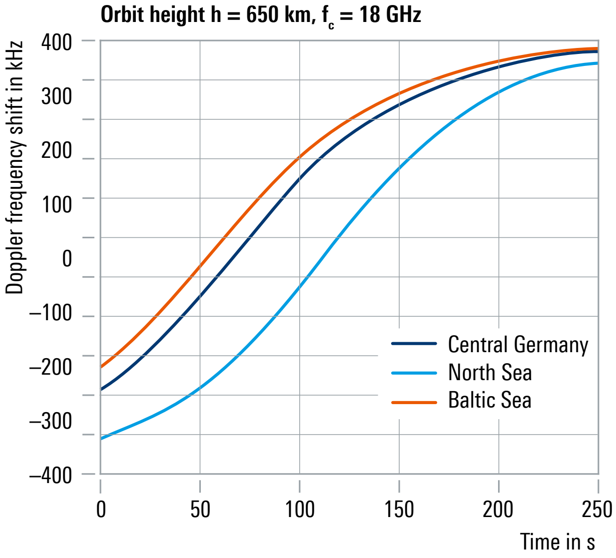
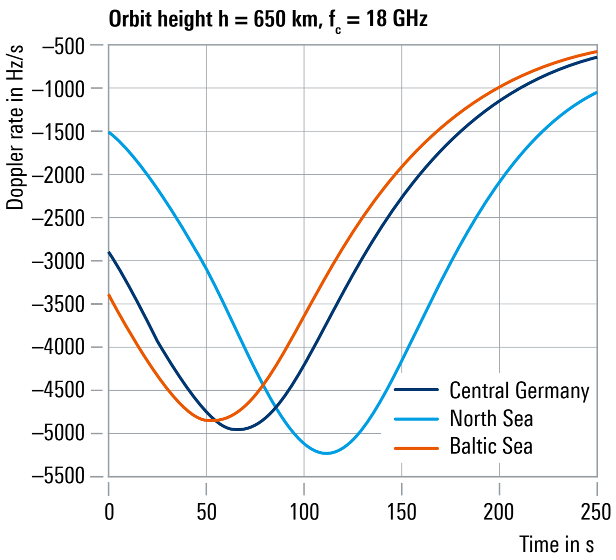


Fig. 80: LEO SATCOM overflight Doppler rate example

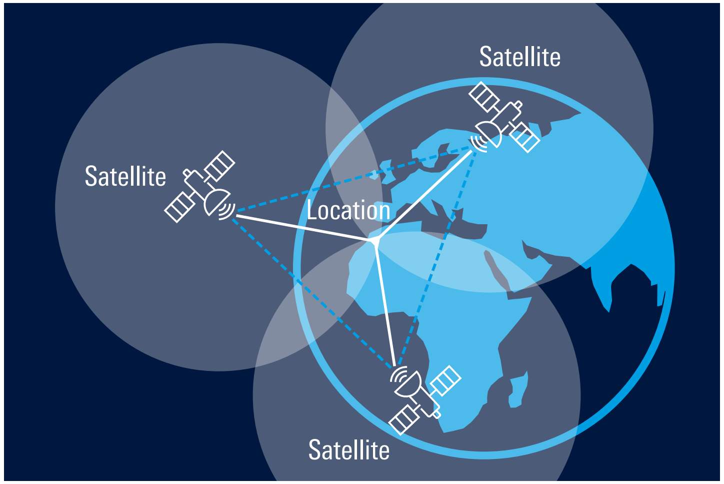


POSITIONING, NAVIGATION AND TIMING (PNT)

PNT systems typically consist of 18 to 30 MEO satellites orbiting the earth. Atomic clocks are used to precisely synchronize the time of all satellites in a constellation. Each satellite broadcasts a signal that encodes its own orbital position, the precise transmission time and a rough almanac of all satellites in the constellation.

Basically, a receiver can calculate its own position through triangulation using the signals from at least three satellites at sea level or four satellites at any altitude.

