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Interagency Operations Advisory Group
Low-Earth Orbit (LEO) 26 GHz K-band Study Group

Low-Earth Orbit (LEO) 26 GHz K-band Study Group Final Report

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Executive Summary

The 26 GHz frequency is a viable option for direct-to-ground communications for low-Earth orbit (LEO) spacecraft. Mission planners may overlook the 26 GHz frequency due to unfamiliarity, perceived risks or the ease of implementing a mission using a legacy approach. By failing to consider the use of 26 GHz, however, missions may be missing out on the opportunities afforded by the higher frequency. This report provides an overview of the use of the 26 GHz frequency and discusses risks and challenges associated with operations.

This report is intended for several different audiences:

- Program and project managers are the primary audience and can use the information in this document as they consider the architecture for upcoming missions
- Systems and communications engineers for these missions will find details regarding propagation effects and the use of Consultative Committee for Space Data Systems (CCSDS) standards for communication, among other topics
- Infrastructure/service providers will find information on architecture considerations
- Implementers of standards and technology will find information regarding current usage and future needs in these areas

Developing this report under the auspices of the IOAG allowed for broad participation from the space-faring agencies and encouraged discussions of interoperability and cross support.

The report attempts to be equitable in articulating both the benefits/positive aspects and the challenges involved with using 26 GHz. It also identifies the trades that project managers should undertake as they consider making the transition to 26 GHz and describes the state-of-the-art status of elements such as hardware and coding and modulation schema.

There are several benefits and positive aspects for mission managers to consider when evaluating the use of 26 GHz for space-to-ground communications from LEO spacecraft:

- 26 GHz allows higher data rates and higher science data return, which enable scientific sensors with higher resolution and wider coverage
- 26 GHz is a less congested spectrum environment
- Missions that already use 26 GHz in other orbits or for space-to-space communications have not had any difficulties during operations
- There are LEO missions under development that will use direct space-to-ground communications at 26 GHz
- Technology and standards for operating at 26 GHz already exist, which facilitates interoperability
- Basic ground tracking station infrastructure to support use of 26 GHz exists and more infrastructure is being planned or is in development
- As more missions use 26 GHz, there will be additional incentive for infrastructure/service providers to upgrade their equipment to support this broader base of missions, thereby encouraging interagency cross support

There are also several challenges flight mission managers must consider as they evaluate the use of 26 GHz for space-to-ground communications. These issues, however, can be mitigated using a variety of known strategies, or are expected to diminish as more missions use the 26 GHz frequency for LEO-to-ground communications. Among these challenges are:

- Atmospheric/propagation attenuation is more pronounced at 26 GHz than at more commonly used frequencies
- The infrastructure availability needs improvement, especially in the polar regions
- While onboard and ground hardware is available, there are fewer vendor options for some components than for those at other more commonly used frequencies

Additionally, there are options available to further enhance 26 GHz communications, such as the development of onboard and ground hardware that will enable the full capability of 26 GHz (around 10 G/s) and provide the flexibility offered by advanced coding and modulation schema.

Since 26 GHz spacecraft antennas can be smaller than X- or S-band antennas for the same performance, they may be amenable to applications on small satellites. A multi-parametric analysis is provided in Appendix G.

This report does not contain cost estimates for transitioning to 26 GHz. Each flight mission will perform its own cost-benefit analysis, since many of the trades are mission-unique. In most cases, the infrastructure/service providers have already begun to analyze the costs required to upgrade their systems and there is no need to repeat that information in this report.

Program and project managers should thoughtfully consider use of 26 GHz when making their initial system architecture decisions for future missions. This frequency enables high data rate return and is a completely viable frequency alternative.

1 Introduction

1.1 Purpose

The Interagency Operations Advisory Group (IOAG) established the Low-Earth Orbit (LEO) 26 GHz Study Group (LEO26SG) because several space agencies have come to the same conclusion: Current methods for transporting high-rate science data from LEO satellites (typically between 300-1500 km altitudes) to the ground are becoming less viable. While spectrum managers and others in the communications arena recognize this issue, this change is not always recognized by the spacecraft program and project managers. Spacecraft managers also appear to be reluctant to consider the use of the 26 GHz band (i.e., between 25.5 and 27 GHz) as they design their missions. The decision to perform this study under the auspices of the IOAG was made to ensure the broadest possible international participation and cooperation.

The purpose of this report is to provide program and project managers with a clearly articulated rationale for moving beyond the current communications methods and, in particular, for seriously considering the use of the 26 GHz spectrum for LEO-to-ground direct communications.

Currently there are a number of missions, ground stations and relays that use 26 GHz, but none of them employ 26 GHz in the direct LEO-to-ground configuration. There are also some LEO satellites under development that plan to use the 26 GHz band for space-to-ground communications. Many technical issues such as wide bandwidth, location of stations and related propagation effects are specific to this band and to the LEO space-to-ground geometry. The IOAG desires to examine use of 26 GHz in such missions, and thus the scope of this study is limited to direct LEO-to-ground scenarios. Information on other scenarios, such as relay satellites, is provided as reference material.

A number of existing and future ground stations will be capable of providing cross support at 26 GHz (see Appendix F), and it is likely that more such stations will be constructed as the number of missions requiring support at 26 GHz increases. Cross support, however, is only one of the important aspects that LEO missions must consider when deciding to use the 26 GHz band. Consequently, this report examines the entire range of specific technical characteristics, benefits, challenges and mitigation strategies that are associated with use of 26 GHz for direct LEO-to-ground communication.

Note that the data volumes generated in this kind of LEO mission are expected to increase in the future, as missions employ more information-intensive (higher resolution, higher coverage) sensors. Such missions will require that very high data rates be employed to send data to Earth during the limited contact time between the satellite and the ground stations. This mission scenario implies specific requirements for the direct LEO-to-ground communication system. Stations may often be located at high latitudes and may need to track signals under extreme conditions, such as very low elevation angles that are affected by atmospheric attenuation, or high-velocity overhead passes. These kinds of technical considerations are further developed in this document.

1.2 Motivation

As satellite missions continue to grow in complexity, the methods for transporting the data to the ground have to change to keep up with the growing data rates. With the increase in the use of space-to-ground spectrum, missions are being forced to evaluate alternatives to the frequency bands that are typically used. It is, therefore, critical that all options for providing satellite communications be examined to ensure the continuing availability of Earth and space science data.

1.3 Study Scope and Methodology

This study and its resulting report will focus on LEO missions and their communication systems from the satellite directly to Earth in the 26 GHz band. Information regarding currently operational missions using 26 GHz in other regimes (e.g., geosynchronous Earth orbit [GEO]-to-ground or L2-to-ground or intersatellite LEO-to-GEO links) is provided as reference material. The information in this report consists of knowledge compiled by the study group members.

1.4 Report Structure

This report is structured to provide information to a variety of communities. The body of the report is designed to inform program and project managers and other decision-makers about the benefits and potential limitations of using the 26 GHz spectrum to provide direct LEO-to-ground satellite communications. The appendices contain information to address specific technical aspects of 26 GHz communications and will be of interest to the implementing engineering teams.

2 Concept of Operations

This section describes how 26 GHz radio frequency (RF) communication from the LEO satellite directly to the ground takes place.

The geometry is presented in section 2.1. The spacecraft and ground systems involved in the communications are addressed in section 2.2. Other mission considerations such as allowable latency and onboard data storage capabilities are not addressed in detail in this document, since such considerations are typically mission-specific.

2.1 Geometry of LEO-to-Ground Communications

Figure 2-1 depicts the typical geometry for direct LEO-to-ground communications.

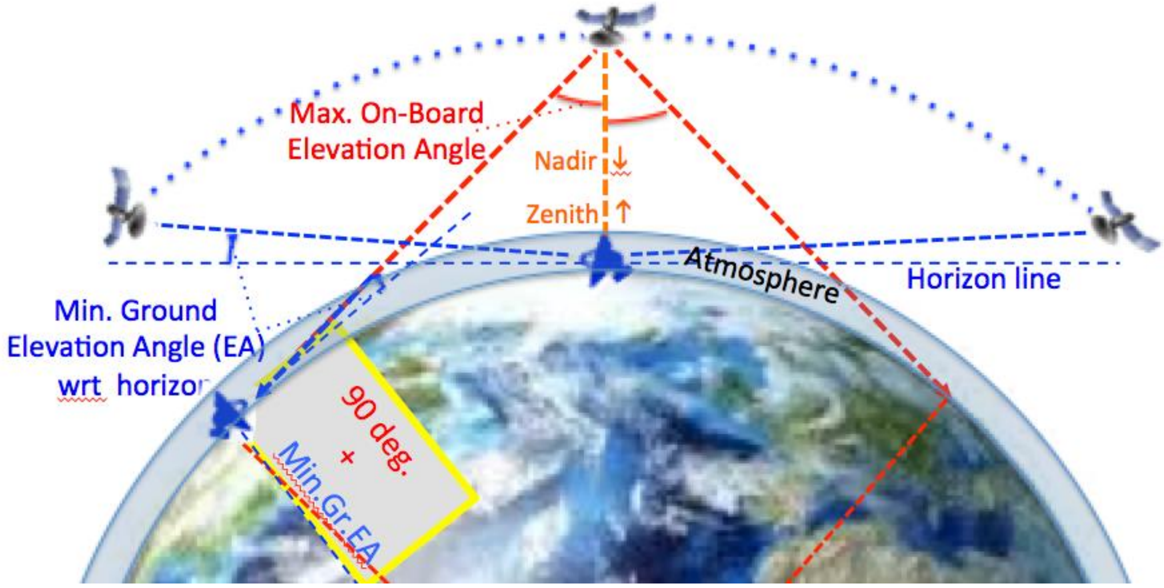


Figure 2-1: Geometry for Direct LEO-to-Ground Communications

The ground elevation angle (typically between 5 and 175 degrees) and the altitude of the LEO satellite determine the onboard elevation angles and distances at which communication can be established between the LEO satellite and the ground station. More than 35 percent of the contact time is spent between a 5- and 10-degree elevation angle (see Appendix H), hence it is important to have operational capabilities at the lowest possible ground elevation angles. It should be noted ground assets have differing minimum elevations for committable contacts due to the atmospheric losses below 10 degrees.

Space losses in the communications link budget are proportional to the square of the product of the frequency and the distance from the spacecraft to the ground station. Some examples of the best (i.e., at zenith) and the worst (i.e., at low ground elevation angle) cases are presented in Table 2-1 as a function of satellite altitude. The 1.5 dB difference between the 500- and 800-km altitudes indicates that we can generalize the analysis in the link design discussed in section 3.4.1. The scanning range of the onboard antennas is defined by the maximum onboard elevation angles and it changes little (a few degrees) among the different

LEO altitude cases. Ground speed is included in Table 2-1 to indicate maximum slew rates of ground antennas.

Table 2-1: Geometrical Parameters for LEO Compared to GEO

@ zenith (Gr. EA=90deg)	@ horizon (for Gr.EA = 5 deg.)		Zenith vs. Horizon	@ zenith
Distance = Satellite Altitude (km)	**Max. Onboard Elev. Angle (deg)**	**Distance (km)**	**Space Loss Difference (dB)**	**Ground Speed (km/s)**
300	72.1	1,500	14.0	7.379
500	67.5	2,078	12.4	7.059
693	64.0	2,547	11.3	6.772
818	62.0	2,822	10.8	6.597
1,300	55.8	3,755	9.2	5.985
35,863 (GEO)	8.7	41,205	1.2	

2.2 *Spacecraft and Ground Systems*

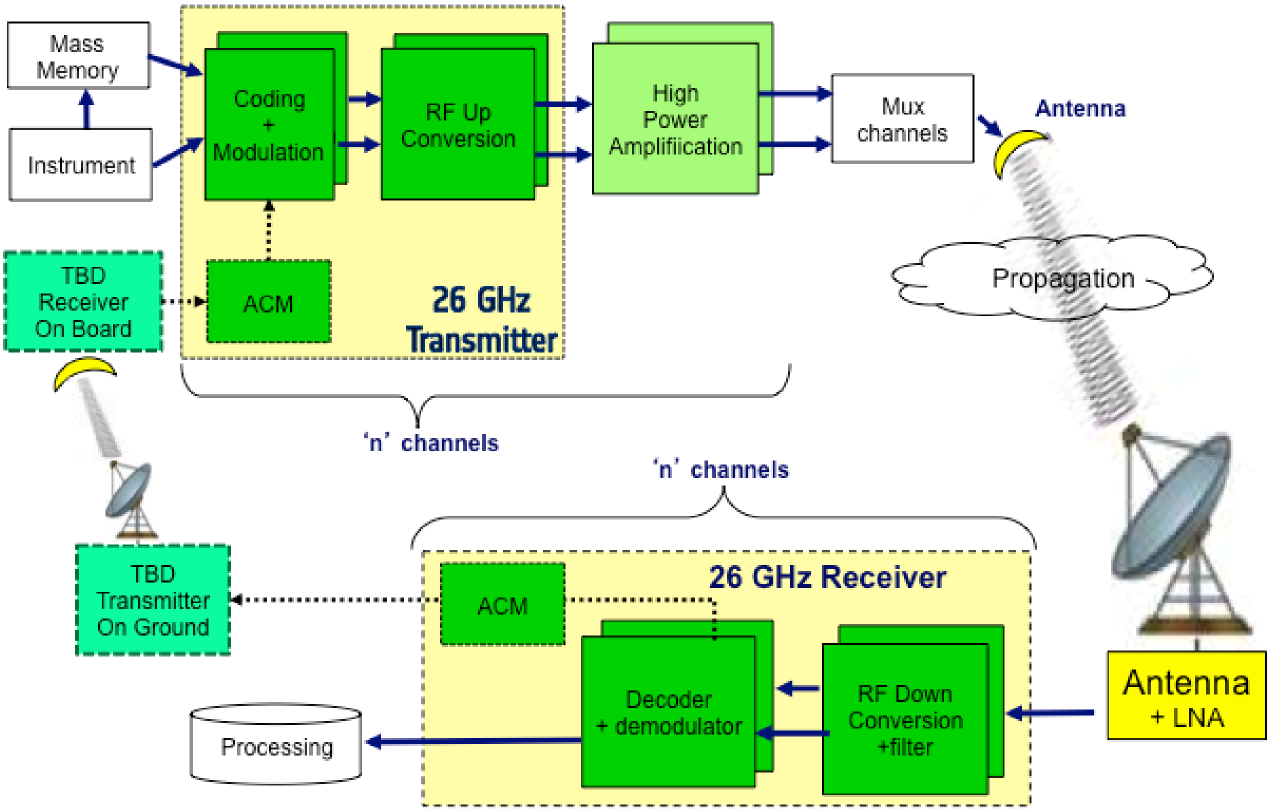
Figure 2-2 illustrates a 26 GHz LEO-to-ground downlink system.

The spacecraft data downlink involves the following onboard subsystems and challenges:

1. **Transmission subsystem**, including coding, modulation and up-conversion: In principle, a second-stage up-conversion from S-band or X-band to the 26 GHz band may be sufficient; however, new coding/modulation technology will be required to support higher speed (symbol rate) and performance (use of flexible Variable Coding and Modulation [VCM]/Adaptive Coding and Modulation [ACM] techniques is optional, and is described in section 3.4.1).
2. **Power amplification at the 26 GHz band**: Key aspects are efficiency (ratio of input to output power) and linearity, which becomes particularly critical with high-order (e.g., 16-APSK or higher) modulations that rely not only on the phase content, but also on the amplitude content. Mitigation techniques, such as pre-distortion, will play a fundamental role in optimizing the overall system. All these aspects are crucial to consider when selecting the technology to employ (solid state power amplifier [SSPA] vs. traveling-wave tube [TWT]). Similar power-amplification technology is available from commercial telecommunication satellites.

3. **Onboard antenna:** Scaling of X-band global coverage antennas with proper surface accuracy could be considered, but to cope with greater attenuation losses in the 26 GHz band, steerable antennas are recommended. This introduces challenges similar to those of any steerable onboard antennas (e.g., reliability of antenna pointing mechanisms, pointing accuracy, vibration levels in the spacecraft to be minimized as needed, etc.). Synergies between antenna pointing mechanisms for X-band and for 26 GHz may exist.

Figure 2-2. Generic Functions of the 26 GHz Communication System



There are system aspects that affect the onboard subsystems, as well as the ground infrastructure. Examples of such aspects include:

- **Coding and modulation**: The transmitter and receiver need to use the same coding and modulation schemes, which are not specific to the frequency band.
- **Number of adjacent RF channels used**: Use of two channels per polarization (see the example in Appendix G) is considered feasible with current digital technology. Use of one channel to cover the whole 1.5 GHz available band is challenging technologically and also for system performance (e.g., for group delay compensation). Having more than two channels is also possible, but it may result in an inefficient implementation.
- **Number of polarizations**: The first systems to use 26 GHz will operate with only a single polarization; however, it is also possible to employ dual polarization with the use of onboard steerable antennas, hence enabling a two-fold data rate increase.

Twenty-six GHz is more susceptible to atmospheric attenuation effects than other bands in great part because of its proximity to the water vapor absorption band at 22 GHz and increased rain attenuation. This effect is more pronounced at lower elevations because the signal passes through more of the atmosphere. This issue can be mitigated via a number of strategies (see section 3.3.2 for details).

The ground infrastructure from Figure 2-2 includes:

1. **Receiver subsystem**: Like the transmission subsystem, the receiver subsystem requires additional development for down-conversion, and also requires higher processing speed, good performance (wider bandwidth, equalization, group delay) and possibly new VCM/ACM coding/modulation technology to mitigate propagation variability and increase operational flexibility.
2. **Ground antenna:** The ground antenna is expected to have a good and efficient gain and good acquisition/tracking capabilities to support fast-moving satellites in LEO. Integration of LEO tracking technology similar to that used in other bands needs to be considered for infrastructure used for 26 GHz. Program tracking seems feasible, but auto-tracking techniques could be an alternative to be further assessed.

The location of the ground station is very important at 26 GHz for reasons (see section 5.4.2 for additional details) such as:

- **Need to optimize contact time**: LEO missions can use ground stations in any location, but especially for high-inclination orbits, the greatest contact time occurs for ground stations located in high latitudes (polar regions).
- **Propagation constraints:** The preference is for dry regions, such as deserts and cold polar regions.

3 Mission and Business Considerations for Use of 26 GHz

3.1 Introduction

Data volume requirements are expected to increase in the future, as missions employ more information-intensive (higher resolution, higher coverage, higher duty cycle) sensors requiring higher speed downlink capabilities that are enabled by 26 GHz.

Consideration of the 26 GHz frequency allocation for operations and/or science data return requires careful lifecycle analysis of the engineering trades associated with the 26 GHz allocation compared to the other frequency band allocations, most notably S-band and X-band.

Table 3-1 lists the frequency bands allocated for space communications that are relevant to this document. More detailed information appears in Appendix C.

Table 3-1: Radio Frequency Allocations for Earth and Space Science Services

Frequency band (MHz)	**Direction**	**Bandwidth (MHz)**
2200 – 2290 (S-band)	space-Earth	90
7750 – 7900 (X-band) 8025 – 8400 (X-band) 8450 – 8500 (X-Band)	space-Earth space-Earth space-Earth	150 375 50
25500 – 27000 (26 GHz band)	space-Earth	1500

The 7.75 GHz to 7.9 GHz range has typically been used by meteorological satellites.

Relay satellites usually use 25.5 GHz to 27 GHz for space-to-space intersatellite links.

The IOAG Optical Link Study Group (OLSG) has also identified optical wavelength ranges (1064 nm and 1550 nm) that can be used for LEO space-to-ground communications (see the Interagency Operations Advisory Group, *Optical Link Study Group Final Report*, June 2012).

As mission and project managers consider the frequency band alternatives for their specific mission requirements, many aspects must be taken into account including bandwidth availability, spectrum congestion, technology and mission concept differences; availability and cost; link differences and atmospheric phenomena associated with each frequency; data volume transfer; and others.

The International Telecommunication Union-Radiocommunication sector (ITU-R) and the Radio Frequency Coordination (RFC) Space Frequency Coordination Group recommend considering the use of the 26 GHz band for future Earth exploration satellite services (EESS) because the resulting increased system performance and uncluttered spectrum access will allow higher data rates (see SFCG Recommendation, *Efficient Sharing of the 25.5-27.0 GHz Band Between EESS [s-E] and SRS [S-E]*, REC SFCG 29-1). The 26 GHz band currently offers uncongested spectrum, providing more flexibility for mission planning along with significantly increased bandwidth availability compared to S-band and X-band.

Frequency differences between 26 GHz, S-band and X-band also present differences in antenna gain, space path loss and link capacity, depending on the frequency. For example, antenna gain will be larger and beam width will be smaller at higher frequencies for the same size antenna, which translates to more data transfer capability for the mission (i.e., missions may accomplish the same data transfer using a smaller, lighter antenna) and possibly less interference. In addition, higher frequency also means higher space path loss, which reduces the amount of mission data transfer. The tradeoffs between frequency selection, antenna size (and therefore gain), pointing accuracy and complexity, along with technology availability at each frequency, are part of the system engineering aspect of mission design. These types of tradeoffs are also key aspects in the system design.

Appendix G provides additional information with equations and numerical examples of a link budget.

Along with the benefits of the 26 GHz allocation, there are, of course, challenges to using the band. In particular, atmospheric propagation attenuation increases at 26 GHz compared to S-band and X-band. The effect is increased at low elevation angles due to the long path length through the atmosphere from the LEO satellite to the ground. Many studies and analyses have been performed for GEO applications to understand this propagation phenomenon. In the case for LEO missions, some studies have been initiated but more studies are needed as indicated in Appendix H.

The advantages, challenges and associated mitigation strategies, and system considerations are further developed in the sections below.

3.2 Advantages

3.2.1 Increased System Performance

Some of the reasons to choose higher carrier frequencies in radio communications include:

- The spectrum or bandwidth availability is higher
- Expected higher energy in the receiver

Previous studies and initial operational experience have shown that, all else being equal (e.g., antenna sizes and transmitter power), when using 26 GHz, we can expect an approximate increase in overall data rate performance of a factor of at least three over X-band. Alternatively, one could choose to realize the system design advantages of 26 GHz over X-band by using a smaller ground antenna, employing reduced power on the spacecraft, etc. Further details and considerations are included in Section 3.4.

3.2.1.1 Expanded Spectrum Availability and Higher Data Rates

As shown in Table 3-1, the 1500 MHz bandwidth allocated in the 26 GHz band is four times larger than the 375 MHz bandwidth allocated in the 8025 – 8400 MHz X-band.

Assuming the same spectrum efficiency in information bits/Hz—which is the case for a given fixed coding, modulation and filtering scheme—the availability of an expanded spectrum results in a linear increase in the data rate and potentially the data volume that can be transmitted. In other words, the 26 GHz band should allow users to transmit about four times more data than the current X-band.

3.2.1.2 Higher Energy Available in the Receiver with Higher Frequency

All else being equal (e.g., the antenna aperture), the increase in performance in the link budget is proportional to the square of the ratio of the new frequency to the former frequency. This increase occurs because the narrower beam concentrates more energy on the receiver. However, other factors create challenges when higher frequencies are used. For example, it is more difficult to achieve accurate pointing using a narrower beam, and additional signal degradations occur due to Earth's atmosphere. Initial operational experience has shown that use of 26 GHz results in an increase in performance 3 to 4 times over that of X-band (*Morabito, et al.*, 1999 and *Rebold, et al*., 1994). One might design the system to take advantage of the overall increase in system performance in other ways:

- One could reduce the spacecraft power by a factor of 3 to 4 and still return the same volume of data
- Another option would be to reduce the spacecraft antenna aperture by a factor of 3 to 4 and still return the same data volume; this option would lessen the pointing requirement on the spacecraft a bit, as well as reduce the mass of the antenna
- Similarly, one could reduce the area of the ground antennas by a factor of 3 to 4
- Higher available energy at the receiver enables the use of higher order, more powerful modulation/coding schemes that result in higher data rates by a factor that varies between 1 and 5, as shown in more detail in Appendix G.

3.2.2 Uncluttered Spectrum Access

Hundreds of satellites and numerous ground stations use the S-band and X-band. At these frequencies, isoflux (radiating to the whole Earth disc) onboard antennas are commonly used. This practice results in interference at the receiving ground station because power is transmitted to all stations visible to the satellite provided with a global coverage (isoflux) antenna, regardless of whether those stations are intended to receive the signal from that satellite.

In addition, it is expected that the 8025-8400 MHz X-band will become more congested in the coming years. To mitigate this problem, more and more missions will need to apply the SFCG recommendations for extended utilization of the X-band: larger dishes with ground stations, steerable onboard antennas, use of VCM, etc.

Currently, the 26 GHz stations to be used to support LEO satellites are not affected by interference (due to low utilization) and in the future it is expected that they will be **less** affected by interference than stations using lower radio frequency bands for several reasons:

- **Stations in high latitudes for LEO missions**: LEO missions can use ground stations in any location, but due to propagation constraints (i.e., preference for dry areas) and the need for contact time optimization, especially for high inclination orbits, the greatest contact time occurs for ground stations located in high latitudes (polar areas).

Stations in high latitudes are less affected by interference from satellites transmitting from GEO or non-LEO orbits.

- **Narrower beam width**: Steerable antennas will be needed in the 26 GHz band to compensate for propagation impairments in this band. These antennas have a narrower beam width and therefore would illuminate a smaller number of ground stations.
- **Reduced number of LEO satellites**: Early adopters of the 26 GHz frequency allocation will benefit from flexibility within the band for their operations. It is expected that initially only a few types of missions will adopt the 26 GHz band:
    - High-end missions requiring very high data rates (due to bandwidth availability)
    - Missions that need to avoid more frequent interference in X-band (e.g., constellations performing "broadcast" transmissions)
    - Meteorological missions that have traditionally used the 7.75 GHz to 7.9 GHz band

Spectrum coordination is becoming more difficult in currently used bands, providing an additional reason to consider the 26 GHz band, especially for missions that present a risk of X-band interference. This spectrum coordination issue applies, for example, to long-term meteorological missions involving a series of satellites that will operate for at least two decades and also to constellations with a significant number of satellites performing “broadcast” transmissions (i.e., quasi-permanent telemetry transmissions).

3.3 Challenges and Mitigation Strategies

3.3.1 Challenges Affecting 26 GHz Use and Possible Mitigation Strategies

The advantages described above (increased system performance, uncluttered spectrum access) need to be traded against challenges affecting the 26 GHz use, such as:

- **Atmospheric propagation effects**: 26 GHz is more susceptible to atmospheric attenuation effects than S- and X-band in great part due to the vicinity to the water vapor absorption band at 22 GHz and increased rain attenuation. This effect is more pronounced at lower elevations because the signal passes through more of the atmosphere. This propagation effect is also variable and depends on the weather conditions; therefore, the location of the ground antenna is important. It may be difficult to predict local weather conditions, which depend on seasonal weather statistics. Additional details are found in Appendix H.
- **Limitations of propagation data/models for LEO-to-ground 26 GHz-band systems:** No comprehensive atmospheric measurement database is currently available in the 26 GHz band for planning direct LEO-to-ground communications. Most of the current atmospheric propagation models are based on GEO-to-ground measurements in mid-latitudes and do not take into account the dynamics of fast-passing LEO satellites, or the atmospheric effects at low elevation angles. These propagation models will be validated and further improved as propagation measurements become available from the first LEO missions and ground stations using the 26 GHz.
- **Some technology would benefit from optimization:** 26 GHz band is used today for communications to data relay satellites (DRS) or from non-LEO missions. Some specific

technologies (e.g., power amplifiers) can be used in their current state for 26 GHz LEO-to-ground communication. Other technologies (e.g., onboard storage and spacecraft interfaces) require optimization to support the higher data rates desired by missions. See section 6.1 for details.

- **Onboard steerable antennas:** To compensate for the higher propagation losses, a small (e.g., 15 cm) high-gain steerable antenna is required on the spacecraft. For example, a 15-cm antenna yields 30 dBi, as compared to 6 dBi from a fixed isoflux antenna. A steerable antenna, however, imposes some challenges regarding the pointing accuracy due to the narrower beam (e.g., 5 degrees for a 15-cm dish), as compared to the traditional onboard isoflux antennas. Steerable antennas include moving mechanisms that may introduce some torque or micro-vibrations that may affect other systems (e.g., attitude and orbit control systems [AOCS], sensor stability) on the spacecraft. This issue needs to be considered in the design of the overall spacecraft system. An alternative based on isoflux antennas is addressed in sections 5.5 and 6.1.1.4.
- **Ground antennas**: LEO satellites need to be tracked at very low elevation angles, and also at very fast speed when the satellite passes overhead (at zenith, see Table 2-1) Mission requirements to ensure continuous data transfer may impose demanding pointing requirements on the ground antenna, which may be challenging for narrow beams generated by large antennas in higher frequencies. Twenty-six-GHz antennas will probably be smaller than those currently in use at X-band (see example in Appendix G of link budget with 6-m antenna), and therefore pointing 26 GHz antennas should not necessarily be more challenging than for existing antennas.
- **High Doppler**: The Doppler frequency shift is proportional to the relative velocity of the transmitter and receiver terminals, and inversely proportional to the wavelength. This issue is not considered critical, but it needs to be considered in the design of the ground station.

3.3.2 Mitigation and Design Strategies

Several mitigation strategies can be envisaged to compensate for the high atmospheric attenuation and variability:

- **Onboard steerable antennas**: Increasing the gain of the onboard antenna mitigates the effects of high atmospheric attenuation, but does not completely address the effects of atmospheric variability. See the Variable Coding and Modulation (VCM)/Adaptive Coding and Modulation (ACM) discussion below for more details on the variability issue.
- **Tradeoff between number of ground contacts and minimum elevation**: To mitigate atmospheric propagation effects, mission designers can choose to reduce the planned contact time over ground stations so that the ground antenna never points too close to the horizon. Using this method, higher data rates can be maintained with less chance of weather outages. A greater number of ground stations would typically be needed to compensate for the resulting reduced contact time for each station. The minimum elevation angle chosen and the number of ground station contacts will be system tradeoffs.
- **Tradeoff between throughput and propagation confidence levels**: At 26 GHz, propagation conditions can vary significantly; therefore, data errors may occur in just

a few passes. This non-uniform performance contrasts with the long-term statistical approach usually used to plan the link. Mission designers may cope with these variations by using short-term weather predictions to adapt the data throughput and reduce the statistical uncertainty, or adopt more costly options like adding worst-case margins in the link budgets (e.g., using bigger antennas or additional ground station contacts for later contingency transmission).

- **Tradeoff between number of ground contacts and ground station availability**: Local atmospheric conditions will affect the overall performance of a ground station. For example, a ground station might have a very high chance of returning good data at a given data rate, but a slightly lower chance of returning good data at a somewhat higher data rate. Mission designers can use this information to trade off the number of scheduled ground station contacts with the expected success of these passes, using slightly more scheduled passes to make up for the decreased probability of success of each individual pass.
- **Site diversity**: To minimize the probability of fading due to unfavorable propagation conditions, it is possible to consider two or more ground stations located a few kilometers from each other (within the onboard antenna footprint on the ground) and operating simultaneously. This strategy requires more ground infrastructure and is further detailed in section 5.4.2.
- **Variable Coding and Modulation (VCM) and Adaptive Coding and Modulation (ACM)**: VCM/ACM provides flexibility to mitigate large variations (e.g., > 15 dB) in received power with respect to elevation angle and high atmospheric variability. VCM/ACM also optimizes the data return and provides operational flexibility. Both VCM and ACM allow the system to inform the receiver that the modulation and coding will change at the end of a frame. VCM works in open loop and ACM works in closed loop with an uplink, as further explained in section 3.4.1. VCM and ACM offer the solution that will result in the greatest link efficiency and flexibility of all the mitigation techniques listed in this present section.
- **Use of multiple RF channels to mitigate the limitations of current technologies:** The 26 GHz band represents an increase of the available bandwidth by a factor of four (i.e., 1500 MHz instead of 375 MHz) with respect to the X-band, when the same polarization schemes are used at both frequencies. It is unlikely with current technology (e.g., flight-qualified digital-to-analog converter [DAC]) that in the short term only one RF channel can use the whole 1500 MHz bandwidth.

3.4 Considerations

3.4.1 Link Design

The link design is the most important factor in assessing the feasibility of a communications system. Detailed link design and examples are provided in Appendix G.

3.4.1.1 Current S- and X-band Approach

The goal in any mission link design is to exchange an adequate amount of information between the spacecraft and the ground in the most efficient way to ensure that the data return objectives of the mission are satisfied. A secondary goal is to be a “good neighbor” by not wasting spectrum that could be used by other missions.

The problem of link design in this specific environment (links between LEO spacecraft and the ground at 26 GHz band) is exacerbated because the available received power-to-noise ratio (P_T/N_0) varies greatly during the period of visibility from a given ground station. This variability is due to great changes in the elevation angle geometries (zenith vs. low elevation angle) between spacecraft and ground station, and can be decomposed in three parts:

- Space losses, as mentioned in section 2.1: differences of more than 10 dB can be expected between zenith and low elevation angles
- Antenna gains and patterns: especially important for fixed (non-steerable) onboard antennas with little directivity
- Propagation effects due to the larger path through the atmosphere at low ground elevation angles: such effects may also affect the efficiency of the ground station

These effects combine to produce a link margin (P_T/N_o) vs. time curve of the kinds shown in Figure 3-1.

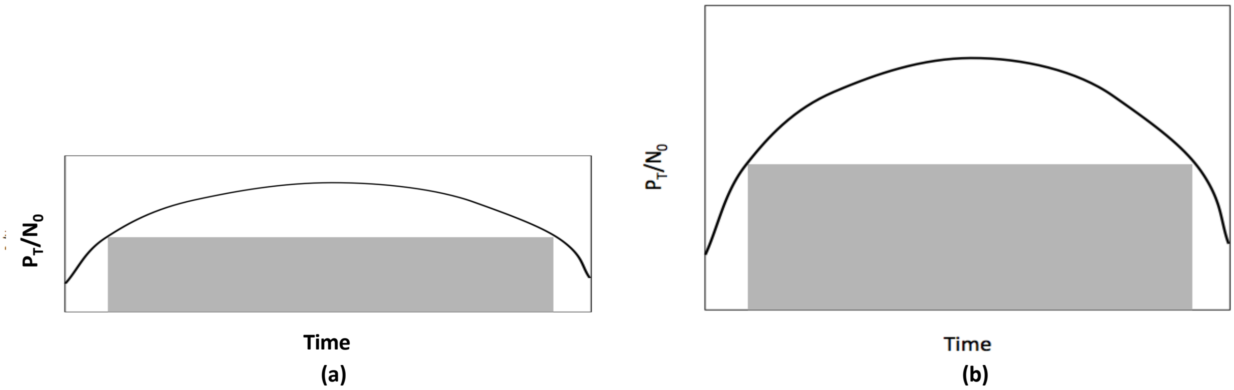


Figure 3-1: Link Margin with Single-code and Modulation Type: (a) S- and X-band Communication vs. Time and (b) 26 GHz Communication vs. Time

The link becomes closed (allowing spacecraft data to be successfully transferred) as soon as the power reaches the required level and remains closed until the power dips below that level again.

There are no scales on these curves, as they represent a generic phenomenon. In the past, mission link designers would typically choose a single code type and single modulation type with a constant data rate so as to maximize the expected data transfer during such a contact. This scenario results in a design that can close the link as long as one specific P_T/N_0 value is achieved. The resulting performance is visualized by the grey areas in Figure 3-1 and is acceptable for S-band because the overall P_T/N_o variation is rather limited due to the mutual cancellation of space losses and onboard antenna gains, hence leaving only the propagation contribution, which varies little (e.g., less than 2 dB) between zenith and low elevation angles. The resulting performance visualized by the grey areas in Figure 3-1 is also acceptable for most X-band systems when the data rate to transmit is not too close to the two Gbits/s limit in X-band.

At 26 GHz band, however, the curve is very pronounced (see Figure 3-1 (b)) due to the high variability of the total power (P_T) at the receiver as a function of elevation angle and time, that with the use of steerable antennas will always be around the peak gain of the antenna pattern. Therefore, the differences in free space losses between zenith and horizon could be very large (typically more than 10 dB).

3.4.1.2 26 GHz Band Approach with Advanced Coding and Modulation

For systems with a more pronounced curve (including 26 GHz), it makes more sense to allow the data rate, coding and modulation schemes to change during the contact period, as visualized in Figure 3-2. In this way, a series of schemes would allow the link to be closed at progressively higher power levels while the power is increasing. The system would then cycle back through those schemes as the power decreases at the end of the contact.

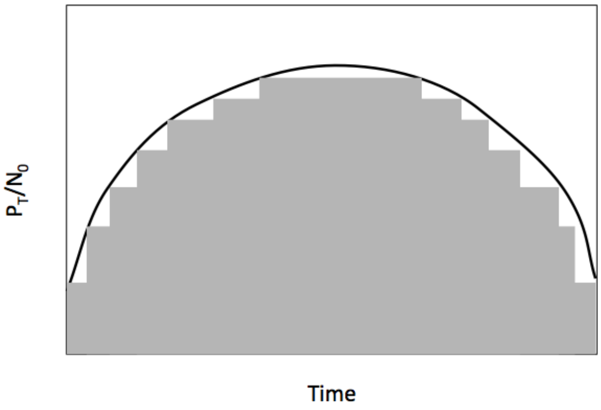


Figure 3-2. Link Budget with Advanced Coding and Modulation Techniques

This kind of advanced technique in the communications system is known as Variable Coding and Modulation (VCM). VCM systems have been used in operational space missions. For example, NASA's Galileo mission to Jupiter and some NASA LEO missions using the Near Earth Network (NEN) have used a simple version of VCM (though neither of these were done at 26 GHz). VCM works in open loop (the use of specific modulation types and code types[1] can be pre-programmed in time as a function of, for example, elevation angles and seasonal propagation statistics or daily propagation predictions). There are two main difficulties with VCM:

- Since VCM is pre-programmed onboard, it cannot use the most up-to-date propagation information (which is important when using 26 GHz). Additional system margins or lower data rates need to be considered to cope with this uncertainty. A possible optimization requires that new VCM sequences be sent regularly (days or hours rather than months) from the ground to the spacecraft via command in a low-speed uplink, possibly in S-band.

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[1] One coding and modulation scheme could be modulation QPSK and coding rate ½. The next coding and modulation scheme could be modulation 8PSK and coding rate 9/10 (i.e., 9 bits of information and 1 bit of redundancy). As a minimum, the same coding and modulation scheme needs to be operated in the same data frame.

- Since the choice of codes and modulations is made in advance, VCM is not robust to real-time changes that might occur in the system

Adaptive Coding and Modulation (ACM) is identical to VCM, except that it works in a closed loop. In ACM, the ground station evaluates the actual conditions of the radio during the contact period and then chooses the optimal coding and modulation schemes in real time. This coding and modulation choice has to be communicated via a low-speed uplink, possibly in S-band, to the satellite transmitter.

Both VCM and ACM allow the system to inform the receiver that the coding and modulation will change at the end of a frame. The Consultative Committee for Space Data Systems (CCSDS) has been working on two coding and modulation standards supporting features for VCM that have reached Blue Book status. A CCSDS recommended practice on VCM is also under preparation (see details in Appendix I). Any of these standards could form the basis for a 26 GHz ACM standard for future missions. The ACM technique requires services defining the ground procedures to allow interaction between the receiver (e.g. evaluating signal quality etc on ground) and the sender (e.g. generating the real-time feedback and sending it to spacecraft with Control Centre coordination/permission) for changing between the codes and modulations on the fly. These ACM protocols on top of the VCM for the feedback link need to be further defined and standardized.

3.4.2 Mission Operations

To achieve high availability of the communication link and maximize the high data rate throughput enabled by 26 GHz, the following issues should be taken into consideration:

1. Scheduling shorter ground contacts to avoid low elevation
2. Using nearby antennas to increase local station availability to mitigate weather effects
3. Using advanced coding and modulation schemes
    a. If VCM is used, there are many coding schemes applied during a pass, but these schemes are pre-programmed in advance
    b. If ACM is used, a continuous low-rate uplink is needed to apply real-time feedback to change the coding schemes

The number and the duration of the ground contacts depend on the location and the capabilities of the selected ground stations. It will be more challenging to use low elevation angles in the 26 GHz band because the atmospheric attenuation increases significantly when the signal has to go through a longer atmospheric path. Seasonal effects also need to be taken into account. For example, the winter period may be drier, allowing for a higher link budget margin.

Once a mission is flying, the main method that the mission operator can use to maximize the data throughput is to modify the coding and modulation. VCM and ACM offer the flexibility to operate reliable communication at moderate to high speed for low elevation angles, and at very high speed for medium to high elevation angles.

If VCM techniques are used, the operators select coding and modulation schemes that were previously determined based on the expected link characteristics (path loss, atmospheric loss/weather forecast, etc.). These coding and modulation schemes are then uploaded to the satellite, which changes its transmitted coding and modulation accordingly.

If ACM techniques are used, the ground station estimates the quality of the received signal and determines when the spacecraft should switch to different coding and modulation schemes in real time. The ground station then transmits a command to the satellite to change its coding and modulation. This process is repeated continuously throughout the pass. The uplink must be co-located with the 26 GHz receiver for this real-time feedback loop.[2] The sending of the command may require the coordination/permission by the spacecraft Control Center.

3.4.3 Lifecycle Cost Considerations

Project managers need to consider the implications to the lifecycle cost of the mission as they determine the data rates at which they will operate. Some considerations include:

- Cost per pass at the tracking station
- Cost of the long-haul fiber connections
- Latency requirements for the data
- Cost of onboard hardware
- Infrastructure upgrade costs

Cost-benefit analysis example 1 – Assuming the same data volume, a mission downlinking at 26 GHz may require fewer passes or contacts than one downlinking at a lower data rate in other frequency bands, thus the cost for tracking station passes is reduced. However, the higher data rate requires a larger fiber connection from the station to the end user, so the cost for that connection is higher (this issue may be partially remedied with the appropriate use of quality of service [QoS], which should be negotiated with the provider of the fiber connection). If low latency is a requirement, the use of high data rate at 26 GHz may help satisfy the mission needs. However, if latency is not an issue, using a different frequency might be sufficient.

Cost-benefit analysis example 2 – The onboard equipment costs and the costs associated with the tracking station passes must be included in the trade between 26 GHz and other bands operating at lower data rates. While the initial outlay of funds for onboard equipment may be more for 26 GHz, if the mission is expected to operate for several years (as is usually the case), the costs for the greater number of tracking station passes required by the other lower-rate bands may outweigh those initial onboard hardware costs. The project manager needs to ensure that trades are not done strictly on the spacecraft costs, but on the mission lifecycle costs.

Infrastructure upgrade costs, while not the responsibility of the project manager, need to be evaluated in the broader context as part of the cost-benefit analysis. The provider of the infrastructure needs to understand the future needs of missions in order to justify the cost of the upgrades. These costs can potentially be reduced if agencies provide more cross support,

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[2] If the measured (ACM) or expected (VCM) total signal to noise ratio at the receiver (SNR) is too high, use a more bandwidth-efficient coding and modulation scheme to increase data rate. If the SNR is too low and there are too many errors, use a more power-efficient coding and modulation scheme to reduce the number of errors and increase the quality of the link.

which will result in a broader base of missions to consider and may enable the agencies to share the costs to upgrade the infrastructure.

The project manager must conduct a thorough cost-benefit analysis for his mission before deciding the downlink frequency. The manager must take into account the long-term operational costs of the use of the tracking assets and the long-haul fiber, the potential for cross support among agencies, and technical requirements, such as data latency.

3.4.4 Interoperability

Past work among the world's space agencies has demonstrated the benefits of interoperable systems in the case where multiple space agencies have either missions or communications infrastructure to support missions. The domain of LEO missions operating at the 26 GHz band is very likely to be another case where interoperability will have substantial benefits for multiple agencies.

Most member agencies already have ground assets that support tracking of LEO missions. Some of these assets will be candidates for providing support at the 26 GHz band. When interoperable standards are established, a much larger set of ground assets can be made available to participating agencies, thereby reducing the upgrade cost to individual agencies and also providing for increased utilization of all such assets.

Furthermore, if the agencies can agree on a manageable set of interoperable standards for this class of missions, they can increase the usage of standard 26 GHz band spacecraft components, resulting in cost savings for all agencies. Establishment and reuse of standards and equipment will also allow the cost of upgrading ground assets to be kept to a minimum by reducing the number of different systems that must be implemented in each station.