Fig. 81: Position determination via triangulation



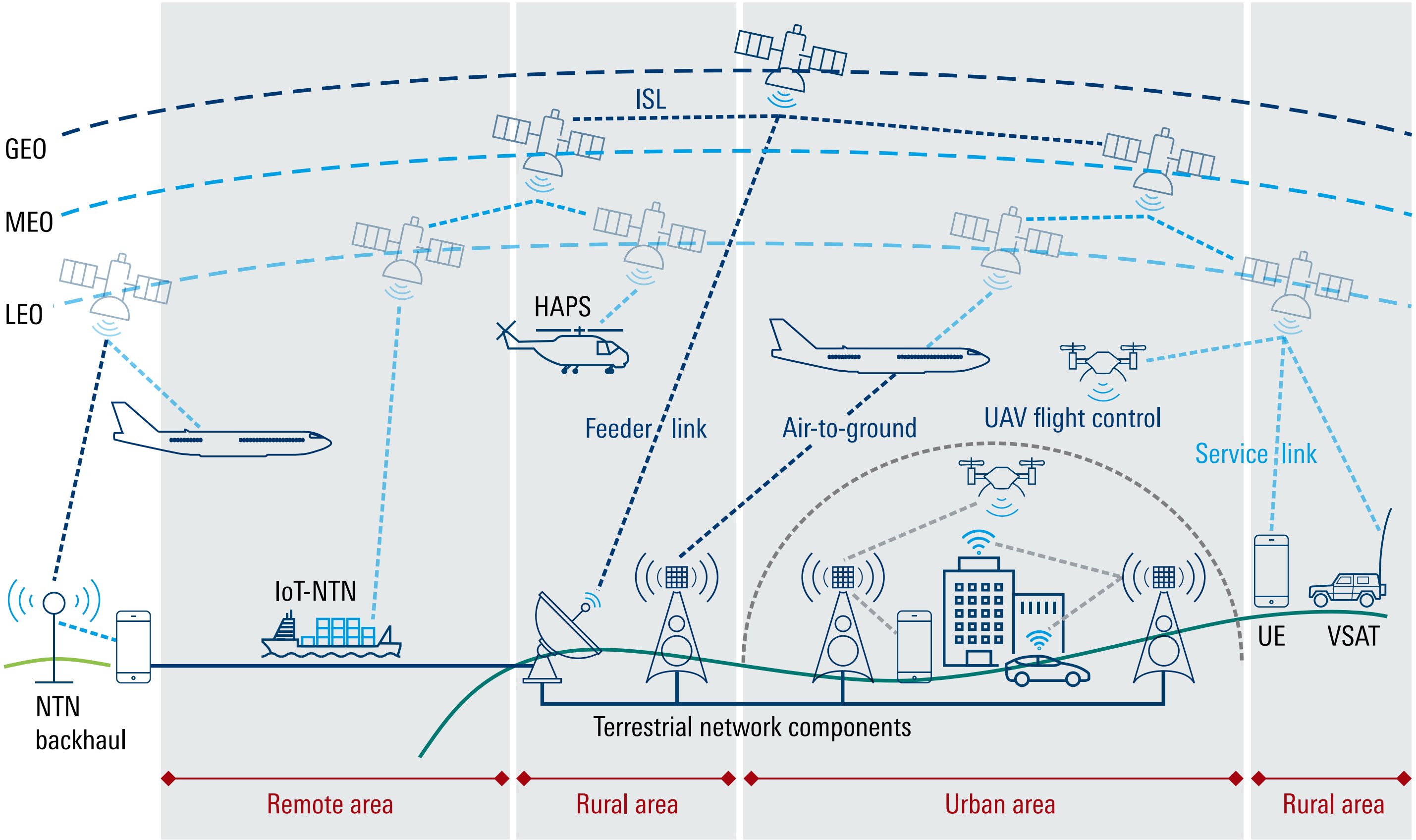
Satellite PNT systems play an indispensable role in many applications and are used for:

- ▶ Global navigation satellite systems (GNSS): GPS (United States of America), Galileo (Europe), GLONASS (Russia), BeiDou (China)
- ▶ Satellite based augmentation systems (SBAS) to enhance the accuracy of GNSS for maritime and aviation safety: WAAS (United States of America), EGNOS (Europe)
- ▶ Precise timing synchronization needed in telecommunications, financial transactions, power grid management and scientific experiments
- ▶ Precise positioning of LEO satellites in orbit

5G non-terrestrial networks (NTN) represent the evolution of wireless communications toward satellite and airborne based global communications. Network nodes are integrated into satellites and move relative to the earth's surface. Over the long term (6G), multi-orbit networks will become reality with 3D network nodes at all LEO, MEO and GEO altitudes.

5G NON-TERRESTRIAL NETWORKS (NTN)

Fig. 82: General connectivity overview of non-terrestrial networks



For more information regarding 5G NTN testing solutions, visit our website.