In particular, areas that require common standards to enable interoperability are:

- Ground system interfaces (e.g., transfer data formats and services between mission operations centers and network ground station nodes, etc.) Ground Link Interface Standards may need to be used/defined to allow ACM. Service Management standards may also be required.
- Space link interface standards, which include coding and modulation schemes, link level protocols and other protocols for options like VCM or ACM, which requires a feedback uplink, etc.
- Accurate and complete propagation data and propagation models for the selected ground stations, e.g. in a form similar to ITU models.

Standards development is further detailed in section 6.2.

3.5 Business Case

As detailed in section 4, there are already a number of missions, ground stations and relays that are using 26 GHz, but currently none of them use 26 GHz in the direct LEO-to-ground configuration.

This LEO26SG considers that given all the technology that has already been demonstrated, it is a low-risk endeavor to reuse or slightly adapt this technology for the direct LEO-to-ground case.

This consideration is reinforced by the ongoing technology developments for the two operational missions (EUMETSAT Polar System - Second Generation [EPS-SG] in Europe and the Joint Polar Satellite System [JPSS] in America) that will operate in the scenario addressed in this report (i.e., direct LEO-to-ground communication in the 26 GHz band) by the end of this decade. For example, EPS-SG intends to use the McMurdo ground station, and JPSS intends to use the ground station at Svalbard (see Appendix D and Appendix F).

For future missions, there is room for improvement with aspects such as:

- Faster data rate (e.g., with higher bandwidth components and more efficient coding and modulation schemes like VCM/ACM)
- More reliability (e.g., with better knowledge of atmospheric models and effects)
- Reduced cost, as equipment can be reused in a larger number of satellites and ground stations
- More operational flexibility and ability to compensate for propagation (e.g., with the use of VCM/ACM techniques)

Cross support will accelerate expansion of the number of stations providing support in the 26 GHz band for LEO missions and will bring substantial benefits such as:

- Increase in the amount of data that can be returned to Earth
- Reliability and more flexibility (e.g., by making available alternative stations in case of unfavorable meteorological conditions at other stations, while ensuring low latency requirements)
- Availability of sites that are operated by other agencies and have good propagation conditions for the use of 26 GHz

4 Missions and Networks Using the 26 GHz Band

Space communication networks, including both ground stations and space-based relay systems, have offered services in the 26 GHz since around the year 2000, and several missions have used or are currently using these assets to transfer data in the 26 GHz band. Section 4.1 summarizes the missions that have used or are currently using 26 GHz, as well as missions that plan to use the band.

Section 4.2 provides an overview of existing and planned space-based relay assets supporting 26 GHz. Although relay systems are not the subject of this study, this information is provided because the technology and experience are relevant, and these assets provide an alternative to direct space-to-ground 26 GHz service.

Section 4.3 provides a description of the ground-based assets that are available today for 26 GHz mission support, as well as those that may potentially provide 26 GHz support in the future.

Appendices provide additional technical details about missions currently using or planning to use 26 GHz (Appendix D), space-based relay assets supporting 26 GHz (Appendix E) and ground-based assets supporting 26 GHz (Appendix F).

4.1 Earth and Space Science Missions

There are a variety of past and existing missions that have used or are using the 26 GHz band for both direct space-to-ground and space-to-space relay links to transfer data from the mission spacecraft to the missions' Earth control and science centers (see Table 4-1). Technological modules and subsystems developed for these missions that can be reused or adapted (e.g., upgraded for antenna pointing or high data rates) for future missions using direct LEO-to-ground communications at 26 GHz include transmitters, receivers, power amplifiers and antenna systems. Section 6 provides detail on these and other technologies.

Table 4-1: Existing/Past Missions Using the 26 GHz Band

Orbit	Agency	Mission	Operational Dates	Link and Support Network
LEO	ESA	Envisat	2002-2012	Transmit: space-to-space To Artemis (DRS)
	JAXA	Advanced Earth Observing Satellite II (ADEOS-2)	2002-2003	Transmit: space-to-space To Artemis and Data Relay Test Satellite (DRTS)
	JAXA	Advanced Land Observation Satellite (ALOS)	2006-2011	Transmit: space-to-space To DRTS
	JAXA	Advanced Land Observation Satellite-2 (ALOS-2)	2014	Transmit: space-to-space To DRTS
	JAXA	Japanese Experiment Module (JEM) (on International Space Station [ISS])	2009-Present	Transmit: space-to-space To DRTS
	NASA	SCaN Testbed	2012-Present	Transmit: space-to-space To Tracking and Data Relay Satellite System (TDRSS) (no visibility to ground)
GEO	ESA	European Data Relay System (EDRS)	2014	Transmit space-to-ground To ESA/EDRS stations: Weilheim, Redu, Harwell
	NASA	Solar Dynamics Observatory (SDO)	2010-Present	Transmit: space-to-ground To ground stations at White Sands, New Mexico (NM)
Lunar Orbit	NASA	Lunar Reconnaissance Orbiter (LRO)	2009-Present	Transmit: space-to-ground To ground station WS1 at White Sands, NM (other ground sites possible)

There are missions in development—including several planning to operate in LEO—that are developing systems for communications in the 26 GHz band (see Table 4-2)**. JPSS-1 and EPS-SG are the first missions to fulfill the main focus of this report—direct LEO-to-ground communications using 26 GHz.**

Note that the JPSS program and EPS-SG are both:

- Meteorological missions - Their predecessors have traditionally used bands that are performance-limited (e.g., the 7.75 GHz to 7.9 GHz band in the EPS first generation case)
- Missions involving more than one satellite (and more than one launch) that are intended to operate for almost two decades; it is difficult to anticipate spectrum congestion levels so far ahead (2040); however, less congestion is expected at 26 GHz than, for example, the X-band at 8.4 GHz band

Note that because European Data Relay System-A (EDRS-A) has 27.2 GHz space-to-space receive capabilities in addition to 26 GHz band space-to-ground capabilities. EDRS is also included in the discussion of space-based relay assets in Section 4.2.

Table 4-2: Missions in Development Planning to Use the 26 GHz Band

Orbit	Agency	Mission	Planned Launch	Link at 26 GHz
LEO	ESA/ EUMETSAT	EPS-SG (Two-satellite configuration with three MetOp SG satellite pairs)	2021, 2022	Transmit: space-to-ground To Svalbard and McMurdo
	ESA	Columbus Ka-Band (COLKa) Terminal on ISS	2018 - 2025	Transmit: space-to-space To EDRS
	JAXA	Advanced Optical Satellite and Advanced Radar satellite	2020	Transmit: LEO to ground
	NASA	NASA- Indian Space Research Organization (ISRO) Synthetic Aperture Radar (SAR) (NISAR)	2021, 2022	Transmit: space-to-ground To ground stations at Fairbanks, AK; Punta Arenas, Chile; and Svalbard, Norway
	NASA	Pre-Aerosol, Clouds, and Ocean Ecosystem (PACE)	2022	Transmit: space-to-ground To ground stations at Fairbanks, AK; Punta Arenas, Chile; and Svalbard, Norway
	NOAA	Joint Polar Satellite System (JPSS) -1	2017	Transmit: space-to-ground To ground sites (Svalbard, Norway; Fairbanks, AK;McMurdo, Troll) Transmit: space-to-space To TDRSS (secondary path)
GEO	ESA/ EUMETSAT	Meteosat Third Generation (MTG) (two spacecraft)	2020, 2022	Transmit: space-to-ground To EUMETSAT ground stations in Lario, Italy, and Leuk, Switzerland
HEO	NASA	Transiting Exoplanet Survey Satellite (TESS)	2017	Transmit: space-to-ground To NASA Deep Space Network (DSN) sites (Canberra, Goldstone, Madrid)
Sun-Earth L2	ESA	Euclid	2020	Transmit: space-to-ground To ESA Estrack sites (Cebreros, Malargue)
	NASA	Wide Field Infrared Survey Telescope (WFIRST)	2024	Transmit: space-to-ground to ground stations at White Sands, NM, and Santiago, Chile
	NASA	James Webb Space Telescope (JWST)	2018	Transmit: space-to-ground To NASA Deep Space Network (DSN) sites (Canberra, Goldstone, Madrid)

Several potential future missions in pre-formulation are considering the use of the 26 GHz band (see Table 4-3). In addition, next-generation Earth observation missions are under consideration by other agencies (mission definition studies still need to be performed; therefore, no specific missions can be specified).

Table 4-3: Potential Future Missions (in Pre-Formulation) Considering the Use of the 26 GHz band

Orbit	Agency	Mission	Status/Planned Launch	Link at 26 GHz
LEO	ESA	Next generation of Copernicus (formerly known as GMES) Sentinel satellites	*After 2025*	TBD
	NOAA	Joint Polar Satellite System (JPSS) -2	*Pre-formulation*	TBD

Appendix D provides additional technical details for these missions. The reasons these missions chose the 26 GHz band vary by mission, but a common theme is the availability of additional bandwidth with fewer spectrum regulatory constraints.

4.2 *Space-based Relay Assets*

Space agencies also operate several space-based relay satellites that can communicate with LEO spacecraft using space-to-space links in the 26 GHz band (see Table 4-4). Appendix E provides additional technical details.

Table 4-4: Existing Space-based Relay Systems Using the 26 GHz Band (Available to Support Missions)

Orbit	Agency	Mission (Launch, Operational Dates)	Link	Data Volume and Link Data
GEO	ESA	Artemis (2001- present)	Receive/transmit space-to-space	Supports 3x150 Mb/s return channels and 10 Mb/s forward channels. Transmits to Europe, including Redu (Belgium) at 20 GHz.
	ESA	EDRS (A 2014, C 2016)	Receive (only on A) space-to-space Transmit space-to-ground to Weilheim, Redu and Harwell	Supports up to 1800 Mb/s in 2 x 450 MHz for a total of four channels (i.e., two in each polarization)
	JAXA	Data Relay Test Satellite (DRTS) (2002-present)	Receive space-to-space	Supports signals up to 330MHz. Can transmit in 23.175-23.545 GHz
	NASA	Tracking and Data Relay Satellite System (TDRSS) (2000-present)	Receive space-to-space	Supports signals up to 225 MHz or 650 MHz in 25.25 to 27.5 Ghz. Can transmit in 22.55-23.55 GHz.

The European Data Relay Satellite (EDRS) will have 26 GHz capabilities for both space-to-space receive (EDRS-A) and space-to-ground communications (see Table 4-5). Note that because of its 26 GHz space-to-ground capabilities, EDRS is also discussed in section 4.1 as a mission in development that is planning to use the 26 GHz band. Appendix E provides additional technical details on EDRS, as well.

Table 4-5: Space-based Relay Systems in Development Using the 26 GHz Band

Orbit	Agency	Mission (Launch, Operational Dates)	Link	Data Volume and Link Data
Medium-Earth orbit (MEO)	ESA	Galileo Global Navigation Satellite System (GNSS) 2nd Generation constellation (TBC)	Transmit space-to-space	TBD

4.3 *Ground Systems*

Given existing mission needs and spectrum regulations that enable direct space-to-ground communications in the 26 GHz band, there are several ground stations that provide service in the 26 GHz band, but not necessarily directly from LEO to ground, as summarized in Table 4-6. For a complete listing of IOAG member agencies' ground station assets, see the IOAG website (https://www.ioag.org/Public%20Documents/Forms/AllItems.aspx).

The NASA and NOAA ground sites were developed to support specific missions; however, as those missions end these ground assets can be used to support future missions. One notable example is NASA's WS1 ground asset (in White Sands, New Mexico) that is already supporting multiple missions and will be available for future missions.

In general terms, some existing infrastructure could be reused with limitations, assuming adaptations or replacement of some subsystems for reasons such as:

- Location of ground stations (see section 5.4.2)
- More challenging antenna pointing and tracking (see section 6.1.2.1)
- Atmospheric characterization (see section 6.3.1)
- High data rate requirements (see section 6.1.2.3)

X-band antennas for LEO could be reused at 26 GHz (*Morabito*, et al. 1999) with some performance limitations, provided that some electronics are replaced (e.g., LNA, down-conversion) or with limited upgrades if X-band intermediate frequency is used. Appendix F provides additional details about the capabilities for the existing ground sites.

Table 4-6: Ground Sites Operating in the 26 GHz Band (Downlink/Receive)

Agency/ Company	Ground Site(s)	Antenna Diameter (m)	Support: Orbit Location	Status and Missions
DLR	Weilheim, Germany	13	GEO, LEO	Operational Multi-mission Includes IOT (In-orbit test) capability
ESA-ASV PPP	Weilheim, Germany (FLGS and RDGS) (2)	6.8	GEO	FLGS operational in 2016 RDGS operational in 2015 Supports space-to-ground link from EDRS
ESA-ASV PPP	Redu, Belgium (BFLGS)	6.8	GEO	Operational in 2016 Supports space-to-ground link from EDRS
ESA-ASV PPP	Harwell, UK (HDSG)	6.8	GEO	Operational in 2015 Supports space-to-ground link from EDRS
NASA	Deep Space Network: Canberra, Australia	34	Highly elliptical orbit (HEO), GEO, Lunar, Lagrange	Operational Will support JWST and TESS
NASA	Deep Space Network: Goldstone, CA USA	34	HEO, GEO, Lunar, Lagrange	Operational Will support JWST and TESS
NASA	Deep Space Network: Madrid, Spain	34	HEO, GEO, Lunar, Lagrange	Operational Will support JWST and TESS
NASA	Near Earth Network: White Sands, NM USA (WS1)	18	LEO, HEO, GEO, Lunar, Lagrange	Operational Supports LRO and available for other users
NASA	White Sands, NM USA (SDO1 and SDO2)	18	LEO, HEO, GEO, Lunar, Lagrange	Operational Dedicated support to SDO

In addition, space agencies and commercial service providers are already planning new ground stations or upgrades to existing ground stations for operations in the 26 GHz band. Future NOAA ground sites supporting the JPSS-1 mission are already in development and various stages of deployment to polar regions, so these ground stations may be useful for future missions (see Table 4-7).

Table 4-7: Potential Future Ground Sites Supporting the 26 GHz Band (Downlink/Receive)

Agency/ Company	Ground Site(s)	Antenna Diameter (m)	Support: Orbit Location	Status and Missions
Commercial	Svalbard, Norway	3-13	LEO	Future: [TBD] Supports space-to-ground link from EPS-SG, JPSS-1
ESA	Cebreros, Spain	35	Deep space	Future: [2017] Supports space-to-ground link from Euclid
ESA	Malargue, Argentina	35	Deep space	Future [2018] Supports space-to-ground link from Euclid
JAXA	Tsukuba and Hatoyama, Japan	5	LEO	Future: [2020]
NASA	AS3 Alaska, USA	11	LEO	Current: [2014] 26 GHz support not yet planned
NASA	New Punta, Chile	12	LEO, HEO	Future: [2020]
NASA	Santiago, Chile	18	LEO, HEO, GEO, Lunar [Lagrange]	Future: [2022]
NASA	Svalbard, Norway	7.3	LEO, HEO	Future: [2020]
NOAA	JPSS Ground Network (formerly part of SafeytNet) Svalbard, Norway	4	LEO	Future: [2014] Dedicated support to JPSS-1 and future weather satellites [TBD: availability for other users]
NOAA	JPSS Ground Network (formerly part of SafeytNet) Fairbanks, AK USA	4	LEO	Future: [2014] Dedicated support to JPSS-1 and future weather satellites [TBD: availability for other users]
NOAA	JPSS Ground Network (formerly part of SafeytNet) McMurdo, Antarctica (2)	4	LEO	Future: [2014] Dedicated support to JPSS-1 and future weather satellites (EPS-SG) [TBD: availability for other users]

Additional discussion of these potential future ground station capabilities is provided in Appendix F.

5 Architecture Considerations

5.1 *Reference Architecture*

Figure 5-1 depicts the reference architecture applicable to this study. The services referenced in this figure follow CCSDS terminology and are described in more detail in Appendix I.

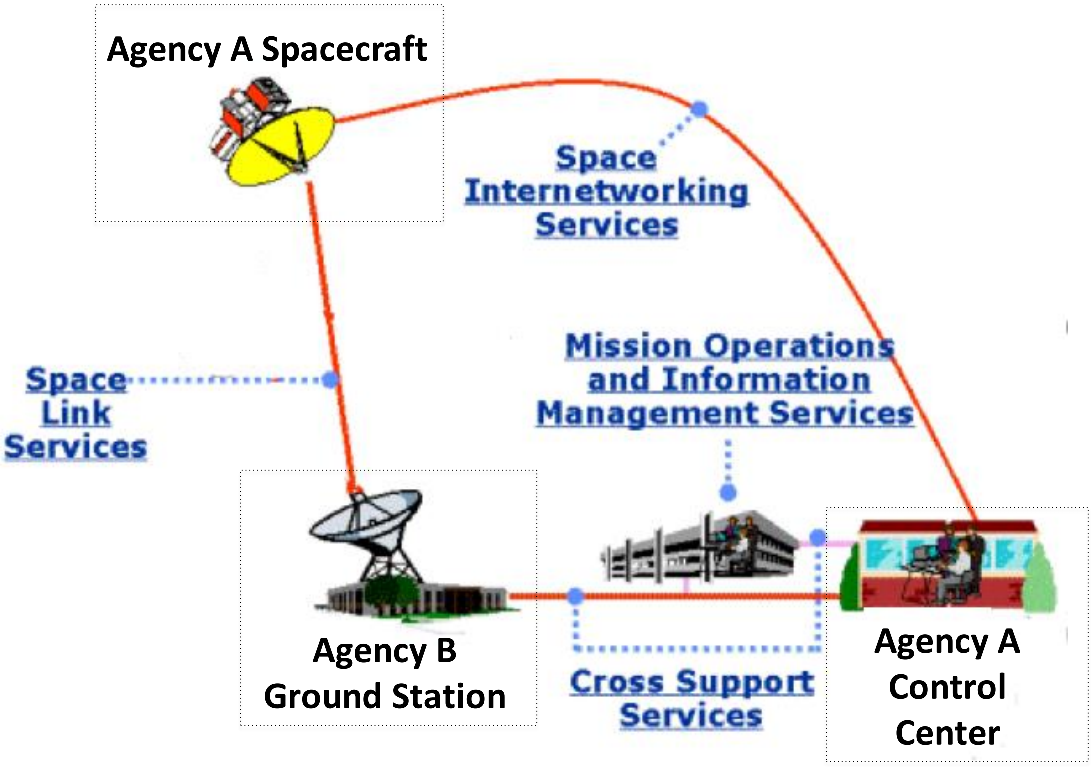

Figure 5-1. Reference Architecture

5.2 *Interoperability and Cross-support Services*

Using the architecture depicted in Figure 5-1, the IOAG developed two catalogs (see Appendix I.2) that define a set of common services that can be offered by space communication networks using a set of space data interoperability standards. These services use CCSDS standards for the space link services, cross-support services and space internetworking services.

The primary difference for these services when using 26 GHz compared with more typically used frequencies is with the space link interface, which is discussed in Appendix I.3. VCM and ACM could be part of the space link services and are not specific to use of 26 GHz. Use of ACM is addressed in more detail section 5.4.4. An example of VCM use is provided inAppendix G.

The only difference in cross-support services when using 26 GHz is the increased bandwidth required for the terrestrial link, which is briefly discussed in Appendix I.4.

There is nothing unique about space internetworking services as a result of using 26 GHz, so these services are discussed at a high level in Appendix I.5.

The mission operations and information management services are not covered by CCSDS standards and are addressed in section 5.3.

5.3 Mission Operations and Information Management Services

Using 26 GHz enables a much higher data rate than lower frequency bands; however, mission operations must take into account the variability in throughput due to weather that causes propagation and signal attenuation. Even if the system is optimized using ACM to mitigate these weather effects, possibly increasing the amount of data downloaded, it will not be possible to predict exactly how much data will be returned.

Assuming recovery of all spacecraft data is important, it will be necessary to communicate to the spacecraft which data are required to be retransmitted on future passes. In addition, it might be beneficial to have a flexible scheduling algorithm to schedule extra passes as needed to compensate for the retransmitted data. Alternately, additional passes or contacts with other stations can be planned to take into account this effect and then the passes may be given up if they are no longer required.

5.4 Ground System Architecture

The function of the ground system architecture is to supply a data path from the ground station receiving the data acquired by the spacecraft to the principal investigator or mission data repository. The fundamental ground system architecture for supporting LEO missions at 26 GHz is very similar to that used today for S- or X-band users. The 26 GHz system will require a set of ground stations, predominantly at high latitudes (both north and south), to enable long contact times between each ground station and the mission satellite. The ground stations will require terrestrial networking to transport user data and configuration information from centralized control centers. The following sections describe the differences that must be considered in architecting the 26 GHz system compared to existing S-band systems.

5.4.1 Number of Available Ground Stations

Few current agency ground stations can support 26 GHz operations. The list of current ground stations supporting 26 GHz is located in section 4.3, and further details are in Appendix F. Section 6.1.2 addresses the development status of additional assets.

5.4.2 Ground Station Location

For LEO high-inclination orbits, the longest contact time is achieved with high-latitude stations. At high latitudes the weather is usually very cold and dry, making these areas appropriate for 26 GHz ground station locations. Many existing 26 GHz stations were designed to support only non-LEO missions and are located in mid- to low-latitude locations that suffer from humid weather conditions and incur related propagation impairments. These propagation effects are not dramatic for ground stations tracking GEO satellites (typically at 30- to 40-degree elevation angles), but would greatly impact tracking LEO satellites at very low elevation angles. In addition, stations that were designed to support GEO missions may not track at low elevation angles and high-speed overhead passes.

Operational availability of 26 GHz ground stations is driven by several factors including ground station location, number of ground stations, signal attenuation statistics (e.g., cumulative distribution functions of signal loss due to rain), RF link margins and signal attenuation mitigation techniques. Because signals at 26 GHz are more susceptible to attenuation by atmospheric moisture, rain and snow, some locations used for S-band ground stations may not be suitable for 26 GHz services. Mitigation strategies can include relocating stations to better, dryer locations; use of multiple stations separated over moderate distances (weather diversity); or simply planning for and building larger RF link margins (or reduced data rate) to mitigate the expected higher attenuation of the stations. Other techniques to optimize data volume transfer include various adaptive data rate systems (as described earlier) that use all available link margin to maximize the ground station data throughput. In these cases, the ground network needs to consider the potential difference in data rate throughout a pass, or the autonomous transfer of the RF link between different sites during rain events.

Environmental and weather conditions at ground station locations may necessitate the use of radomes to protect the antennas from wind, rain or other environmental effects. Radomes for 26 GHz band signals are available and are deployed at some ground stations. Although radomes protect the antenna, radomes degrade the signal strength, typically around 1-2 dB, thus affecting link availability.

5.4.3 Ground Station Issues

5.4.3.1 Elevation Angle Limitations

It is possible that because of the extra atmospheric attenuation, depending on the ground station location, 26 GHz operation may not be possible at ground antenna elevation angles as low as are possible at S-band. This issue needs to be taken into account when planning and scheduling ground passes.

5.4.3.2 Antenna Surface Quality

To achieve the same aperture efficiency as lower frequency stations at the higher frequency, 26 GHz antennas need to have higher surface quality and should be stiffened so as to maintain this quality even at low elevation angles.

5.4.3.3 Use of Radomes

The use of radomes, especially in polar locations, on a 26 GHz band antenna may alleviate the stiffness requirements against wind. Radome use, however, is a challenge due to impacts on efficiency and link availability.

The 26 GHz band is more sensitive to rain and snow than lower frequencies and this sensitivity needs to be considered in the design of the radome. Since ground antennas have higher gain in higher frequencies, the same gain can be achieved at 26 GHz with smaller antennas, thus allowing for the use of smaller radomes.

5.4.3.4 Antenna Pointing

Like the spacecraft antenna, the 26 GHz ground antenna has more gain than a lower frequency antenna of the same size. Depending on the engineering trades of data rate, antenna size, link margin, higher pointing accuracy, etc., an antenna at 26 GHz will result in a beam width significantly less than at S-band (for similar aperture sizes). Due to the smaller beam width, more accurate antenna pointing is required to maintain the same expected pointing loss to the mission spacecraft. This issue could be critical for overhead passes of LEO spacecraft. The additional pointing accuracy may require higher precision encoders for measuring antenna position or actuator control, or improved positioning and movement.

5.4.3.5 Availability of 26 GHz Electronics

Antenna front-end electronics are already available for 26 GHz. However, in some cases they are less mature than their S-band counterparts. This factor can be taken into account when calculating system reliability and availability.

The signal processing in the ground station may have to be improved to handle higher data rates.

5.4.4 ACM Support

As mentioned earlier, ACM is a common technique that uses all available RF signal energy to maximize the data rate. ACM improves the efficiency of the link by adapting the coding/modulation scheme and associated data rate to the available link margin at the moment of transmission. If a mission chooses to use ACM as part of the 26 GHz design, then equipment must be provided at the ground stations to enable the capability of estimating the available link margin in real time. This equipment will include an uplink capability during the pass. Since very little information needs to be sent to achieve the ACM control messages, this uplink can be the same one used for the spacecraft’s telemetry, tracking and command (TT&C) services (this antenna must be co-located with the 26 GHz receive antenna).

5.4.5 Terrestrial Networking

Since one of the reasons for migrating to 26 GHz support is to enable higher data rate downlinks from user spacecraft, correspondingly higher-bandwidth terrestrial network links will be required. Missions should perform a tradeoff among bandwidth, store and forward, and the level of data processing at the ground station.

5.5 Spacecraft Systems and Architecture

This section describes the different functions depicted in Figure 2-2.

Onboard Transmitter:

- Interfaces from the instrument and solid state mass memories (SSMM): With higher data rates, higher capacity (e.g., using flash memories) and higher data transfers (greater than 5 Gb/s peak per channel) may be required.
- Coding and modulation schemes: Coding and modulation schemes could operate with a symbol rate four times larger than that of current equipment designed for X-band, if 26 GHz is used with all the available bandwidth (1.5 GHz). Initially, traditional QPSK or 8PSK modulations can be used, but it is expected that more advanced schemes supporting the higher flexibility and higher order modulations enabling VCM and ACM will take over when the technology is available. Pre-distortion techniques will be needed.
- RF up-conversion from baseband to the 26 GHz band (not considered critical): Both direct up-conversion and two-stage (e.g., with an intermediate frequency) up-conversion are feasible.

High Power Amplification:
There is technology in the form of TWT with a maximum output power of some 70 W per chain. Significantly lower output power is possible with the use of high-gain onboard antennas and may open the door to less efficient SSPA technology, which becomes an enabling factor for small satellites. The upcoming GaN SSPA will very soon become a much more attractive solution since its efficiency (about 30%) and output power (about 10 W) typically doubles the performance of already existing GaAs SSPAs in this frequency band.

Onboard Antenna:
Three configurations are possible, plus some hybrid between the mechanically and electrically steerable antenna:

- Isoflux: The same gains (e.g., 6 dBi at horizon) are expected as in other lower frequency bands, due to the illuminated geometry (see Table 2-1). With the smaller wavelength, the overall antenna will be smaller and will require higher manufacturing accuracy. Due to the low directivity (e.g., 6 dBi), the link budget margin will be critical and some system compromises may be needed such as:
  - Moderate performance with less link availability or lower data rates
  - Compensation by the ground system (e.g., use of large ground antennas (e.g., 15 m diameter) in locations with favorable propagation characteristics)
- Mechanically steerable antennas: High gains (e.g., 30 dBi for a 15-cm dish) are expected. With lower gains (e.g., 20 dBi), horns may also be an option. The reliability of the mechanism may be critical. Required pointing accuracy is feasible given the beam width (e.g., 5 degrees for a 15-cm dish).
- Electrical steerable antennas: These antennas do not need pointing mechanisms, but they may be complex given the 1-cm wavelength and may result in phase jumps that require a thorough analysis at system level (e.g., regarding possible loss of track).

An attractive alternative solution for small satellites could be to have a small fixed-mounted antenna (e.g. 10-cm dish) with a high gain similar to the one in mechanically steerable antennas. In this case the steerability may be provided by gently pointing the whole spacecraft during the data transmission, probably at the expense of not being able to operate the observing instruments during the data transmission time.

6 Technology and System Development

Based on the above architecture, this section covers:

- Technology availability, and in case of technology development needs, the main issues that those developments must address
- Standards availability and possible further development of those standards
- Mission planning and analysis support, with special emphasis on propagation data and modeling

6.1 Technology Availability and Development

A very significant part of the spacecraft, ground and system technology needed for direct LEO-to-ground communication is available today. However, in some areas, adaptations from other systems (e.g., those already in use in relay satellites) may be needed in the electronics or mechanics to accommodate, for example, different pointing requirements. Improvements in other specific areas can result in increased performance to enable higher data rates, replacement of aging components or decreased cost, and therefore should be considered by agencies.

The link budget example presented in Appendix G presents a general example that enables better understanding of the details of the systems described below.

6.1.1 Spacecraft

There are several commercially available 26 GHz band components and processes to manufacture those components in the same band or very similar bands (e.g., Ka-band for telecommunications spacecraft).

The need for high-rate systems is driven by the capability of instruments and sensors to acquire more Earth science data in terms of geometric and radiometric resolution, higher coverage, or increased data acquisition time within each orbit. This need is not dependent on the use of the 26 GHz downlink, but 26 GHz may solve the downlink data rate limitation and enable missions to meet those Earth science data requirements.

6.1.1.1 Spacecraft High-rate Systems

This higher volume of data from sensors and instruments imposes a significant challenge, not only in the communication to ground, but also within the spacecraft, and hence is not specific to the use of the 26 GHz band or to Earth science. Missions collecting high volumes of data will require:

- High-speed spacecraft interfaces to transport the generated data from the acquisition instruments and sensors to storage and communication systems within the spacecraft. This technology is also needed in planetary and telecommunication satellites.
- Onboard data storage with higher capacity and faster access. Storage is needed to cover the time gap between sensors' data acquisition and visibility of the ground station to transmit the data to Earth. This technology is usually based on commercial off-the-shelf (COTS) components and is also needed in planetary missions.
- Space internetworking services able to run fast and handle high data rates.

6.1.1.2 Transmitter

The transmitter includes coding, modulation and up-conversion functionality.

Today's existing technology (typically use of QPSK and 8PSK modulations and traditional coding schemes with symbol rates compatible with the available bandwidth [375 MHz] in X-band) could be used for 26 GHz by adding a simple second stage up-conversion of a factor of three (i.e., from X-band to 26 GHz). Given the larger available bandwidth in the 26 GHz band, n-fold parallel coder/modulators or channels could be considered to increase the data rate at the expense of mass, power and interfaces. In case VCM is used, additional protocols at the frame level on top of the traditional coding schemes might need to be implemented especially at very high speed.

To increase the information data rate (in bit/s) efficiently, two approaches can be considered in the coders and modulators:

- Increase the symbol rate so that less parallel coder/modulators are needed: Current digital processes are fast enough to cover the whole 26 GHz band (1500 MHz) with just two channels.
- Increase spectral efficiency (by a peak factor between 1 and 5 in terms of bit/sec/Hz): This requires higher order modulations (e.g., 16-APSK, 32 APSK, 64-APSK) and more efficient coding schemes. Developments are ongoing to comply with newly available CCSDS standards, which also include the modulations, coding and VCM (see Appendix I.3.2).

The introduction of higher order modulations, with non-constant amplitudes, as opposed to the traditional QPSK or 8PSK, becomes more challenging, especially in terms of linearity and phase noise. Advanced techniques (e.g., pre-distortion) are available and it is recommended that they are included in the design of the modulator and up-conversion.

6.1.1.3 High-power Amplifiers (HPA)

TWT are available today in the 26 GHz band with output powers on the order of 100 W. Further development could improve:

- Linearity, which becomes very important with higher modulations
- Overall power and efficiency: The HPA is the most power-demanding stage in the whole 26 GHz onboard system

Solid state power amplifiers (SSPA) represent an alternative to TWTs, but are less efficient at higher frequencies and are not widely commercially available yet in the 26 GHz band. Upcoming GaN SSPA, doubling the efficiency and output power performance with respect to existing GaAs, will very soon become an enabling technology, especially for missions unable to accommodate the larger sized TWTs.

HPAs need to pass the signal to antennas. Waveguides are more efficient than cables especially at higher frequencies, but they need to be manufactured (e.g., for rotary joints) taking into account the mechanical constraints of the onboard antenna.

6.1.1.4 Antennas

Today, mechanically steerable antennas exist and are operational for space-to-space and lunar communication in the 26 GHz band, for communication to Earth in the X-band, and for

Earth remote-sensing instruments, thus proving the reliability of such mechanisms. Antenna development for missions like JPSS and EPS-SG that will use 26 GHz for direct LEO-to-ground communication is ongoing, in terms of:

- Manufacturing tolerances and surface: These depend on the wavelength and affect efficiency
- Pointing: LEO-to-ground geometry is more demanding than pointing to far-distance targets (e.g., in lunar-to-Earth or LEO-to-GEO scenarios); for small satellites, a feasible alternative to using mechanisms is to gently point the whole spacecraft when the mission allows for attitude changes

Isoflux antennas are not currently available; a minor challenge is manufacturing tolerance. These types of antennas could be useful for low data rate missions requiring broadcasting or missions that are very sensitive to micro-vibrations.

Electrically steerable antennas are not currently available commercially. Some pre-development is ongoing in similar frequencies for telecommunication applications. Phase jumps may be challenging for the receiver when using these antennas.

6.1.2 Ground

6.1.2.1 Antenna System Equipment

Existing X-band antenna dishes with only an upgraded feed horn could be used at 26 GHz at the expense of some performance in the link budget and possibly with limited pointing capabilities. Other upgrades are also possible by integrating smaller dishes optimized for the 26 GHz band with the LEO X-band mechanical systems.

Several European antenna manufacturers have realized the importance of this frequency band and are incorporating antenna systems operating in the 26 GHz band in their product catalogues or are developing such systems. Some of these systems will offer an S-band up/down capability in parallel to 26 GHz, for standard TT&C use.

6.1.2.2 Low Noise Amplifier (LNA) and Down-converter

Technology is available. One European company offers an LNA operating in the 26 GHz band that functions at cryogenic and room temperatures. Additional development to create competition would be beneficial.

6.1.2.3 High Data Rate Receiver Equipment

Several equipment manufacturers in Europe and the U.S. provide or are developing telemetry receivers that cover very high data rates. None of them are specific to X-band or the 26 GHz band but provide the data rate and the spectral efficiency that are needed.

The available equipment is typically based on modulations like QPSK and 8PSK, which have a constant amplitude envelope and are very robust against non-linearity.

Similar to the onboard transmitter described in section 6.1.1.2, two complementary approaches can be considered to achieve more demanding, higher data rates (more bits per second):

- Higher symbol rate (more symbols per second), which also implies a wider bandwidth with larger group delay effects. Mitigation techniques like adaptive band equalizers are widely used.

- Increased spectral efficiency (more bits per second per Hz) by higher order modulation schemes (e.g., 16-APSK, 32-APSK, 64- APSK), which are more sensitive to non-linearity and phase noise. Advanced digital processing is recommended, including, for example, digitalization of the receive signals at intermediate frequencies (typically a bit higher than 1 GHz).

Development is ongoing to comply with newly available CCSDS standards, and also includes demodulators and decoders that are compatible with the advanced coding/decoding schemes and VCM, and that can function at higher symbol rates than current equipment.

6.1.2.4 Cross-support Services

The cross-support services will need to run faster and handle higher and possibly more variable data rates than they do today. This is due to higher date rates and is independent of the use of 26 GHz.

6.1.3 System

6.1.3.1 Variable Coding and Modulation (VCM)

VCM has been used to a limited extent. Significant improvements could be made if additional coding and modulation schema, like those mentioned in Appendix I, were available both onboard and on the ground.

6.1.3.2 Adaptive Coding and Modulation (ACM)

ACM is a common technique that uses all available RF signal energy to maximize the data rate. ACM improves the efficiency of the link by adapting the coding/modulation scheme and associated data rate to the available link margin at the moment of transmission. Implementation of ACM assumes an uplink capability is used in real time during the pass.

6.2 Standards Development

6.2.1 Space Internetworking Services

No additional standards development is required beyond what is already being worked in CCSDS.

6.2.2 Space Link Services

The set of cross-supportable codes and modulations needs to be standardized. If ACM is used as a cross-supported service, the standard for real-time switching among codes and modulations must be developed.

A detailed list of applicable space link services CCSDS standards is provided in Appendix I.

6.2.3 Cross-support Services

No additional standards development is required beyond what is already being worked in CCSDS.

6.3 Mission Planning and Analysis Support

Atmospheric attenuation is higher and more variable in 26 GHz than in X-band, and therefore it needs to be taken into account in mission planning.

6.3.1 Propagation Data and Modeling

Developing propagation models for 26 GHz LEO systems is important to further understanding of 26 GHz operations. The objective is to acquire realistic data from orbiting LEO systems at 26 GHz to develop confidence in advanced atmospheric propagation models that reliably predict system performance, link margins and system availability. Reliable propagation models need to cover all elevation angles, all seasons and the dynamic characteristics (atmospheric and orbit dynamics) of LEO systems.

The 26 GHz band is more sensitive to atmospheric effects compared to X-band, especially at very low elevation angles. The accuracy of propagation models for 26 GHz LEO systems depends on several factors, including:

- Accurate knowledge of the propagation characteristics of the ground station location and its meteorological conditions (e.g., precipitation, temperature, etc.).
- The description of time/space dynamics between LEO satellites and ground stations, especially the contact durations at low elevation angles. This particular item differs compared with current propagation measurements from GEO satellites, which do not properly capture the aspects of LEO-based systems.
- The exploitation of numerical meteorological models in physical radio atmospheric channel simulators. Simulators can also support the design of mitigation techniques (e.g., VCM).
- The availability of measurements that are relevant for the 26 GHz LEO configuration. This data is essential to support the development of accurate models and their validation.

Therefore, it is recommended that specific experimental campaigns be carried out at candidate Earth science ground stations (e.g., arctic regions) using GEO and LEO satellites.

To facilitate use by industry, these models should be proposed to radio regulatory bodies (e.g., ITU-R) for adoption as recommendations. In addition, the information gathered in these studies should be shared with all missions.

These topics are further discussed in Appendix H.

6.3.2 Mission Operations

The high dependency on weather conditions may also result in substantial differences in data volumes that can be received by the ground station for different passes. This situation is already the case in other bands due to different durations of the contact time with the LEO satellite. The condition may be aggravated, however, by propagation impairments that force the mission operators to plan different data rates for specific periods of time when using VCM and even for specific passes when using ACM.

7 Conclusion

The 26 GHz frequency is a viable option for direct-to-ground communications for LEO spacecraft. Missions using 26 GHz for space-to-ground communications will realize several benefits including higher data rates and higher science data return (which enable scientific sensors with higher resolution and wider coverage) and operations in a less congested spectrum environment.

Technology and standards to support communications at 26 GHz exist today. Several missions have already successfully used 26 GHz in non-LEO orbits or for space-to-space communications, and there are several LEO missions under development that will use 26 GHz for direct space-to-ground communications. In addition, the basic ground tracking station infrastructure to support 26 GHz operations exists and more infrastructure is being planned or is in development.

There are several challenges flight mission managers must consider as they evaluate use of 26 GHz for LEO space-to-ground communications compared to the frequency ranges typically used for downlink. Such challenges include pronounced atmospheric/propagation attenuation; the need to improve ground infrastructure, especially in the polar regions; and fewer available vendor options for some components than for those at other, more commonly used frequencies. These issues, however, can be mitigated using a variety of known strategies or are expected to diminish as more missions use the 26 GHz frequency for LEO-to-ground communications.

Additionally, there are options available to further enhance 26 GHz communications, such as the development of onboard and ground hardware that will enable the full capability of 26 GHz (around 10 Gb/s) and provide the flexibility offered by advanced coding and modulation schema. The 26 GHz band also opens the possibility, with small high-gain antennas, to have hundreds of Mb/s communications. A multi-parametric analysis is provided in Appendix G.

The next steps toward further enhancing capabilities to achieve the full potential of 26 GHz include:

- Performing experimental campaigns to validate the propagation models
- Proposing propagation models to radio regulatory bodies (e.g., ITU-R)
- Sharing the propagation models and the information gathered in these campaigns with all missions

In addition, the CCSDS could complete relevant standards by expanding the RF and modulation recommendations for use of the 26 GHz band for EESS, and further developing the ACM/VCM protocols to guarantee interoperability. Additional technology upgrades are required to take advantage of the higher data rates enabled by the increased bandwidth available using 26 GHz.

Appendix A List of Acronyms

ACM	Adaptive Coding and Modulation
ADEOS	Advanced Earth Observing Satellite
ADEOS-2	Advanced Earth Observing Satellite-2
ALOS	Advanced Land Observing Satellite
AOCS	Attitude and orbit control systems
AOS	Advanced orbiting systems
APSK	Amplitude and phase-shift keying
ARTEMIS	Acceleration, Reconnection, Turbulence and Electrodynamics of the Moon’s Interaction with the Sun mission
ASI	Agenzia Spaziale Italiana
ASV	Astrium GmbH, Business Unit Services
AZ	Azimuth
BP	Bundle protocol
BPSK	Binary phase-shift keying
CCM	Constant code and modulation type
CCSDS	Consultative Committee for Space Data Services
CFDP	CCSDS file delivery protocol
CNES	Centre National d'Études Spatiales
COM	Communication
COTS	Commercial off-the-shelf
DGS	Data ground stations
DL	Downlink
DLR	Deutsches Zentrum für Luft- und Raumfahrt
DRS	Data relay satellite
DRTS	Data Relay Test Satellite
DS	Deep space
DSN	Deep Space Network
DTN	Disruption-tolerant networking
DVB-S2	Digital Video Broadcasting - Satellite - Second Generation
D-VCM	Dynamic-VCM
EA	Elevation angle
EDRS	European Data Relay System
EES	Earth exploration satellite
EESS	Earth exploration satellite services
EIRP	Equivalent isotropically radiated power
EL	Elevation
EO	Earth observation
EPS-SG	EUMETSAT Polar System - Second Generation
ESA	European Space Agency
ESOC	European Space Operations Centre
ESTEC	European Space Research and Technology Centre
ESTRACK	ESA tracking station network
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
FEC	Forward error correction
FER	Frame error rate
FLGS	Feeder link ground station
G/S	Ground station
G/T	Gain/temperature

GaAs	Gallium Arsenide (SSPA)
GaN	Gallium Nitride (SSPA)
GEO	Geosynchronous Earth orbit
GMES	Global Monitoring for Environment and Security
GMSK	Gaussian Minimum Shift Keying
GNSS	Global Navigation Satellite System
GRC	Glenn Research Center
GSFC	Goddard Space Flight Center
HEO	Highly elliptical orbit
HPA	High-power Amplifier
HQ	Headquarters
IOAG	Interagency Operations Advisory Group
IOT	In-orbit test
ISL	Intersatellite link
ISO	International Organization for Standardization
ISS	International Space Station
ITU	International Telecommunication Union
ITU-R	International Telecommunication Union - Radiocommunication
JAXA	Japan Aerospace Exploration Agency
JEM	Japanese Experiment Module
JPL	Jet Propulsion Laboratory
JPSS	Joint Polar Satellite System
JWST	James Webb Space Telescope
LCT	Laser communication terminal
LDPC	Low-density parity check
LEO	Low-Earth orbit
LEO26SG	Low-Earth Orbit 26 GHz Study Group
LHCP	Left-hand circular polarization
LNA	Low noise amplifier
LRO	Lunar Reconnaissance Orbiter
LTDN	Local time descending node
LTP	Licklider transmission protocol
MCC	Mission control center
MEO	Medium-Earth orbit
MOC	Mission operations center
MTG	Meteosat Third Generation
N/A	Not applicable
NASA	National Aeronautics and Space Administration
NASDA	National Space Development Agency of Japan
NM	New Mexico
NOAA	National Oceanic and Atmospheric Administration
NRE	Non-recurring engineering
OLSG	Optical Link Study Group
OQPSK	Offset quadrature phase-shift keying
OSI	Open systems interconnection
PFD	Power flux density
PPP	Public-private partnership
PSK	Phase-shift keying
PT	Total power
QPSK	Quadrature phase-shift keying

RDGS	Receiving downlink ground station
RF	Radio frequency
RFC	Radio frequency coordination
RFM	Radio frequency and modulation
RHCP	Right-hand circular polarization
RS	Reed Solomon
SCC	Satellite control center
SCCC	Serially concatenated convolutional turbo coding
SDO	Solar Dynamics Observatory
SFCG	Space Frequency Coordination Group
SKDR	S-Ka band data relay
SLE	Space link extension
SNIP	Space Networks Interoperability Panel
SNPP	Suomi National Polar-orbiting Partnership
SO	Space operations
SR	Space research
SSMM	Solid state mass memories
SSPA	Solid state power amplifiers
S-VCM	Static-VCM
TBC	To be confirmed
TBD	To be determined
TC	Telecommunication
TCM	Trellis-coded modulation
TDRSS	Tracking and Data Relay Satellite System
TM	Telemetry
TT&C	Telemetry, tracking and command
TWT	Traveling-wave tube
U.S	United States
UK	United Kingdom
UL	Uplink
UOQPSK	Unfiltered offset quadrature phase-shift keying
VCM	Variable Coding and Modulation

Appendix B List of Applicable and Reference Documents

Below is a list of documents referenced in this report (reference location is specified in parentheses after each listing) as well as other helpful references. Documents are grouped according to subject matter.