There are two application areas for NTN that address different applications and markets:

- **NTN-IoT:** Will provide true global coverage of IoT across land, sea and air using GEO and LEO satellites
- **NTN-NR:** Aims to connect LEO satellites directly to mobile phones and provide connectivity in rural areas

SATCOM MONITORING

A monitoring ground station typically distinguishes between two infrastructure parts:

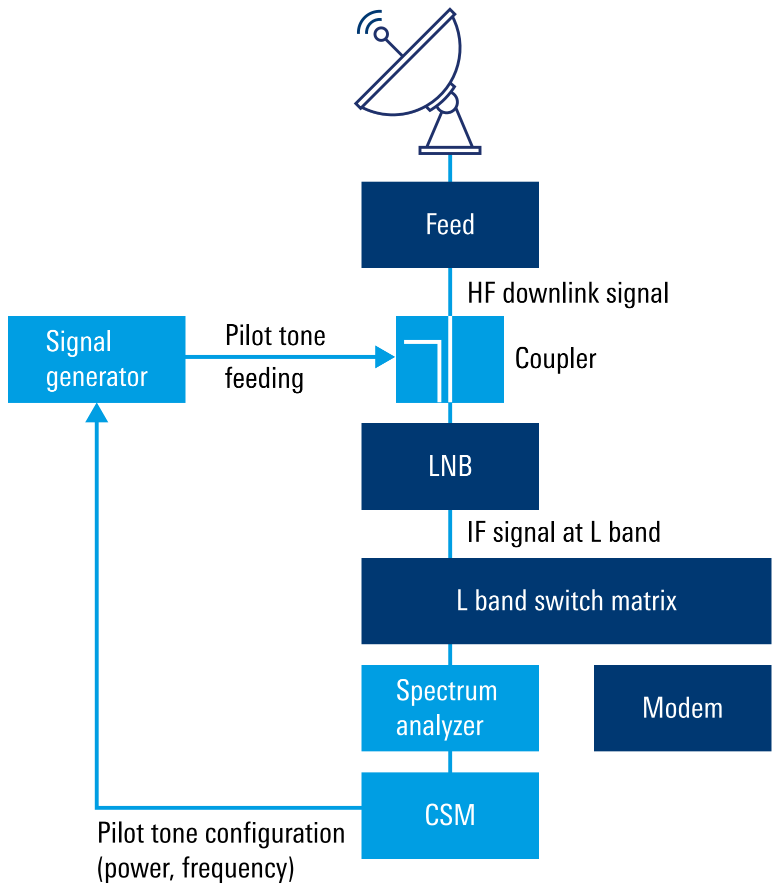
- Payload/data communications system with internet and WAN access
- Communications system monitoring (CSM)

Antenna signals are typically downconverted to an intermediate frequency in the L band and made available to data modems via a switching matrix.

The CSM uses spectrum analyzer hardware that is also connected to the switch matrix. Hence, the CSM can measure each of the incoming antenna signals by L band switching. CSM typically uses software defined radio functions to demodulate the downlink signals for advanced monitoring and QoS reporting.

For highly accurate receive signal power measurements, pilot tone feeding is used to provide a reference signal to the monitoring system.

Fig. 83: Communications system monitoring infrastructure



Any communications system monitoring (CSM) system uses signal spectrum measurements to monitor fundamental SATCOM carrier parameters:

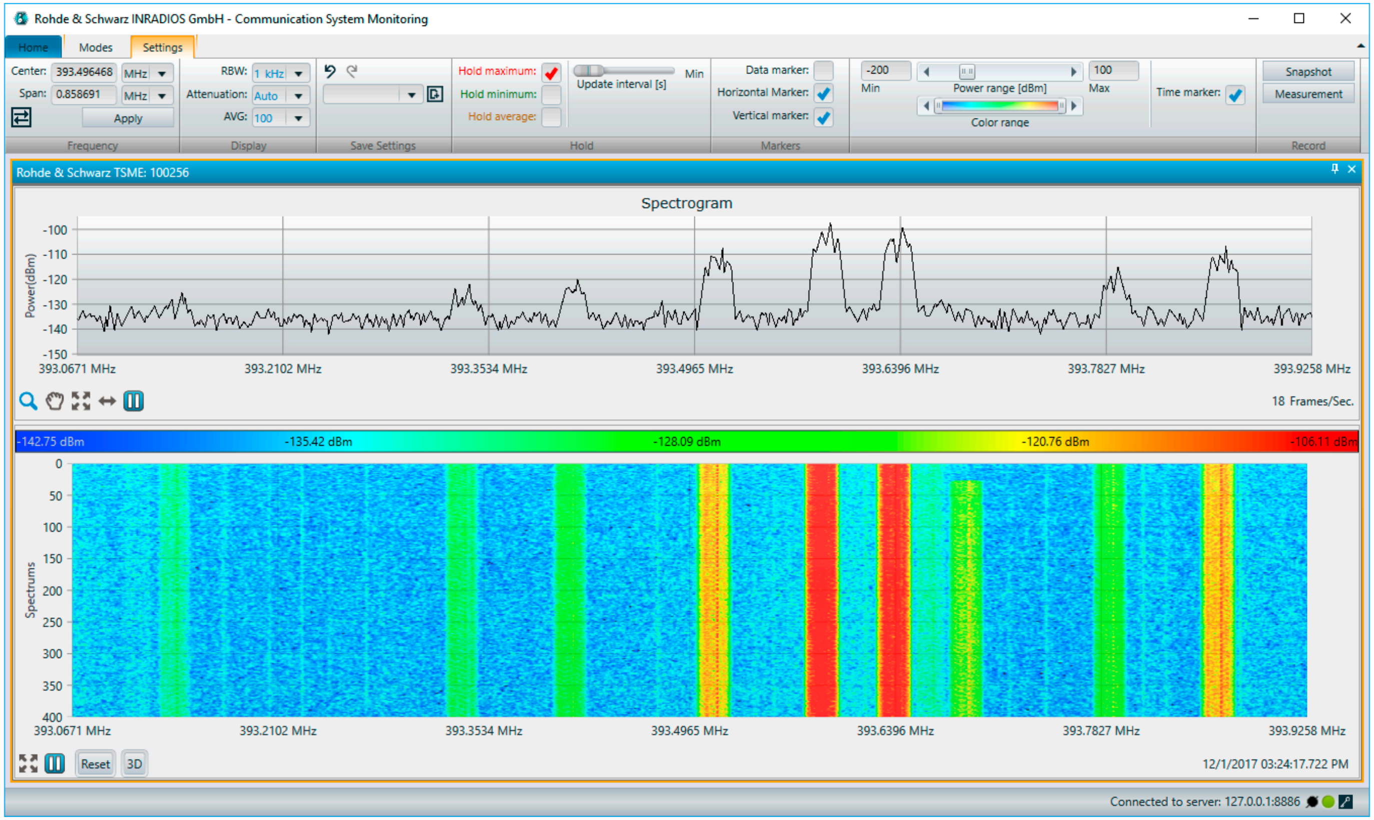
- Bandwidth and center frequency
- Received signal power
- Carrier-to-noise ratio
- Carrier stability and time fluctuations

In most monitoring tools, spectra are measured continuously over time. Frequency spectrum measurements over time are known as spectrograms or waterfall charts.

CSMs can use advanced software defined radio functions to demodulate dedicated carriers for the following purposes:

- Check if desired MODCOD is set
- Measure in-band SNR of carrier to identify in-band interference
- Monitor QoS parameters such as data rate or outages Power definitions on a logarithmic scale

Fig. 84: CSM graphical user interface example



MISCELLANEOUS

Power definitions on a logarithmic scale

The auxiliary unit Bel expresses the logarithmic ratio between the input and output of any given component, circuit or system. It may be expressed in terms of voltage, current or power:

$$\mathrm{P} = 10\log_{10}\left(\frac{P}{1\mathrm{W}}\right) \quad \text{in d}$$

$$\mathrm{P} = 10\log_{10}\left(\frac{P}{1\mathrm{mW}}\right) \quad \text{in dBm}$$

Examples

$10\log_{10}(1) = 0$ dB
$10\log_{10}(2) = 3$ dB
$10\log_{10}(3) = 4.7$ dB
$10\log_{10}(4) = 6$ dB
$10\log_{10}(10) = 10$ dB
$10\log_{10}(20) = 13$ dB

Conversion from linear scale to logarithmic scale

0.8 W = 2 · 2 · 2 · 100 mW = 3 dB + 3 dB + 3 dB + 20 dBm = 29 dBm

Logarithmic scales are also often used for gains and losses. The gain of an electronic component (e.g. amplifier) is defined as follows:

$$\mathrm{G} = 10\log_{10}\left(\frac{P_{out}}{P_{in}}\right) = P_{out} - P_{in} \quad \text{in dB}$$