CCSDS Standards:

131.0-B-2 CCSDS. *TM Synchronization and Channel Coding*. Recommendation for Space Data System Standards, CCSDS 131.0-B-2. Blue Book. Issue 2. Washington, D.C.: CCSDS, August 2011. (Appendices F.1.2, I.3.2, I.3.3)

131.2-B-1 CCSDS. *Flexible Advanced Coding and Modulation Scheme for High Rate Telemetry Applications*. Recommendation for Space Data System Standards, CCSDS 131.2-B-1. Blue Book. Issue 1. Washington, D.C.: CCSDS, March 2012. (I.3.2, I.3.3)732.0-B-2 CCSDS. *AOS Space Data Link Protocol.* Recommendation for Space Data System Standards, CCSDS 732.0-B-2. Blue Book. Issue 2. Washington, D.C.: CCSDS, July 2006. (Appendix I.3.1)

131.3-B-1 CCSDS. *CCSDS Space Link Protocol over ETSI DVB-S2 Standard*. Recommendation for Space Data System Standards, CCSDS 131.3-B-1. Blue Book. Issue 1. Washington, D.C.: CCSDS, March 2013. (Appendices I.3.1, I.3.2, I.3.3)

132.0-B-1 CCSDS. *TM Space Data Link Protocol.* Recommendation for Space Data System Standards, CCSDS 132.0-B-1. Blue Book. Corrigendum 1. Washington, D.C.: CCSDS, September 2013. (I.3.1)

401.0-B-26 CCSDS. *Radio Frequency and Modulation Systems—Part 1: Earth Stations and Spacecraft*, Recommendations for Radio Frequency and Modulation Systems Standard, Blue Book. Issue 26. Washington, D.C.: CCSDS, October 2016.Appendices F.1.2, I.3.2, I.3.3)

431.1-M *CCSDS. Variable Coded Modulation Protocol* CCSDS 431.1-M Magenta book This CCSDS standard was not yet published at the time this report was released in 2016

720.7-B-4 CCSDS. *CCSDS File Delivery Protocol (CFDP).* Recommendation for Space Data System Standards, CCSDS-720.7-B-4. Blue Book. Issue 4. Washington, D.C.: CCSDS, January 2007. (Appendix I.5)

734.1-R-2 CCSDS. *Licklider Transmission Protocol (LTP) for CCSDS*. Draft Recommendation for Space Data System Standards, CCSDS 734.1-R-2. Red Book. Issue 2. Washington, D.C.: CCSDS, February 2012. (Appendix I.5)

734.2-R-1 CCSDS. *CCSDS Bundle Protocol Specification*. Draft Recommendation for Space Data System Standards, CCSDS 734.2-R-1. Red Book. Issue 1. Washington, D.C.: CCSDS, February 2012. (Appendix I.5)

910.4-B-2 CCSDS. *Cross Support Reference Model—Part 1: Space Link Extension Services*. Recommendation for Space Data System Standards, CCSDS 910.4-B-2. Blue Book. Issue 2. Washington, D.C.: CCSDS, October 2005. (Appendix I.4)

910.11-B-1 CCSDS. *Space Communication Cross Support—Service Management—Service Specification*. Recommendation for Space Data System Standards, CCSDS 910.11-B-1. Blue Book. Issue 1. Washington, D.C.: CCSDS, August 2009. (Appendix I.4)

911.1-B-3 CCSDS. *Space Link Extension—Return All Frames Service Specification*. Recommendation for Space Data System Standards, CCSDS 911.1-B-3. Blue Book. Issue 3. Washington, D.C.: CCSDS, January 2010. (Appendix I.4)

911.2-B-2 CCSDS. *Space Link Extension—Return Channel Frames Service Specification*. Recommendation for Space Data System Standards, CCSDS 911.2-B-2. Blue Book. Issue 2. Washington, D.C.: CCSDS, January 2010. (Appendix I.4)

911.5-B-2 CCSDS. *Space Link Extension—Return Operational Control Fields Service Specification*. Recommendation for Space Data System Standards, CCSDS 911.5-B-2. Blue Book. Issue 2. Washington, D.C.: CCSDS, January 2010. (Appendix I.4)

912.1-B-3 CCSDS. *Space Link Extension—Forward CLTU Service Specification*. Recommendation for Space Data System Standards, CCSDS 912.1-B-3. Blue Book. Issue 3. Washington, D.C.: CCSDS, July 2010. (Appendix I.4)

912.3-B-2 CCSDS. *Space Link Extension—Forward Space Packet Service Specification*. Recommendation for Space Data System Standards, CCSDS 912.3-B-2. Blue Book. Issue 2. Washington, D.C.: CCSDS, July 2010. (Appendix I.4)

913.1-B-1 CCSDS. *Space Link Extension—Internet Protocol for Transfer Services*. Recommendation for Space Data System Standards, CCSDS 913.1-B-1. Blue Book. Issue 1. Washington, D.C.: CCSDS, September 2008. (Appendix I.4)

Information about Missions and Ground Stations:

Astrium. (n.d.). *EDRS Space Data Highway*. Retrieved from http://www.edrs-spacedatahighway.com/. (Appendix D.1.1.2)

EUMETSAT. (2013) *Meteosat Third Generation*. Retrieved from http://www.eumetsat.int/Home/Main/Satellites/MeteosatThirdGeneration/index.htm. (Appendix H)

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Appendix C Frequency Allocations for Earth and Space Science Services

Table C-1 lists the radio frequency bands allocated for Earth and space science services, including space research (SR), space operations (SO), Earth exploration satellite (EES), and SR deep space, SR (DS). Regarding the ones relevant to this document (i.e., EES and SO service in the space-Earth direction), only the following frequency bands are allocated: 2,200 – 2,290 MHz, 8,025 – 8,400 MHz and 25,500 – 27,000 MHz.

Table C-1: Frequency Allocations for Earth and Space Science Services

Frequency band (MHz)	Allocated service	Direction	Allocation status	Bandwidth (MHz)
2,025 –2,110	SR, SO, EES	Earth–space	Primary	85
2,110 – 2,120	SR (DS)	Earth–space	Primary	10
2,200 – 2,290 (S-band)	SR, SO, EES	Space–Earth	Primary	90
2,290 – 2,300	SR (DS)	Space–Earth	Primary	10
7,145 – 7,190	SR (DS)	Earth–space	Primary	45
7,190 – 7,250	SR	Earth–space	Primary	45
7,750 – 7,900 (X-band)	SO	Space–Earth	Primary	150
8,025 – 8,400 (X-band)	EES	Space–Earth	Primary	375
8,400 – 8,450	SR (DS)	Space–Earth	Primary	50
8,450 – 8,500	SR	Space–Earth	Primary	50
22,550 – 23,150	SR	Earth–space	Primary	600
25,500 – 27,000 (26 GHz band)	SR, SR (DS), EES	Space–Earth	Primary	1,500
31,800 – 32,300	SR (DS)	Space–Earth	Primary	500
34,200 – 34,700	SR (DS)	Earth–space	Primary	500
37,000 – 38,000	SR	Space–Earth	Primary	1,000
40,000 – 40,500	SR	Earth–space	Primary	500

Appendix D Missions Using the 26 GHz Band: Supplemental Information

D.1 Existing Missions Using 26 GHz for Communications Other Than LEO-to-Ground (e.g., GEO- or L2-to-Ground or Intersatellite Link [ISL])

This section describes missions using 26 GHz for communications other than LEO-to-ground (e.g., GEO- or L2-to-ground or ISL). There are no existing LEO satellites using the 26 GHz band for space-to-ground communications.

D.1.1 *ESA*

D.1.1.1 *Envisat*

The only ESA mission that has used the 26 GHz band is Envisat, which used 26 GHz to communicate with the relay satellite, Artemis (see Appendix G). Envisat was operational for 10 years. The characteristics of the 26 GHz link are described in detail in references listed in Appendix B (*European Space Agency*, 2013; *Mas-Albaiges, and Huertas*, 1996).

Table D-1 lists the key characteristics of the intersatellite link from Envisat to Artemis.

Table D-1: Envisat Characteristics

Satellite	**Envisat**
Launch year - last year of operation	2002 – 2012
Orbit type (and mean altitude, inclination)	LEO (800 km, 98 deg.)
Type of mission	Earth observation
Data volume per day (Tbits)	
Is 26 GHz downlink used for LEO-to-ground?	No, X-band is used
Usage of 26 GHz band	Link to Artemis (DRS)
Number channels active	1
Center frequency channels in 26 GHz band	27.1 GHz
Bandwidth per channel	234 MHz
Data rate (average)	100 Mbit/s information (200 Mbit/s after conv. 0.5 coding)
Modulation and coding	QPSK Differential convolutional 0.5 coding (no Reed Solomon [RS])
Transmit power in 26 GHz band (W and dBW)	58.50 W = 17.67 dBW
Onboard antenna (size, gain)	Mechanically steerable - Cassegrain 90 cm. Gain: 43,93 dBi
Polarization	RHCP
Equivalent isotropically radiated power (EIRP) (dBW)	57.26 dBW
Minimum elevation angle	N/A (link to DRS, not to ground)
Distance (km) and path losses (dB)	45,400 km space loss - 214 dB
Availability	99%
Ground segment	TBD stations
G/S receiver antenna (type) diameter; directivity; G/T	N/A (DRS)

D.1.1.2 *EDRS*

The European Data Relay System (EDRS) is an independent European satellite system designed to reduce time delays in the transmission of large quantities of data.

The EDRS infrastructure consists of:

- Two geostationary payloads: EDRS-A and EDRS-C. The space-to-ground link for both satellites is in the 26 GHz band. Only EDRS-A has a space-to-space link at 27.2 GHz
- A ground system consisting of a satellite control center (SCC)
- A mission operations center (MOC) in Ottobrunn (Germany)
- A feeder link ground station (FLGS): Redu and Weilheim
- Data ground stations (DGS): Harwell and Weilheim

User data ransmitteds from LEO user satellites to either of the EDRS payloads and relayed to the FLGS and/or the DGS on the ground, from where it makes available to the users' sites. ESA developed four ground stations in Europe to provide the users with the EDRS data.

Table D-2 lists the characteristics of the EDRS-A and EDRS-C.

Table D-2: EDRS-A and EDRS-C Characteristics

Satellite	EDRS-A	EDRS-C
Launch year - last year of operation	2016-2031	2017-2032
Orbit type (and mean altitude, inclination)	GEO: 35,786 km (9 deg. E)	GEO: 35,786 km (31 deg. E)
Type of mission	Data Relay Satellite (DRS)	
Data volume per day (Tbits)		
Is 26 GHz downlink used for LEO-to-ground?	No (GEO to ground)	
Usage of 26 GHz band	GEO to ground [3]	
Number channels active	4 (2 carriers in the 2 polarizations)	
Center frequency channels in 26 GHz band	25.785 GHz, 26.335 GHz	
Bandwidth per channel	450 MHz (symbol rate = 300 Mbaud)	
Data rate (average)	Advanced mode: 1800 Mb/s information with 4 single downlink channels	
Modulation and coding	Offset QPSK plus hard-keyed (no shaping filter) FEC convolutional 3/4 + RS (255,239) with 4 channels FEC convolutional 1/2 +RS (255,239) with 2 channels	
Transmit power in 26 GHz band (W and dBW)	Approx. 60 W (per channel) = 17.7 dBW	
Onboard antenna (size, gain)	2.2 m single offset feed for GEO to ground	
Polarization	RHCP and LHCP	
EIRP (dBW)	52.9 dBW to ground	
Minimum elevation angle	Europe coverage	
Distance (km) and path losses (dB)	41,200 km at 5-degree elevation angle Space loss - 213 dB	
Availability	99.6 % (over the year) – TBC	
Ground segment	Europe, including Weilheim (D), Redu (B), and Harwell (UK)	
G/S receiver antenna (type) diameter; directivity; G/T	6.8 m diameter, G/T from 36.35 to 36.8 dB/K.	

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[3] For EDRS-A only, there is also a LEO to EDRS-A link at 27.2 GHz (see E.1.1.2). Both EDRS-A and EDRS-C can also receive data from LEO satellites via optical links.

Communication from LEO to EDRS is done via a laser communication terminal (LCT) and also on the 26 GHz band, and is further detailed in Appendix E.1.1.2.

More information on the EDRS project can be found in the references listed in Appendix B (*Astrium*, [n.d.]; *European Space Agency*, [n.d.].).

D.1.2 JAXA

The JAXA missions that used the 26 GHz band are the Advanced Earth Observing Satellite 2 (ADEOS-2), Advanced Land Observing Satellite (ALOS), the Japanese Experiment Module (JEM) attached to the International Space Station (ISS).

Table D-3 through Table D-5 list the key characteristics of the intersatellite links of these satellites.

D.1.2.1 ADEOS-2

Table D-3: ADEOS-2 Characteristics

Satellite	**ADEOS-2**
Launch year - last year of operation	2002 – 2003
Orbit type (and mean altitude, inclination)	LEO (803 km, 99 deg.)
Type of mission	Earth observation
Data volume per day (Tbits)	
Is 26 GHz downlink used for LEO-to-ground?	No (X-band is used)
Usage of 26 GHz band	Link to DRTS (DRS)
Number channels active	1
Center frequency channels in 26 GHz band	
Bandwidth per channel	
Data rate (average)	66 Mbit/s information (122 Mbit/s after conv. 0.5 coding)
Modulation and coding	QPSK + RS coding Differential convolutional 0.5 coding
Transmit power in 26 GHz band (W and dBW)	
Onboard antenna (size, gain)	Mechanically steerable - Cassegrain
Polarization	LHCP
Equivalent isotropically radiated power (EIRP) (dBW)	
Minimum elevation angle	N/A (DRS)
Distance (km) and path losses (dB)	45,400 km Space loss - 214 dB
Availability	
Ground segment	N/A (DRS)
G/S receiver antenna (type) diameter; directivity; G/T	N/A (DRS)

D.1.2.2 *ALOS*

Table D-4: ALOS Characteristics

Satellite	**ALOS**
Launch year - last year of operation	2006 – 2011
Orbit type (and mean altitude, inclination)	LEO (691 km, 98.16 deg.)
Type of mission	Earth observation
Data volume per day (Tbits)	
Is 26 GHz downlink used for LEO-to-ground?	No, X-band is used
Usage of 26 GHz band	Link to DRTS (DRS)
Number channels active	1
Center frequency channels in 26 GHz band	26.1 GHz
Bandwidth per channel	300 MHz
Data rate (average)	240Mbit/s information (480Mbit/s after conv. 0.5 coding)
Modulation and coding	QPSK + RS coding Differential convolutional 0.5 coding
Transmit power in 26 GHz band (W and dBW)	
Onboard antenna (size, gain)	Mechanically steerable – Cassegrain 77 cm
Polarization	LHCP
Equivalent isotropically radiated power (EIRP) (dBW)	
Minimum elevation angle	N/A (DRS)
Distance (km) and path losses (dB)	45,400 km Space loss - 214 dB
Availability	
Ground segment	N/A (DRS)
G/S receiver antenna (type) diameter; directivity; G/T	N/A (DRS)

D.1.2.3 *ALOS-2*

Table D-5: ALOS-2 Characteristics

Satellite	**ALOS-2**
Launch year - last year of operation	2014
Orbit type (and mean altitude, inclination)	LEO (628 km, 98 deg.)
Type of mission	Earth observation
Data volume per day (Tbits)	
Is 26 GHz downlink used for LEO-to-ground?	No, X-band is used
Usage of 26 GHz band	Link to DRTS (DRS)
Number channels active	1
Center frequency channels in 26 GHz band	26.1 GHz
Bandwidth per channel	300 MHz
Data rate (average)	240 Mbit/s information (480 Mbit/s after conv. 0.5 coding)
Modulation and coding	QPSK + RS coding Differential convolutional 0.5 coding
Transmit power in 26 GHz band (W and dBW)	
Onboard antenna (size, gain)	Mechanically steerable – Cassegrain 77 cm
Polarization	LHCP
Equivalent isotropically radiated power (EIRP) (dBW)	
Minimum elevation angle	N/A (DRS)
Distance (km) and path losses (dB)	45,400 km Space loss - 214 dB
Availability	
Ground segment	N/A (DRS)
G/S receiver antenna (type) diameter; directivity; G/T	N/A (DRS)

D.1.2.4 *JEM*

Table D-6: JEM Characteristics

Satellite	JEM
Launch year - last year of operation	2009 – present
Orbit type (and mean altitude, inclination)	LEO (400 km, 51.6 deg.)
Type of mission	Japanese module attached to ISS
Data volume per day (Tbits)	
Is 26 GHz downlink used for LEO-to-ground?	No
Usage of 26 GHz band	Link to DRTS (DRS)
Number channels active	1
Center frequency channels in 26 GHz band	26.35 GHz
Bandwidth per channel	120MHz
Data rate (average)	50 Mbit/s information (100 Mbit/s after conv. 0.5 coding)
Modulation and coding	QPSK + RS coding Differential convolutional 0.5 coding
Transmit power in 26 GHz band (W and dBW)	
Onboard antenna (size, gain)	Mechanically steerable – Cassegrain gain: 44 dBi
Polarization	LHCP
Equivalent isotropically radiated power (EIRP) (dBW)	
Minimum elevation angle	N/A (DRS)
Distance (km) and path losses (dB)	45,400 km Space loss - 214 dB
Availability	
Ground segment	N/A (DRS)
G/S Receiver antenna (type) diameter; directivity; G/T	N/A (DRS)

D.1.3 NASA

D.1.3.1 *SCaN Testbed*

Table D-7: SCaN Testbed Characteristics

Satellite	**SCaN Testbed**
Launch year - last year of operation	2012-2018
Orbit type (and mean altitude, inclination)	LEO, 56-degree inclination (ISS external payload)
Type of mission	Technology advancement
Data volume per day (Tbits)	Experiment-dependent
Is 26 GHz downlink used for LEO-to-ground?	Possible, but not directly
Usage of 26 GHz band	Space-to-space (relay satellite)
Number channels active	2
Center frequency channels in 26 GHz band	25.65 GHz
Bandwidth per channel	225 MHz
Data rate (average)	100 Mbps
Modulation and coding	OQPSK, convolutional rate ½, K=7
Transmit power in 26 GHz band (W and dBW)	40 W
On-board antenna (size, gain)	45cm, 37dBi
Polarization	LHCP
EIRP (dBW)	52 dBW
Minimum elevation angle	
Distance (km) and path losses (dB)	43,549 km, 213.5 dB
Availability	Schedule- and use-dependent
Ground segment	WSC Space Network, and/or any frequency-compatible S-band ground station
G/S receiver antenna (type) diameter; directivity; G/T	Various

D.1.3.2 *SDO*

Table D-8: SDO Characteristics

Satellite	**SDO**
Launch year - last year of operation	2010
Orbit type (and mean altitude, inclination)	Geosynchronous earth orbit (102 West)
Type of mission	Science (heliophysics)
Data volume per day (Tbits)	About 11 Tb/day
Is 26 GHz downlink used for LEO-to-ground?	No
Usage of 26 GHz band	GEO to ground
Number channels active	2 (different polarizations)
Center frequency channels in 26 GHz band	26.5 GHz
Bandwidth per channel	300 MHz
Data rate (average)	130 Mb/s (300 Ms/s after coding)
Modulation and coding	OQPSK, convolutional rate ½, K=7 with Reed-Solomon (223, 255)
Transmit power in 26 GHz band (W and dBW)	2.5 W = 4 dBW
On-board antenna (size, gain)	Two parabolic reflectors: 0.75 m each Gain: 43.8 dBi Each mounted on a boom
Polarization	One antenna left-hand circular (LHCP) and one right-hand circular (RHCP)
EIRP (dBW)	41 dBW (max)
Minimum elevation angle	
Distance (km) and path losses (dB)	
Availability	
Ground segment	SDO1 and SDO2 (at White Sands, NM USA)
G/S receiver antenna (type) diameter; directivity; G/T	Parabolic 18m antennas (see SDO1/SDO2 table)

D.1.3.3 *LRO*

Table D-9: LRO Characteristics

Satellite	**LRO**
Launch year - last year of operation	2009-
Orbit type (and mean altitude, inclination)	50 km mean (+/-5km) Near-circular polar lunar orbit
Type of mission	Lunar surface reconnaissance
Data volume per day (Tbits)	TBD
Is 26 GHz downlink used for LEO-to-ground?	No
Usage of 26 GHz band	Lunar orbit to ground
Number channels active	1 in the 26 GHz band (also has S-band link)
Center frequency channels in 26 GHz band	25.65 GHz
Bandwidth per channel	229 MHz
Data rate (average)	100 Mb/s (max information rate) (114.35 Ms/s after coding)
Modulation and coding	OQPSK, convolutional rate ½, K=7 with Reed-Solomon (223, 255)
Transmit power in 26 GHz band (W and dBW)	40 W = 16 dBW
On-board antenna (size, gain)	Parabolic reflector: 0.75 m Gain: 44 dBi
Polarization	Left-hand circular (LHCP)
EIRP (dBW)	58 dBW (max)
Minimum elevation angle	
Distance (km) and path losses (dB)	
Availability	
Ground segment	WS1 (at White Sands, NM USA)
G/S receiver antenna (type) diameter; directivity; G/T	Parabolic 18m antenna (see WS1 table)

D.2 Missions in Development Using 26 GHz for Communications Other than LEO-to-Ground

D.2.1 ESA

D.2.1.1 *Euclid*

Table D-10: Euclid Characteristics

Satellite	Euclid (TBD)
Launch year - last year of operation	2020
Orbit type (and mean altitude, inclination)	L2
Type of mission	Science
Data volume per day (Tbits)	0.94
Is 26 GHz downlink used for LEO-to-ground?	Not LEO
Usage of 26 GHz band	Downlink of TM to ground
Number channels active	1
Center frequency channels in 26 GHz band	TBD
Bandwidth per channel	115 MHz
Data rate (average)	73.84 Mbps
Modulation and coding	LDPC (8192,4096). OQPSK.
Transmit power in 26 GHz band (W and dBW)	TBD
Onboard antenna (size, gain)	65 cm, 39.2 dBi gain
Polarization	
EIRP (dBW)	52.68 dbW
Minimum elevation angle	
Distance (km) and path losses (dB)	
Availability	
Ground segment	Cebreros and Malargüe ESA ESTRACK stations
G/S receiver antenna (type) diameter; directivity; G/T	Cassegrain; 35 meter

D.2.1.2 *Columbus Ka-Band (COKLa) Terminal on ISS*

Table D-11: COLKa Characteristics

Satellite	**Columbus Ka-Band (COLKa) Terminal on ISS**
Launch year - last year of operation	2018 - 2025
Orbit type (and mean altitude, inclination)	LEO (400 km, 51.6 deg.)
Type of mission	European module attached to ISS
Data volume per day (Tbits)	
Is 26 GHz downlink used for LEO-to-ground?	No
Usage of 26 GHz band	Link to EDRS (DRS)
Number channels active	1
Center frequency channels in 26 GHz band	27.2 GHz
Bandwidth per channel	70 MHz
Data rate (average)	50 Mbit/s information
Modulation and coding	QPSK FEC encoding (LDPC 1/2)
Transmit power in 26 GHz band (W and dBW)	34.27 W 15.35 dBW
Onboard antenna (size, gain)	Mechanically steerable - offset shaped Cassegrain 50 cm gain: 39.34 dBi
Polarization	LHCP
Equivalent isotropically radiated power (EIRP) (dBW)	54.7 dBW
Minimum elevation angle	N/A (link to DRS, not to ground)
Distance (km) and path losses (dB)	45,400 km Space loss – 212.2 dB
Availability	40%
Ground segment	N/A (DRS)
G/S receiver antenna (type) diameter; directivity; G/T	N/A (DRS)

D.2.2 ESA/EUMETSAT

D.2.2.1 *EPS-SG*

The second-generation EUMETSAT Polar System (EPS-SG) mission is the follow-on mission from the original EUMETSAT Polar System (EPS). The objective of both of these missions is to generate and provide Europe's LEO satellite meteorological data to European National Meteorological Services and international partners.

The baseline for EPS-SG is for a two-spacecraft (paired) configuration with an instrument complement to be split over both spacecraft. (See reference in Appendix B.) The EPS-SG satellites are called Metop-SG and a total of 6 Metop-SG satellites (three pairs of satellites:

Metop-SGA and Metop-SGB) will be deployed to span the operational lifetime of the program over 21 years.

The first Metop-SG flight models are developed by the European Space Agency. The satellites will be operated by EUMETSAT, and all global data will be received, processed and transmitted to users by EUMETSAT’s ground segment. A complementary Antarctic ground station service will be provided via NOAA.

Table D-12: EPS-SG Preliminary Characteristics

Satellite	**MetOp-SGA**	**MetOp-SGB**
Launch year - last year of operation	3 satellites 1st one to launch in 2021 Last one to launch in 2035	3 satellites 1st one to launch in 2022 Last one to launch in 2037
Last year of operations	> 2044	
Orbit type (and mean altitude, inclination)	LEO (850 km altitude; 98.7 degrees included) 09:30 LTDN	Same as MetOp-SGA
Type of mission	Meteorology	
Data volume per day (Tbits)	~ 4 Tbits	~ 1.5 Tbits
Is 26 GHz downlink used from LEO-to-ground?	Yes	
Usage of 26 GHz band	Earth science data downlink to ground	
Number channels active	2	1
Center frequency channels in 26 GHz band	26.295 and 26.700 GHz	26.700 GHz
Bandwidth per channel	~ 390.5 Mbps per channel (366 MHz)	~ 390.5 Mbps (366 MHz)
Data rate (average)	781 Mbps total	390.5 Mbps
Modulation and coding	OQPSK + RS (255,223)	
Transmit power in 26 GHz band (W and dBW)	30 W – 15.5 dBW per carrier	
Onboard antenna (size, gain)	Mechanically steerable 22 cm gain 32 dBi	
Polarization	RHCP or LHCP	
EIRP (dBW)	~ 43 dBW	
Minimum elevation angle	5 degrees G/S ant. EL	
Distance (km) and path losses (dB)	2,822 km (at 5 degrees G/S ant. EL) Free space loss – 189.8 dB	
Availability	Availability due to atmospheric attenuation of 99.9% [TBC], orbit averaged over one-year period	
Ground segment G/S receiver antenna (type) diameter; directivity; G/T	EUMETSAT EPS-SG ground segment includes radome, pointing losses.Baseline stations: Svalbard (EUM), McMurdo (NOAA/NASA/NSF) 6.4 m , 35 dB/K Svalbard (clear sky conditions) 4 m, 28 dB/K McMurdo (sky temp. 275K)	

D.2.2.2 *MTG*

The MTG series will comprise six satellites (four MTG-I, two MTG-S) providing space-acquired meteorological data until at least the late 2030s. To cover the wide range of observational products requested by the users, the MTG space segment architecture comprises two satellite types, the MTG-I and MTG-S, both utilizing a common three-axis stabilized platform, but with a different payload complement. (See reference in Appendix B). The full operational capability (FOC) consists of 2 MTG-I (one acting as in-orbit hot backup for the prime MTG-I satellite and supporting the RSS services) and a MTG-S.

Within the overall MTG program, ESA is responsible for the development of the first MTG-I and first MTG-S satellites and for the procurement of recurrent satellite models. EUMETSAT is responsible for the overall MTG system, the development and procurement of the MTG ground segment, the procurement of the launch and LEOP services, and the operations.

Table D-13: MTG Preliminary Characteristics

Satellite	**MTG-I**	**MTG-S**
Launch year - last year of operation	4 satellites MTG-I (1st one in 2020)	2 satellites MTG-S (1st one in 2022)
Last year of operations	> 2040	
Orbit type (and mean altitude, inclination)	GEO (between 50 degrees W and 70 degrees E)	GEO (between 10 degrees E and W)
Type of mission	Meteorology	
Data volume per day (Tbits)	13.5 Tbits	20.3 Tbits
26 GHz downlink used from LEO-to-ground?	No (GEO)	
Usage of 26 GHz band	Payload data downlink (GEO to ground)	
Number channels active	1	1
Center frequency channels in 26 GHz band	26.360 GHz	26.760 GHz
Bandwidth per channel	284 MHz (188 Msymbol/s)	448 MHz (282 Msymbol/s)
Data rate (average)	164 Mb/s information	246 Mb/s information
Modulation and coding	Filtered offset-QPSK Convolutional 0.5 coding + RS (I=5; 223/255)	
Transmit power in 26 GHz band (W and dBW)	~ 35 W = 15.5 dBW	
Onboard antenna (size, gain)	1m single reflector, steerable +/- 8.7 degrees Gain: 42.5 dBi	
Polarization	RHCP or LHCP	
EIRP (dBW)	55 dBW	
Minimum elevation angle	10 degrees (final location still TBD)	
Distance (km) and path losses (dB)	40,657 km @ 9 degrees; Space loss = - 213 dB	
Availability	99.9 % single station 99.99% with site diversity	
Ground segment	Two MTG GS sites with up to 4 antennas per site	
G/S receiver antenna (type) diameter; directivity; G/T	Cassegrain, 6.5 m diameter, 63.4 dBi directivity, ~38.3 dB/K (@10 deg, clear sky)	

D.2.3 JAXA

D.2.3.1 *Advanced Optical Satellite*

Table D-14: Advanced Optical Satellite Characteristics

Satellite	**JAXA Advanced Optical Satellite (Name Provisional)**
Launch year - last year of operation	1 satellite Launch in 2020
Last year of operations	> 2027
Orbit type (and mean altitude, inclination)	LEO (669 km altitude; 98.062 deg. incl) 10:30 LTDN
Type of mission	Earth observation
Data volume per day (Tbits)	~ 40 Tbits
Is 26 GHz downlink used from LEO-to-ground?	Yes
Usage of 26 GHz band	Earth observation data downlink to ground
Number channels active	1
Center frequency channels in 26 GHz band	26.375GHz[TBC]
Bandwidth per channel	~ 980 MHz per channel[TBC]
Data rate (average)	~ 1,800 Mbps(450Msps)
Modulation and coding	16QAM+RS coding
Transmit power in 26 GHz band (W and dBW)	23.3 W – 13.67 dBW [TBC]
Onboard antenna (size, gain)	Mechanically steerable 35 cm gain ~36.5 dBi
Polarization	RHCP or LHCP
EIRP (dBW)	~ 48.77 dBW [TBC]
Minimum elevation angle	5 degree G/S ant. EL
Distance (km) and path losses (dB)	2,492 km (at 5 degree G/S ant. EL) Free space loss – 188.1 dB
Availability	95.0 % single station (TBC) 99.0% with site diversity (TBC)
Ground segment G/S receiver antenna (type) diameter; directivity; G/T	One stations each at two sites for site diversity operations. 5m dish: AZ/EL, Cross-EL: 36.0dB/K at EL=5 degrees

D.2.3.2 *Advanced Radar Satellite*

Table D-15: Advanced Radar Satellite Characteristics

Satellite	**JAXA Advanced Radar Satellite (Name Provisional)**
Launch year - last year of operation	1 satellite Launch in 2020 (TBC)
Last year of operations	>2027 (TBC)
Orbit type (and mean altitude, inclination)	LEO (628km altitude; 97.9 degrees included) TBD LTDN
Type of mission	Earth observation
Data volume per day (Tbits)	~ TBD Tbits
Is 26 GHz downlink used from LEO-to-ground?	Yes
Usage of 26 GHz band	Earth observation data downlink to ground
Number channels active	2
Center frequency channels in 26 GHz band	TBD GHz[TBC]
Bandwidth per channel	~ TBD MHz per channel[TBC]
Data rate (average)	~ 3600 Mbps(TBDMsps)
Modulation and coding	TBD
Transmit power in 26 GHz band (W and dBW)	TBD dBW
Onboard antenna (size, gain)	TBD TBD cm Gain ~TBD dBi
Polarization	RHCP or LHCP
EIRP (dBW)	~ TBD dBW [TBC]
Minimum elevation angle	TBD degrees G/S ant. EL
Distance (km) and path losses (dB)	TBD km (at TBD degrees G/S ant. EL) Free space loss – TBD dB
Availability	95.0 % single station (TBC) 99.0% with site diversity (TBC)
Ground segment G/S receiver antenna (type) diameter; directivity; G/T	One stations each at two sites for site diversity operations 5m dish: AZ/EL, Cross-EL: 36.0dB/K at EL=5 degrees

D.2.4 NASA

D.2.4.1 *JWST*

Table D-16: James Webb Space Telescope (JWST) Characteristics

Satellite	James Webb Space Telescope (JWST)
Launch year - last year of operation	2018 – 2023 (Potential extended mission to 2028)
Orbit type (and mean altitude, inclination)	Halo orbit at L2 Sun-Earth Lagrange point
Type of mission	Astrophysics
Data volume per day (Tbits)	[TBD: 0.27]
Is 26 GHz downlink used for LEO-to-ground?	No
Usage of 26 GHz band	Space-to-Earth science data downlink
Number channels active	1
Center frequency channels in 26 GHz band	25900 MHz
Bandwidth per channel	56 MHz (max)
Data rate (average)	28 Mb/s information (Variable: 7, 14, 28 Mb/s (14, 28, 56 Ms/s after coding))
Modulation and coding	OQPSK RS (223, 255) and Rate 1/2 convolutional
Transmit power in 26 GHz band (W and dBW)	55 W = 17.4 dBW
Onboard antenna (size, gain)	Parabolic reflectors: [TBD] m each Gain: 46.08 dBi
Polarization	Right-hand circular (RHCP)
EIRP (dBW)	[TBD] dBW
Minimum elevation angle	[TBD: 10 deg]
Distance (km) and path losses (dB)	About 1.5 million km
Availability	[TBD]
Ground segment	NASA Deep Space Network (DSN) at Goldstone, CA, Madrid, Spain, and Canberra, Australia
G/S receiver antenna (type) diameter; directivity; G/T	Parabolic reflectors, 34m diameter G/T = 61.6 dB/K

D.2.4.2 *TESS*

Table D-17: TESS Characteristics

Satellite	Transiting Exoplanet Survey Satellite (TESS)
Launch year - last year of operation	2017 – 2020
Orbit type (and mean altitude, inclination)	HEO orbit, 17Re x 59Re (nominal)
Type of mission	Astrophysics
Data volume per day (Tbits)	109 Gbits
Is 26 GHz downlink used for LEO-to-ground?	No
Usage of 26 GHz band	Space-to-Earth science data downlink
Number channels active	1
Center frequency channels in 26 GHz band	26,000 MHz
Bandwidth per channel	250 MHz
Data rate (average)	109 Mb/s information (250 Ms/s after coding))
Modulation and coding	OQPSK RS (223, 255) and Rate 1/2 convolutional
Transmit power in 26 GHz band (W and dBW)	4.8 W = 6.8 dBW
Onboard antenna (size, gain)	Parabolic reflector: 0.75m Gain: 42.47 dBi
Polarization	Left-hand circular (LHCP)
EIRP (dBW)	48.1 dBW
Minimum elevation angle	10 degrees
Distance (km) and path losses (dB)	About 143,00 km for science downlink, -224 dB path loss
Availability	[TBD]
Ground segment	NASA Deep Space Network (DSN) at Goldstone, CA, Madrid, Spain, and Canberra, Australia
G/S receiver antenna (type) diameter; directivity; G/T	Parabolic reflectors, 34m diameter G/T = 50.1dB/K

D.2.5 NOAA

D.2.5.1 JPSS-1

Table D-18: JPSS-1 Characteristics

Satellite	JPSS-1
Launch year - last year of operation	2017
Orbit type (and mean altitude, inclination)	LEO polar orbit (sun-synchronous, 98.7-degree inclination, 824-km altitude)
Type of mission	Weather observation
Data volume per day (Tbits)	
Is 26 GHz downlink used for LEO-to-ground?	Yes
Usage of 26 GHz band	LEO-to-ground and LEO-to-GEO relay satellite (mission data)
Number channels active	1 active in the 26 GHz band (also has 2 GHz and 7 GHz links)
Center frequency channels in 26 GHz band	26.7034 GHz
Bandwidth per channel	300 MHz (max)
Data rate (average)	130.66 Mb/s (info rate with overhead) 150 Ms/s (after RS encoding, with convolutional coding) or 300 Ms/s (after RS encoding, no convolutional coding)
Modulation and coding	OQPSK, convolutional rate ½, K=7 with Reed-Solomon (223, 255)
Transmit power in 26 GHz band (W and dBW)	70 W = 18.5 dBW (max)
Onboard antenna (size, gain)	One gimballed, nadir pointing for ground stations (gain = 39 dBi) One gimballed, zenith pointing for GEO relay (gain = 39 dBi)
Polarization	Right-hand circular (RHCP)
EIRP (dBW)	51.8 dBW
Minimum elevation angle	
Distance (km) and path losses (dB)	40,420 km (max)
Availability	
Ground segment	JPSS ground system Svalbard, Norway, Fairbanks, AK, McMurdo, Antarctica, Troll, Antarctica
G/S receiver antenna (type) diameter; directivity; G/T	Parabolic 4m antenna (see JPSS ground system table)

D.3 Potential Future Missions (in Pre-formulation) Considering the Use 26 GHz for Communications

D.3.1 ESA

No specific mission has been officially identified yet to use the 26 GHz direct downlink from LEO after MetOP-SG. However, it is expected that MetOp-SG will pave the way for other missions like the next generation of Sentinels in the Copernicus (former Global Monitoring for Environment and Security [GMES]) program, where instruments will generate multi Gb/s data rates by the beginning of the 2020s decade. In addition, there are technology developments (e.g., VCM-compatible transmitters and receivers) ongoing that will bring additional performance to the one in MetOp-SG. These future missions have not been defined in enough detail yet, and no further information can be provided at this stage.

D.3.2 NASA

D.3.2.1 NISAR

Table D-19: NISAR Characteristics (TBR)

Satellite	**NISAR**
Launch year - last year of operation	2021 – 2026
Orbit type (and mean altitude, inclination)	LEO (747 km, 98.4 degrees)
Type of mission	Earth science
Data volume per day (Tbits)	32 Tbits/day
Is 26 GHz downlink used for LEO-to-ground?	Yes
Usage of 26 GHz band	Link to NEN
Number channels active	2
Center frequency channels in 26 GHz band	26.25 GHz
Bandwidth per channel	4 GHz
Information rate (average)	3.484 Gbps (Total=LHCP Ch. + RHCP Ch.) LHCP channel: 1.742 Gbps RHCP channel: 1.742 Gbps
Coded symbol rate	4. Gsps (Total=LHCP Ch. + RHCP Ch.) LHCP channel: 2 Gsps RHCP channel: 2 Gsps
Modulation and coding	OQPSK Rate 7/8 LDPC (8160, 7136)
Transmit power in 26 GHz band (W and dBW)	1 W
Onboard antenna (size, gain)	Mechanically gimbal – Parabolic 70 cm
Polarization	Dual polarization: LHCP and RHCP
Equivalent isotropically radiated power (EIRP) (dBW)	38 dBW
Minimum elevation angle	10 degrees
Distance (km) and path losses (dB)	2256 km Space loss – 187.9 dB
Availability	95% and 99%
Ground segment	NASA Near Earth Network (NEN) at Fairbanks, AK; Punta Arenas, Chile; Svalbard, Norway
G/S receiver antenna (type) diameter; directivity; G/T	TBD

D.3.2.2 *PACE*

Table D-20: PACE Characteristics (TBR)

Satellite	**PACE**
Launch year - last year of operation	2021 – 2027
Orbit type (and mean altitude, inclination)	LEO (675 km, 98 degrees)
Type of mission	Earth science
Data volume per day (Tbits)	5 Tbits/day
Is 26 GHz downlink used for LEO-to-ground?	Yes
Usage of 26 GHz band	Link to NEN
Number channels active	2
Center frequency channels in 26 GHz band	TBD GHz
Bandwidth per channel	1.4 GHz
Information rate (average)	600 Mbps to 1.2 Gbps
Coded symbol rate	689 Msps to 1.378 Gsps
Modulation and coding	OQPSK Rate 7/8 LDPC (8160, 7136)
Transmit power in 26 GHz band (W and dBW)	65 W
Onboard antenna (size, gain)	Earth coverage isoflux antenna
Polarization	TBD
Equivalent isotropically radiated power (EIRP) (dBW)	24.1 dBW
Minimum elevation angle	10 degrees
Distance (km) and path losses (dB)	2100 km Space loss – 187.3 dB
Availability	95%
Ground segment	NASA Near Earth Network (NEN) at Fairbanks, AK; Punta Arenas, Chile; Svalbard, Norway
G/S receiver antenna (type) diameter; directivity; G/T	TBD

D.3.2.3 *WFIRST*

Table D-21: WFIRST Characteristics (TBD)

Satellite	**WFIRST**
Launch year - last year of operation	2024 – 2030
Orbit type (and mean altitude, inclination)	Sun-Earth L2
Type of mission	Space observatory
Data volume per day (Tbits)	11.3 Tbits/day (TBR)
Is 26 GHz downlink used for LEO-to-ground?	Yes
Usage of 26 GHz band	Link to 18m ground stations
Number channels active	2
Center frequency channels in 26 GHz band	TBD GHz
Bandwidth per channel	TBD
Information rate (average)	290 Mbps
Coded symbol rate	333 Msps
Modulation and coding	OQPSK Rate 7/8 LDPC (8160, 7136)
Transmit power in 26 GHz band (W and dBW)	70 W
Onboard antenna (size, gain)	TBD
Polarization	TBD
Equivalent isotropically radiated power (EIRP) (dBW)	TBD
Minimum elevation angle	10 degrees
Distance (km) and path losses (dB)	1,605,258 km Space loss – 245 dB
Availability	95%
Ground segment	NASA 18m ground stations at White Sands, NM, and Santiago, Chile (TBR)
G/S receiver antenna (type) diameter; directivity; G/T	TBD

D.3.2.4 *Exploration Upper Stage (EUS)*

Table D-22: EUS Characteristics (Under Development)

Satellite	**WFIRST**
Launch year - last year of operation	2024 – 2030
Orbit type (and mean altitude, inclination)	LEO/lunar
Type of mission	Space Launch System (SLS) upper stage
Data volume per day (Tbits)	[TBD]
Is 26 GHz downlink used for LEO-to-TDRS?	Yes
Usage of 26 GHz band	Link to TDRS
Number channels active	1
Center frequency channels in 26 GHz band	TBD GHz
Bandwidth per channel	TBD
Information rate (average)	TBD
Coded symbol rate	TBD
Modulation and coding	OQPSK Rate 7/8 LDPC (8160, 7136)
Transmit power in 26 GHz band (W and dBW)	TBD
Onboard antenna (size, gain)	TBD
Polarization	TBD
Equivalent isotropically radiated power (EIRP) (dBW)	TBD
Minimum elevation angle	1.5 degrees
Distance (km) and path losses (dB)	40,000 km
Availability	TBD
Ground segment	TDRS
G/S receiver antenna (type) diameter; directivity; G/T	TBD

D.3.3 NOAA

D.3.3.1 *JPSS-2*

With the launch of the Suomi National Polar-orbiting Partnership (SNPP) spacecraft in 2011, NOAA initiated the next generation of satellite weather and environmental monitoring utilizing five sensitive instruments to advance weather, climate, environmental and oceanographic science. The JPSS-1 (2017) and JPSS-2 (after 2020) satellites, both polar LEO spacecraft, will not only provide operational continuity of satellite-based observations and products but also introduce advanced spacecraft technologies. Unlike SNPP, which uses the 8

GHz band for space-to-Earth transmission of the science data, JPSS-1 and JPSS-2 will use the 26 GHz band for transmitting the science observation data.