Absolute dB levels

(instead of an input signal, an absolute reference value is used)

Power

dBm: power relative to 1 mW
dBW: power relative to 1 W (usually at 50 Ω)

Voltage

dBV: voltage relative to 1 V, regardless of impedance
dBmV: voltage relative to 1 mV
dBµV: voltage relative to 1 µV

Antenna gain

dBi: gain compared with isotropic antenna
dBd: gain compared with half-wave dipole

Radar cross section

dBsm: radar cross section relative to 1 m^2

Wavelength and speed of light

The frequency of an oscillation is independent of the propagation speed, but the wavelength is dependent on the propagation speed. In a vacuum, the speed of light is c_0 = 299 792 458 m/s. However, the value $c_0 = 3 \cdot 10^8$ m/s is usually sufficiently accurate for most purposes. The speed of propagation depends on the density of the medium. Therefore, the speed of light in the lower atmosphere is lower than in a vacuum, causing refraction.

Conversion from frequency to wavelength is handled as follows:

$$\lambda = \frac{c_{0\ (\text{in m/s})}}{f_{\ (\text{in Hz})}} \approx \frac{300}{f_{\ (\text{in MHz})}} = \frac{0.3}{f_{\ (\text{in GHz})}}$$

GLOSSARY

Term	Explanation
8PSK	eight-phase shift keying
ACM	adaptive coding and modulation
ADC	analog-to-digital conversion
AGC	automatic gain control
APSK	amplitude phase shift keying
ASI	adjacent satellite interference
AWGN	additive white Gaussian noise
BGAN	broadband global area network
BPSK	binary phase shift keying
BER	bit error rate
BUC	block upconverter
CFO	carrier-frequency offset
CID	carrier ID
CNR	carrier-to-noise ratio
CSM	communications system monitoring
CubeSat	class of small satellites with a form factor based on 10 cm (3.9 in) cubes
DFE	digital frontend
DFT	discrete Fourier transformation
DQPSK	differential quadrature phase shift keying
EHF	extremely high frequency
EIRP	effective isotropic radiated power
ERP	effective radiated power

Term	Explanation
E_s	energy per symbol
ESA	electronically steerable antenna; European Space Agency
FDM	frequency division multiplexing
FDMA	frequency division multiple access
FEC	forward error correction
FER	frame error rate
FSS	fixed satellite service
GEO	geostationary earth orbit
GSE	generic stream encapsulation
GSO	geostationary orbit
HEO	highly elliptical orbit
HPA	high power amplifier
HF	high frequency
IBO	input power backoff
IF	intermediate frequency
IP	internet protocol
I/Q	baseband signal real (I) and imaginary (Q)parts
ITU	International Telecommunication Union
LCT	laser communications terminal
LDPC	low density parity check codes
LEO	low earth orbit
LNA	low-noise amplifier

Term	Explanation
LNB	low-noise block converter
M-QAM	M-ary quadrature amplitude modulation
M-PSK	M-ary phase shift keying
MAC	medium access control
MEO	medium earth orbit
MF-TDMA	multi-frequency time division multiple access
MODCOD	modulation and coding
N_0	noise power spectral density
NCC	network control center
NCS	network control station
NTN	non-terrestrial network
OBO	output power backoff
PA	power amplifier
PAM	pulse amplitude modulation
PC	polar codes
PCMA	paired carrier multiple access
PEB	power equivalent bandwidth
PFD	power flux density
PHY	physical layer
PLL	phase locked loop
PNT	positioning, navigation and timing
PPM	parts per million
PSD	power spectral density

Term	Explanation
PSK	phase shift keying
QAM	quadrature amplitude modulation
QoS	quality of service
QPSK	quadrature phase shift keying
SBAS	satellite based augmentation system
SCPC	single channel per carrier
SDR	software defined radio
SHF	super high frequency
SNR	signal-to-noise ratio
SOTM	SATCOM on the move
SSO	sun synchronous orbit
TDM	time division multiplexing
TDMA	time division multiple access
TM&TC	telemetry and telecommand
TPC	turbo product codes
UHF	ultra high frequency
VCO	voltage controlled oscillator
VGA	variable gain amplifier
VHF	very high frequency
VSAT	very small aperture terminal

About Rohde & Schwarz

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