D.3.4 Other Space Agencies

Like for the ESA missions, MetOp-SG and ongoing technology developments should facilitate the adoption of the 26 GHz downlink by the next generation of European national missions that will generate multi-Gb/s data rates. These future missions have not been defined in enough detail yet, and no further information can be provided at this stage.

Appendix E Space-based Relay Assets with 26 GHz Band Capabilities: Supplemental Information

E.1 Existing Space-based Relay Systems Using the 26 GHz

E.1.1 ESA

E.1.1.1 ARTEMIS

The Advanced Relay and Technology Mission Satellite (ARTEMIS) has several payloads. The one relevant to this document is the SKDR (S-Ka band Data Relay).

Table E-1: ARTEMIS Characteristics

	Satellite: Artemis	
Relay **Satellite**	Agency	ESA
	Operational date (year)	2001 onwards
	Orbital position	GEO: 35,786 km; 21.5 deg E
	Attitude control (e.g., 3-axis, spin stabilized)	Yes
Operation	Bent pipe or onboard processing	Bent pipe
	Number of return 26 GHz channels	3 (2 simultaneously)
	Forward link with user? If present, at what data rate and frequency?	Yes (45 MHz at 23 GHz band from Artemis to LEO) Ground to Artemis in S-band and at 30 GHz
Return Link Characteristics **(from the user satellite to relay)**	Antenna size (diam. in m.) (with user, not TT&C)	2.85m mechanically steerable single-offset reflector for ISL (53 dBi)
	Field of view (deg)	
	Program tracking and/or autotracking?	Program and autotrack
	Center frequency channels	26.85, 27.1 and 27.35 GHz
	Polarization	RHCP/LHCP selectable
	Bandwidth	234 MHz per channel
	Data rate	It depends on source (bent pipe)
	Coding and modulation schemes supported	Bent pipe (no onboard processing, except for frequency conversion)
	G/T (typical)	22.3 dB/K

The Artemis satellite transmits to ground at 20 GHz and this link to ground is not further reported in this report.

E.1.1.2 *EDRS-A*

Table E-2: EDRS-A Characteristics

	Satellite: EDRS-A	
Relay Satellite	Agency	ESA
	Operational date (year)	2016-2031
	Orbital position	GEO: 35,786 km; 9 deg. E
	Attitude control (e.g., 3-axis, spin stabilized)	Yes
Operation	Bent pipe or onboard processing	Bent pipe
	Number of return 26 GHz channels	1
	Forward link with user? If present, at what data rate and frequency?	Yes, 2 MHz bandwidth EDRS-A to LEO at 23.2 GHz (Ground to GEO is at Ku-band)
Return Link Characteristics (from the user satellite to relay)	Antenna size (diam. in m.) (with user, not TT&C)	1.3m mechanically steerable single-offset reflector for ISL (45 to 48.6 dBi)
	Field of view (deg)	Any LEO position within 0-2 km altitude and 45,000-km distance from satellite (or 11.5-deg half cone)
	Program tracking and/or autotracking?	Yes (open loop)
	Center frequency channels	27.2 GHz
	Polarization	LHCP
	Bandwidth	450 MHz
	Data rate	Not specified as this is a transparent bent pipe channel. The limitation is the 450 MHz available bandwidth.
	Coding and modulation schemes supported	Bent pipe (no digital processing; just frequency conversion from 27.2 GHz LHCP to 25.785 GHz RHCP)
	G/T (typical)	

E.1.2 JAXA

E.1.2.1 *Data Relay Test Satellite (DRTS)*

JAXA is operating the Data Relay Test Satellite (DRTS) in a GEO orbit using the 26 GHz band for intersatellite return link. The DRTS, launched in 2002, has operated and is planning to operate several user satellites using the 26 GHz intersatellite return link. These satellites include Advanced Earth Observing Satellite 2 (ADEOS-2), Advanced Land Observing Satellite (ALOS), the Japanese Experiment Module (JEM) attached to the International Space Station (ISS), and Advanced Land Observing Satellite-2 (ALOS-2). The DRTS is designed to enable interoperability among data relay satellites of NASA and ESA, by adopting Space Networks Interoperability Panel (SNIP) Recommendations (*Space Networks Interoperability Panel*, 1995). In 2006, the DRTS demonstrated its interoperable capability by communicating with Envisat of ESA through the Ka-band intersatellite link.

Table E-3: DRTS Characteristics

	Satellite: DRTS	
Relay Satellite	Agency	JAXA
	Operational date (year)	2002 onwards
	Orbital position	GEO: 35,786 km; 90.75deg E
	Attitude control (e.g., 3-axis, spin stabilized)	Yes
Operation	Bent pipe or onboard processing	Bent pipe
	Number of return 26 GHz channels	1
	Forward link with user? If present, at what data rate and frequency?	Yes (100kbps-50Mbps @ 23 GHz band DRTS to LEO)
Return Link Characteristics (from the user satellite to relay)	Antenna size (diam. in m.)	3.6m mechanically steerable single-offset reflector for ISL
	Field of view (deg)	
	Program tracking and/or autotracking?	Yes Program tracking and autotracking
	Center frequency channels	25.45 GHz – 27.5 GHz
	Polarization	RHCP and LHCP
	Bandwidth	330 MHz
	Data rate	100kbps – 240Mbps, depending on LEO S/C (bent pipe)
	Coding and modulation schemes supported	Bent pipe (no onboard processing, except for frequency conversion)
	G/T (typical)	28.7 dB/K

E.1.3 NASA

E.1.3.1 *TDRSS*

Table E-4: TDRSS Characteristics

	Satellite: Tracking and Data Relay Satellite TDRS8, TDRS9, TDRS10 (2nd Generation)	
Relay Satellite	Agency	NASA
	Operational date (year)	2000, 2001, 2002 (respectively)
	Orbital position	Nominally; 41 ° W, 174 ° W, 271 ° W
	Attitude control (e.g., 3-axis, spin stabilized)	3-axis stabilized
Operation	Bent pipe or onboard processing	Bent pipe
	Number of return 26 GHz channels	2 per satellite
	Forward link with user? If present, at what data rate and frequency?	Freq: 22.55-23.55 GHz BW: 50 MHz Data Rate (DR) ≤ 7 Mbps Modulation: SS-BPSK: DR <300 kbps BPSK: 300 kbps < DR < 7 Mbps No forward error correction
Return Link Characteristics (from the user satellite to relay)	Antenna size (diam. in m.) (with user, not TT&C)	5 m
	Field of view (deg)	- +22° E-W, +28 ° N-S
	Program tracking and/or autotracking?	Program track or autotrack
	Center frequency channels	25.25-27.50 GHz
	Polarization	LHCP or RHCP
	Bandwidth	≤225 MHz or 650 MHz
	Data rate	≤ 300 Mbps
	Coding and modulation schemes supported	BPSK, QPSK, OQPSK FEC: Rate ½
	G/T (typical)	Autotrack: 26.5 dB Program track: 19.1 dB/K

E.2 Space-based Relay Systems in Development Using the 26 GHz

E.2.1 ESA

E.2.1.1 *Galileo GNSS constellation*

The European Global Navigation Satellite System (GNSS), called Galileo, will also provide medium-rate (50 MHz bandwidth) intersatellite links in the 26 GHz bandwidth. No detailed table is provided in this document.

Appendix F Ground Systems Supporting 26 GHz Services: Supplemental Information

F.1 *Existing Ground Systems Supporting the 26 GHz Band (Other than for LEO-to-Ground)*

F.1.1 *DLR*

Table F-1: Characteristics of the Existing 13m Weilheim Antenna

	Weilheim	**26 GHz band downlink**	**Uplink (for ACM)**
Site	Name (country)	Weilheim (Germany)	
	Agency	DLR (German Aerospace Center)	
	Purpose (GEO, Deep Space, LEO?)	LEO, GEO, Near-Earth, IOT	
	Operational date (year)	2012	
	Lat/long/altitude	47.88º N / 11.08ºE / 660m	
Antenna	Antenna size (diam. in m.)	13.1	13.1 (same antenna as for downlink)
	Gain (dBi)	COM-band: 65.5 dBi EO-band: 68.5 dBi (operational by request)	COM-band: 68.1 dBi EO-band: 68.2 dBi (operational by request)
	Beamwidth (deg.)	0.01	0.055
	G/T (dBK) at zenith and dry conditions	41.4 dBK @ 20 GHz 43.8 dBK @ 10º elevation at 26 GHz	EIRP: COM-band: 90.5 dBW EO-band: 85.1 dBW (operational by request)
	Frequency range (min, max)	COM-band: 18.1 – 21.2 GHz EO-band: 25.5 – 27.5 GHz (operational by request)	COM-band: 27.5 – 31.0 GHz EO-band 22.55 – 23.15 GHz (operational by request)
	Mount type (azimuth/elevation or x/y)	Azimuth/elevation	Azimuth/elevation
	Tracking rate (degrees/sec)	Azimuth (AZ): 0.015º - 15º per second Elevation (EL): 0.006º - 6º per second	Azimuth (AZ): 0.015º - 15º per second Elevation (EL): 0.006º - 6º per second
	Min. elevation angles	0º -91º	0º -91º
	Horizon mask, if available	Complete GEO arc.	Complete GEO arc.

	Supports overhead passes (yes/no/partially)?	Partially*	Partially*
	Program tracking and/or autotracking?	Autotrack/program track	Autotrack/program track
	Polarization	Linear, circular (RHCP/LHCP)	Linear, circular (RHCP/LHCP)
	Mbaud supported	Refer to cortex specification	Refer to cortex specification
Receiver	Range of frequencies supported	Refer to cortex specification	
	Coding and modulation schemes supported	Refer to cortex specification	
	Standards supported? (IOAG Service Catalog #1: page 10, plus which subsets of RFM and TC S&C are supported, or FTP)	Yes Compliance to radio frequency and modulation (RFM) (CCSDS 401.0-B-26): Sec. 2.1.1. – 2.1.8 Sec. 2.2.1. – 2.2.8 Sec. 2.3.1. – 2.3.8 Sec. 2.4.2 – 2.4.14 (ltd. by cortex spec) Sec. 2.5.1 – 2.5.6 (ltd. by cortex spec) Sec. 2.6.9., 2.6.10.	
Standards	Rates (Gb/s) or media (e.g., optical fiber). This backhaul section is optional (if you do not have it)	Fiber optics is available.	
Backhaul Interfaces (non-26 GHz)			

* The ground station can support overhead passes with certain limitations, which occur only on a few specific passes. When the elevation approaches its upper limits for the overhead passes (e.g., higher than 80 degrees), the antenna must be moved very quickly and may not be able to follow the satellite for a few seconds.

F.1.2 ESA

F.1.2.1 *Weilheim*

Table F-2: Characteristics of the 6.8-m Antennas in Weilheim

	Ground Site Name	**26 GHz band downlink**	**Uplink (for ACM)**
Site	Name (country)	Weilheim (Germany)	
	Agency	ESA/EDRS	
	Purpose (GEO, Deep Space, LEO?)	GEO. Supports space-to-ground link from EDRS	
	Operational date (year)	2015	
	Lat/long/altitude	47.88° N, 11.08° E, 606 m	
Antenna	Antenna size (diam. in m.)	Two 6.8 m antennas FLGS and RDGS	Two 6.8 m antennas (same antenna as for downlink)
	Gain (dBi)	FLGS 62.01 dBi RDGS 62.21 dBi	FLGS 62.96 dBi
	Beamwidth (deg.)	0.128 deg.	0.128 deg.
	G/T (dBK) at zenith and dry conditions	FLGS 36.41 4 dBK RDGS 36.764 dBK	EIRP = 75 dBW
	Frequency range (min, max)	25.5 GHz, 26.56 GHz 4 channels: LCT-RTN1: 25560 –26010 MHz LCT-RTN2: 26110 –26560 MHz LCT-RTN3: 25560 –26010 MHz LCT-RTN4: 26110 –26560 MHz	27.5 GHz, 27.51 GHz
	Mount type (azimuth/elevation or x/y)	Elevation over azimuth	Elevation over azimuth
	Tracking rate (degrees/sec)	GEO	GEO

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[4] **10° elevation angle LNA noise temperature 150 K**

	Min. elevation angles		
	Horizon mask, if available	Visible arc: Max. elevation: 35.00º Left azimuth: 260.19º Orbital position: 65.8ºW Right azimuth: 99.78º Orbital position: 88.0ºE	Visible arc: Max. elevation: 35.00º Left azimuth: 260.19º Orbital position: 65.8ºW Right azimuth: 99.78º Orbital position: 88.0ºE
	Supports overhead passes (yes/no/partially)?	No	No
	Program tracking and/or autotracking?	Autotrack (monopulse) and program track	Autotrack (monopulse) and program track
	Polarization	RHCP/LHCP	RHCP/LHCP
Receiver	Mbaud supported	4 channel at 500 Mbaud each	
	Range of frequencies supported	950 1750 MHz	70 +/- 20 MHz
	Coding and modulation schemes supported	CCSDS-401.0-B-26 RF and modulation: BPSK, QPSK, OQPSK, 8-PSK, 4D 8-PSK, UOQPSK CCSDS-131.0-B-2 TM and coding. Viterbi and 4D-8PSK trellis-coded modulation (TCM).	
Standards	Standards supported? (IOAG Service Catalog #1: page 10, plus which subsets of RFM and TC S&C are supported, or FTP)		
Backhaul Interfaces (non 26 GHz)	Rates (Gb/s) or media (e.g., optical fiber). This backhaul section is optional (if you do not have it)		

F.1.2.2 ***Redu***

Table F-3: Characteristics of the 6.8 m Antenna in Redu

	Ground Site Name	**26 GHz band downlink**	**Uplink (for ACM)**
Site	**Name (country)**	**Redu (Belgium)**	
	Agency	**ESA/EDRS**	
	Purpose (GEO, Deep Space, LEO?)	**GEO. Supports space-to-ground link from EDRS**	
	Operational date (year)	**2015**	
	Lat/long/altitude	**50.00° N, 5.14 E°, 324 m**	
Antenna	**Antenna size (diam. in m.)**	**6.8 m**	6.8 m (same antenna as for downlink)
	Gain (dBi)	**61.93 dBi**	62.96 dBi
	Beamwidth (deg.)	**0.13 deg.**	0.13 deg.
	G/T (dBK) at zenith and dry conditions	**37.76 5 dBK**	EIRP = 83.7 dBW
	Frequency range (min, max)	**25.5 GHz, 26.56 GHz** **4 channels:** **LCT-RTN1: 25560 –26010 MHz** **LCT-RTN2: 26110 –26560 MHz** **LCT-RTN3: 25560 –26010 MHz** **LCT-RTN4: 26110 –26560 MHz**	27.502 GHz, 27.504 GHz
	Mount type (azimuth/elevation or x/y)	**Elevation over azimuth**	Elevation over azimuth
	Tracking rate (degrees/sec)	**GEO**	GEO
	Min. elevation angles	**--**	--
	Horizon mask, if available	**Visible arc:** **Max. elevation: 32.68º** **Left azimuth: 259.46º** **Orbital position: 71.2ºW** **Right azimuth: 100.53º**	Visible arc: Max. elevation: 32.68º Left azimuth: 259.46º Orbital position: 71.2ºW Right azimuth: 100.54º Orbital position: 81.5ºE

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[5] **10° elevation angle LNA noise temperature 150 K**

		Orbital position: 81.5ºE	
	Supports overhead passes (yes/no/partially)?	**No**	No
	Program tracking and/or autotracking?	**Autotrack (monopulse) and program track**	Autotrack (monopulse) and program track
	Polarization	**RHCP/LHCP**	RHCP/LHCP
Receiver	**Mbaud supported**	**4 channel at 500 Mbaud each**	
	Range of frequencies supported	**950 1750 MHz**	70 +/- 20 MHz
	Coding and modulation schemes supported	**CCSDS-401.0-B-26 RF and modulation: BPSK, QPSK, OQPSK, 8-PSK, 4D 8-PSK, UOQPSK** **CCSDS-131.0-B-2 TM synch and channel coding. Viterbi and 4D-8PSK TCM.**	
Standards	**Standards supported? (IOAG Service Catalog #1: page 10, plus which subsets of RFM and TC S&C are supported, or FTP)**		
Backhaul Interfaces (non 26 GHz)	**Rates (Gb/s) or media (e.g., optical fiber). This backhaul section is optional (if you do not have it)**		

F.1.2.3 *Harwell*

Table F-4: Characteristics of the 6.8 m Antenna in Harwell

	Ground Site Name	26 GHz band downlink	Uplink (for ACM)
Site	Name (country)	Harwell (UK)	**Uplink not available**
	Agency	ESA/EDRS	
	Purpose (GEO, Deep Space, LEO?)	GEO. Supports space-to-ground link from EDRS	
	Operational date (year)	2015	
	Lat/long/altitude	51.58° N, 1.31° W, 122 m	
Antenna	Antenna size (diam. in m.)	6.8 m	N/A
	Gain (dBi)	62.21 dBi	N/A
	Beamwidth (deg.)	0.125 deg.	N/A
	G/T (dBK) at zenith and dry conditions	36.76 [6] dBK	N/A
	Frequency range (min, max)	25.5 GHz, 26.56 GHz 4 channels: LCT-RTN1: 25560 –26010 MHz LCT-RTN2: 26110 –26560 MHz LCT-RTN3: 25560 –26010 MHz LCT-RTN4: 26110 –26560 MHz	N/A
	Mount type (azimuth/elevation or x/y)	Elevation over azimuth	N/A
	Tracking rate (degrees/sec)	GEO	N/A
	Min. elevation angles	--	N/A
	Horizon mask, if available	Visible arc: Max. elevation: 30.97º Left azimuth: 258.86 º Orbital position: 77.2ºW Right azimuth: 101.13º Orbital position: 74.6ºE	N/A
	Supports overhead passes (yes/no/partially)?	No	N/A
	Program tracking and/or autotracking?	Autotrack (monopulse) and program track	N/A
	Polarization	RHCP/LHCP	N/A
Receiver	Mbaud supported	4 channel at 500 Mbaud each	
	Range of frequencies supported	950…1750 MHz	
	Coding and modulation schemes supported	CCSDS-401.0-B-26 RF and modulation: BPSK, QPSK, OQPSK, 8-PSK, 4D 8-PSK, UOQPSK CCSDS-131.0-B-2 TM synch and channel coding. Viterbi and 4D-8PSK TCM.	
Standards	Standards supported? (IOAG Service Catalog #1: page 10, plus which subsets of RFM and TC S&C are supported, or FTP)		

Backhaul Interfaces (non 26 GHz)	Rates (Gb/s) or media (e.g., optical fiber). This backhaul section is optional (if you do not have it)		

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[6] **10° elevation angle LNA noise temperature 150 K**

F.1.3 JAXA

Table F-5: Characteristics of Tsukuba and Hatoyama

	JAXA Tsukuba and Hatoyama	**26 GHz band downlink**	**Uplink (for ACM)**
Site	Name (country)	Tsukuba and Hatoyama, Japan	**Uplink not available**
	Agency	JAXA	
	Purpose (GEO, Deep Space, LEO?)	LEO	
	Operational date (year)	2020	
	Lat/long/altitude	Tsukuba, Hatoyama	
Antenna	Antenna size (diam. in m.)	5m	N/A
	Gain (dBi)	60.4dBi	N/A
	Beamwidth (deg.)	0.14deg	N/A
	G/T (dBK) at zenith and dry conditions	36.0dB/K at EL=5deg	N/A
	Frequency range (min, max)	25.5 – 27.0	N/A
	Mount type (azimuth/elevation or x/y)	AZ/EL, Cross-EL	N/A
	Tracking rate (degrees/sec)	AZ: 10deg/sec, EL: 6deg/sec, Cross-EL: 1deg/sec	N/A
	Min. elevation angles	-5deg	N/A
	Horizon mask, if available		N/A
	Supports overhead passes (yes/no/partially)?	Yes by Cross-EL	N/A
	Program tracking and/or autotracking?	Program tracking and autotracking	N/A
	Polarization	Circular	N/A
Receiver	Mbaud supported	400M~2Gbps(QPSK), 800M=4Gbps(16QAM)	
	Range of frequencies supported	25.5-27GHz	
	Coding and modulation schemes supported	QPSK, 16QAM	
Standards	Standards supported? (IOAG Service Catalog #1: page 10, plus which subsets of RFM and TC S&C are supported, or FTP)		
Backhaul Interfaces (non 26 GHz)	Rates (Gb/s) or media (e.g., optical fiber). This backhaul section is optional (if you do not have it)		

F.1.5 NASA

F.1.5.1 DSN Canberra

Table F-6: Characteristics of the NASA Canberra, Australia Antenna

	NASA Canberra, Australia	26 GHz band downlink	Uplink (for ACM)
Site	Name (country)	Canberra, Australia	
	Agency	NASA	
	Purpose (GEO, Deep Space, LEO?)	HEO, GEO, lunar, Lagrange	
	Operational date (year)	2008	
	Lat/long/altitude	-35:23:54.52383, 148:58:55.07191, 692.020	
Antenna	Antenna size (diam. in m.)	34	34
	Gain (dBi)	76.5	56.2
	Beamwidth (deg.)	0.021	0.263
	G/T (dBK) at zenith and dry conditions	59.1	EIRP = 128.6 dBm
	Frequency range (min, max)	25.5 – 27.0	2.025-2.120 GHz
	Mount type (azimuth/elevation or x/y)	Az/el	Az/el
	Tracking rate (degrees/sec)	0.8	0.8
	Min. elevation angles	6	10 deg
	Horizon mask, if available	< 12 deg	< 12 deg
	Supports overhead passes (yes/no/partially)?	Partially, up to 85-deg elevation	Partial, up to 85 deg
	Program tracking and/or autotracking?	Program, auto	Program
	Polarization	RHCP, LHCP	RHCP, LHCP
Receiver	Mbaud supported	300	
	Range of frequencies supported	720 MHz input	
	Coding and modulation schemes supported	BPSK, QPSK/OQPSK, [LDCP available in 2022] Convolutional and Reed-Solomon	
Standards	Standards supported? (IOAG Service Catalog #1: page 10, plus which subsets of RFM and TC S&C are supported, or FTP)	Yes (e.g., RAF, RCF, RUF, CFDP)	
Backhaul Interfaces (non 26 GHz)	Rates (Gb/s) or media (e.g., optical fiber). This backhaul section is optional (if you do not have it)	27 Mbps max., shared with other mission users and DSN operations. [65 Mbps available in 2017]	

F.1.5.2 *DSN Goldstone*

Table F-7: Characteristics of the NASA Goldstone, CA Antenna

	NASA Goldstone, CA	**26 GHz band downlink**	**Uplink (for ACM)**
Site	Name (country)	Goldstone, CA, USA	
	Agency	NASA	
	Purpose (GEO, Deep Space, LEO?)	HEO, GEO, lunar, Lagrange	
	Operational date (year)	2009	
	Lat/long/altitude	35:20:23.61416, 243:07:30.74007, 951.499	
Antenna	Antenna size (diam. in m.)	34	34
	Gain (dBi)	76.5	56.2
	Beamwidth (deg.)	0.021	0.263
	G/T (dBK) at zenith and dry conditions	59.1	EIRP = 128.6 dBm
	Frequency range (min, max)	25.5 – 27.0 GHz	2.025-2.120 GHz
	Mount type (azimuth/elevation or x/y)	Az/el	Az/el
	Tracking rate (degrees/sec)	0.8	0.8
	Min. elevation angles	6 deg	10 deg
	Horizon mask, if available	< 7 deg	10 deg
	Supports overhead passes (yes/no/partially)?	Partially, up to 85-deg elevation	Partial, up to 85 deg
	Program tracking and/or autotracking?	Program, auto	Program
	Polarization	RHCP, LHCP	RHCP, LHCP
Receiver	Mbaud supported	300	
	Range of frequencies supported	720 MHz input	
	Coding and modulation schemes supported	BPSK, QPSK/OQPSK, [LDCP available in 2022] Convolutional and Reed-Solomon	
Standards	Standards supported? (IOAG Service Catalog #1: page 10, plus which subsets of RFM and TC S&C are supported, or FTP)	Yes (e.g., RAF, RCF, RUF, CFDP)	
Backhaul Interfaces (non 26 GHz)	Rates (Gb/s) or media (e.g., optical fiber). This backhaul section is optional (if you do not have it)	37 Mbps max., shared with other mission users and DSN operations [65 Mbps available in 2017]	

F.1.5.3 *DSN Madrid*

Table F-8: Characteristics of the NASA Madrid, Spain Antenna

	NASA Madrid, Spain	26 GHz band downlink	Uplink (for ACM)
Site	Name (country)	Madrid, Spain	
	Agency	NASA	
	Purpose (GEO, Deep Space, LEO?)	HEO, GEO, lunar, Lagrange	
	Operational date (year)	2009	
	Lat/long/altitude	40:25:32.23805, 335:44:45.25141, 837.051	
Antenna	Antenna size (diam. in m.)	34	34
	Gain (dBi)	76.5	56.2
	Beamwidth (deg.)	0.021	0.263
	G/T (dBK) at zenith and dry conditions	59.1	EIRP = 128.6 dBm
	Frequency range (min, max)	25.5 – 27.0	2.025-2.110 GHz (2.110-2.120 GHz restricted from radiation)
	Mount type (azimuth/elevation or x/y)	Az/el	Az/el
	Tracking rate (degrees/sec)	0.8	0.8
	Min. elevation angles	6	10 deg
	Horizon mask, if available	<13 deg	< 13 deg
	Supports overhead passes (yes/no/partially)?	Partially, up to 85-deg elevation	Partial, up to 85 deg
	Program tracking and/or autotracking?	Program, auto	Program
	Polarization	RHCP, LHCP	RHCP, LHCP
Receiver	Mbaud supported	300	
	Range of frequencies supported	720 MHz input	
	Coding and modulation schemes supported	BPSK, QPSK/OQPSK, [LDCP available in 2022] Convolutional and Reed-Solomon	
Standards	Standards supported? (IOAG Service Catalog #1: page 10, plus which subsets of RFM and TC S&C are supported, or FTP)	Yes (e.g., RAF, RCF, RUF, CFDP)	
Backhaul Interfaces (non 26 GHz)	Rates (Gb/s) or media (e.g., optical fiber). This backhaul section is optional (if you do not have it)	27 Mbps max., shared with other mission users and DSN operations [65 Mbps available in 2017]	

F.1.5.4 *NEN WS1 (White Sands)*

Table F-9: Characteristics of the Whites Sands 1 (WS1) Antenna

	Ground Site Name	26 GHz band downlink	Uplink (for ACM)
Site	Name (country)	White Sands 1 (WS1) (USA)	
	Agency	NASA	
	Purpose (GEO, Deep Space, LEO?)	Multi-mission LEO, HEO, GEO, lunar, [Lagrange]	
	Operational date (year)	2009	
	Lat/long/altitude	32º 32’ 26" N 106º 36’ 44" W	
Antenna	Antenna size (diam. in m.)	18m	18m (same antenna as for downlink)
	Gain (dBi)	70.5 dBi	49 dBi
	Beamwidth (deg.)	0.04 deg.	0.5 deg.
	G/T (dBK) at zenith and dry conditions	47.9 dB/K @ 10 deg (clear sky)	EIRP = 81 dBW
	Frequency range (min, max)	25.5 – 27.0 GHz	2025-2120 MHz
	Mount type (azimuth/elevation or x/y)	Azimuth/elevation	Azimuth/elevation
	Tracking rate (degrees/sec)	2 deg./sec (slew rate)	2 deg./sec (slew rate)
	Min. elevation angles	5 deg. (typical for operations)	5 deg. (typical for operations)
	Horizon mask, if available	[TBD]	[TBD]
	Supports overhead passes (yes/no/partially)?	Limited due to tracking rate	Limited due to tracking rate
	Program tracking and/or autotracking?	Program and autotracking	Program and autotracking
	Polarization	RHCP or LHCP	RHCP or LHCP
Receiver	Mbaud supported	470 Ms/s (max)	100 bps - 1 Mbps
	Range of frequencies supported	25.5 – 27.0 GHz	2025-2120 MHz
	Coding and modulation schemes supported	PSK, BPSK, QPSK, OQPSK, AQPSK, AUQPSK, AUSQPSK Coding: Reed Solomon, Viterbi decoding (1/2, 1/4), 4D-TCM	PCM Encoding, FM or PM FSK, BPSK (currently, no coding supported)
Standards	Standards supported? (IOAG Service Catalog #1: page 10, plus which subsets of RFM and TC S&C are supported, or FTP)	TBD	
Backhaul Interfaces (non 26 GHz)	Rates (Gb/s) or media (e.g., optical fiber). This backhaul section is optional (if you do not have it)	TBD	

F.1.5.5 *SDO1*

Table F-10: Characteristics of the SDO1 Antenna

	Ground Site Name	26 GHz band downlink	Uplink (for ACM)
Site	Name (country)	SDO1 (USA)	
	Agency	NASA	
	Purpose (GEO, Deep Space, LEO?)	Dedicated support to SDO mission	
	Operational date (year)	2009	
	Lat/long/altitude	32.540556 deg N 253.38778 deg E	
Antenna	Antenna size (diam. in m.)	18m	18m (same antenna as for downlink)
	Gain (dBi)	70.5 dBi	49 dBi
	Beamwidth (deg.)	0.04 deg.	0.5 deg.
	G/T (dBK) at zenith and dry conditions	46.98 dB/K	EIRP = 72 dBW
	Frequency range (min, max)	25.5 – 27.0 GHz	2025-2120 MHz
	Mount type (azimuth/elevation or x/y)	Azimuth/elevation	Azimuth/elevation
	Tracking rate (degrees/sec)	2 deg./sec (slew rate)	2 deg./sec (slew rate)
	Min. elevation angles	5 deg. (typical for operations)	5 deg. (typical for operations)
	Horizon mask, if available	TBD	TBD
	Supports overhead passes (yes/no/partially)?	Limited due to tracking rate	Limited due to tracking rate
	Program tracking and/or autotracking?	Program and autotracking	Program and autotracking
	Polarization	RHCP or LHCP	RHCP or LHCP
Receiver	Mbaud supported	470 Ms/s (max)	100 bps - 1 Mbps
	Range of frequencies supported	25.5 – 27.0 GHz	2025-2120 MHz
	Coding and modulation schemes supported	PSK, BPSK, QPSK, OQPSK, AQPSK, AUQPSK, AUSQPSK Coding: Reed Solomon, Viterbi decoding (1/2, 1/4), 4D-TCM	PCM Encoding, FM or PM FSK, BPSK (currently, no coding supported)
Standards	Standards supported? (IOAG Service Catalog #1: page 10, plus which subsets of RFM and TC S&C are supported, or FTP)	TBD	
Backhaul Interfaces (non 26 GHz)	Rates (Gb/s) or media (e.g., optical fiber). This backhaul section is optional (if you do not have it)	TBD	

F.1.5.6 *SDO2*

Table F-11: Characteristics of the SDO2 Antenna

	Ground Site Name	26 GHz band downlink	Uplink (for ACM)
Site	Name (country)	SDO2 (USA)	
	Agency	NASA	
	Purpose (GEO, Deep Space, LEO?)	Dedicated support to SDO mission	
	Operational date (year)	2009	
	Lat/long/altitude	32.5407549 deg N 253.3879005 deg E	
Antenna	Antenna size (diam. in m.)	18m	18m (same antenna as for downlink)
	Gain (dBi)	70.5 dBi	49 dBi
	Beamwidth (deg.)	0.04 deg.	0.5 deg.
	G/T (dBK) at zenith and dry conditions	47.9 dB/K	EIRP = 72 dBW
	Frequency range (min, max)	25.5 – 27.0 GHz	2025-2120 MHz
	Mount type (azimuth/elevation or x/y)	Azimuth/elevation	Azimuth/elevation
	Tracking rate (degrees/sec)	2 deg./sec (slew rate)	2 deg./sec (slew rate)
	Min. elevation angles	5 deg. (typical for operations)	5 deg. (typical for operations)
	Horizon mask, if available	TBD	TBD
	Supports overhead passes (yes/no/partially)?	Limited due to tracking rate	Limited due to tracking rate
	Program tracking and/or autotracking?	Program and autotracking	Program and autotracking
	Polarization	RHCP or LHCP	RHCP or LHCP
Receiver	Mbaud supported	470 Ms/s (max)	100 bps - 1 Mbps
	Range of frequencies supported	25.5 – 27.0 GHz	2025-2120 MHz
	Coding and modulation schemes supported	PSK, BPSK, QPSK, OQPSK, AQPSK, AUQPSK, AUSQPSK Coding: Reed Solomon, Viterbi decoding (1/2, 1/4), 4D-TCM	PCM Encoding, FM or PM FSK, BPSK (currently, no coding supported)
Standards	Standards supported? (IOAG Service Catalog #1: page 10, plus which subsets of RFM and TC S&C are supported, or FTP)	TBD	
Backhaul Interfaces (non 26 GHz)	Rates (Gb/s) or media (e.g., optical fiber). This backhaul section is optional (if you do not have it)	TBD	

F.2 *Ground Systems in Development Supporting 26 GHz for LEO-to-Ground*

F.2.1.1 *Cebreros*

Table F-12: Characteristics of the Future 35 m Antenna in Cebreros

	Ground Site Name	26 GHz band downlink	Uplink (for ACM)
Site	Name (country)	Cebreros (Spain)	
	Agency	ESA	--
	Purpose (GEO, Deep Space, LEO?)	Deep Space	Deep Space
	Operational date (year)	2017	--
	Lat/long/altitude	40.45° N, 4.37° W , 794 m	--
Antenna	Antenna size (diam. in m.)	35 m	35 m (same antenna as for downlink)
	Gain (dBi)	77.58 dBi	77.58 dBi
	Beamwidth (deg.)	0.0212 deg.	0.083 deg.
	G/T (dBK) at zenith and dry conditions	57.9 dBK	EIRP=107 dBW
	Frequency range (min, max)	25.5 GHz, 27.00 GHz	7.145 GHz, 7.235 GHz
	Mount type (azimuth/elevation or x/y)	Elevation over azimuth	Elevation over azimuth
	Tracking rate (degrees/sec)	1	1
	Min. elevation angles	0 degrees	0 degrees
	Horizon mask, if available	See Figure F-1	See Figure F-1
	Supports overhead passes (yes/no/partially)?	No	No
	Program tracking and/or autotracking?	Autotrack (monopulse) and program track	Program track
	Polarization	RHCP/LHCP	RHCP/LHCP
Receiver	Mbaud supported	150 Mbaud (upgradeable to 500 Mbaud)	
	Range of frequencies supported	1250-1850 MHz	230 ± 40 MHz
	Coding and modulation schemes supported	CCSDS-401.0-B-26 RF and modulation: BPSK, QPSK, OQPSK, GMSK. Remnant carrier. (Upgradeable to SCCC). CCSDS-131.0-B-2 TM synch and channel coding. RS, Convolutional, concatenated, Turbo and LDPC.	
Standards	Standards supported? (IOAG Service Catalog #1: page 10, plus which subsets of RFM and TC S&C are supported, or FTP)	Forward SLE CLTU and SLE FSP as well as Return SLE RAF + SLE RCF + SLE ROCF Validated Radio Metric and Delta DOR are supported.	
Backhaul Interfaces (non 26 GHz)	Rates (Gb/s) or media (e.g., optical fiber). This backhaul section is optional (if you do not have it)		

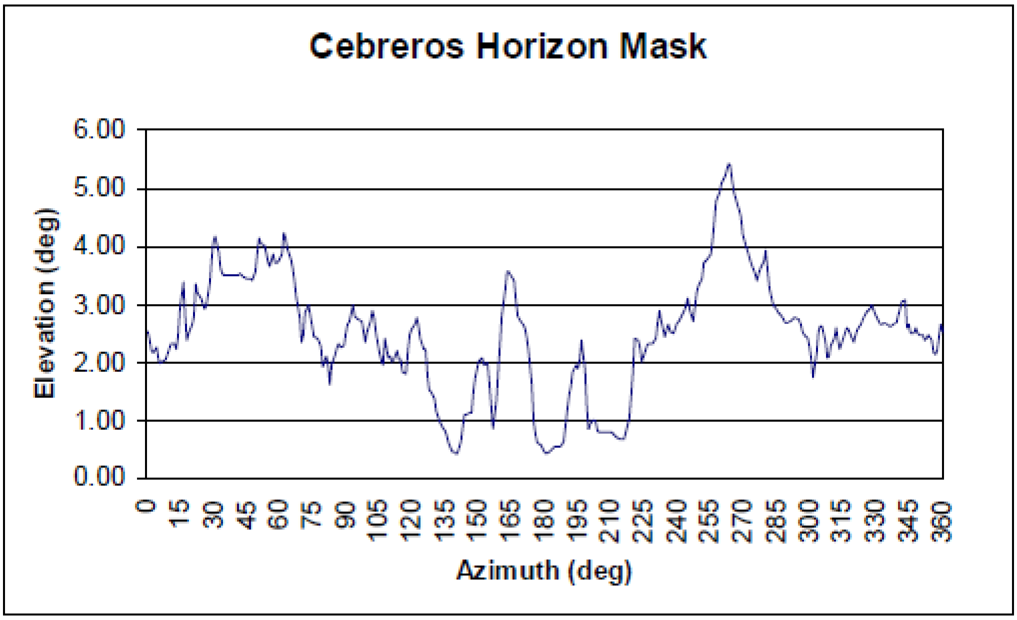


Figure F-1. Cebreros Horizon Mask

F.2.1.2 *Malargüe*

Table F-13: Characteristics of the Future 35 m Antenna in Malargüe

	Ground Site Name	**26 GHz band downlink**	**Uplink (for ACM)**
Site	Name (country)	Malargüe (Argentina)	
	Agency	ESA	
	Purpose (GEO, Deep Space, LEO?)	Deep Space	Deep Space
	Operational date (year)	2018	
	Lat/long/altitude	35.78° S, 69.40° W, 1550 m	
Antenna	Antenna size (diam. in m.)	35 m	35 m (same antenna as for downlink)
	Gain (dBi)	77.58 dBi	77.58 dBi
	Beamwidth (deg.)	0.021 deg.	0.083 deg.
	G/T (dBK) at zenith and dry conditions	57.9 dBK	EIRP = 107 dBW
	Frequency range (min, max)	25.5 GHz, 27.00 GHz	7.145 GHz, 7.235 GHz
	Mount type (azimuth/elevation or x/y)	Elevation over azimuth	Elevation over azimuth
	Tracking rate (degrees/sec)	1	1
	Min. elevation angles	0 degrees	0 degrees
	Horizon mask, if available	See Figure F-2	See Figure F-2
	Supports overhead passes (yes/no/partially)?	No	No
	Program tracking and/or autotracking?	Autotrack (monopulse) and program track	Program track
	Polarization	RHCP/LHCP	RHCP/LHCP
Receiver	Mbaud supported	150 Mbaud (upgradeable to 500 Mbaud)	
	Range of frequencies supported	1250-1850 MHz	230 ± 40 MHz
	Coding and modulation schemes supported	CCSDS-401.0-B-26 RF and modulation: BPSK, QPSK, OQPSK, GMSK. Remnant carrier. (Upgradeable to SCCC). CCSDS-131.0-B-2 TM synch and channel coding. RS, Convolutional, concatenated, Turbo and LDPC.	
Standards	Standards supported? (IOAG Service Catalog #1: page 10, plus which subsets of RFM and TC S&C are supported, or FTP)	Forward SLE CLTU and SLE FSP as well as Return SLE RAF + SLE RCF + SLE ROCF Validated Radio Metric and Delta DOR are supported.	
Backhaul Interfaces (non 26 GHz)	Rates (Gb/s) or media (e.g., optical fiber). This backhaul section is optional (if you do not have it)		

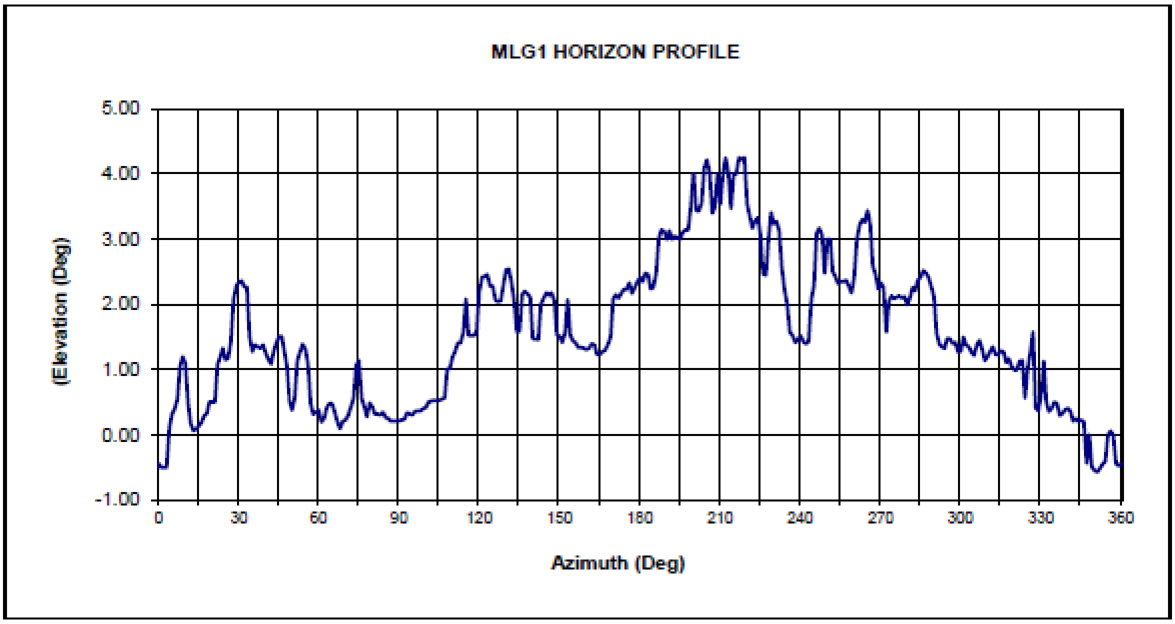


Figure F-2. Malargüe Horizon Mask

F.2.2 NASA

F.2.2.1 *NEN Fairbanks*

Table F-14: Characteristics of the Alaska Satellite Facility 11 m Antenna (ASF3)

	Ground Site Name	26 GHz band downlink	Uplink (for ACM)
Site	Name (country)	Alaska Satellite Facility 11m (AS3) (USA)	
	Agency	NASA	
	Purpose (GEO, Deep Space, LEO?)	Multi-mission LEO, HEO	
	Operational date (year)	2014 (26 GHz support not yet planned)	
	Lat/long/altitude	64º 51' N 147º 51' W	
Antenna	Antenna size (diam. in m.)	11	11 (same antenna as for downlink)
	Gain (dBi)	67.3 dBi	44.8 dBi
	Beamwidth (deg.)	.08 deg.	0.95 deg.
	G/T (dBK) at zenith and dry conditions	42.9 dBK	EIRP = 66 dBW
	Frequency range (min, max)	25.5 – 29 GHz	2025-2120 MHz
	Mount type (azimuth/elevation or x/y)	3-axis (az, el, 3rd)	3-axis (az, el, 3rd)
	Tracking rate (degrees/sec)	Azimuth: 15°/sec Elevation: 12°/sec Third axis: 5°/sec	Azimuth: 15°/sec Elevation: 12°/sec Third axis: 5°/sec
	Min. elevation angles	0 deg. all azimuth	0 deg. all azimuth
	Horizon mask, if available	TBD	TBD
	Supports overhead passes (yes/no/partially)?	Yes	Yes
	Program tracking and/or autotracking?	Program and autotrack	Program and autotrack
	Polarization	Dual Polarization	RHCP or LHCP
Receiver	Mbaud supported	4 GSPS	< 200 kbps
	Range of frequencies supported	25.5 – 27 GHz	2025-2120 MHz
	Coding and modulation schemes supported	LDPC 7/8 OQPSK	PM, FM or BPSK (currently, no coding supported)
Standards	Standards supported? (IOAG Service Catalog #1: page 10, plus which subsets of RFM and TC S&C are supported, or FTP)	TBD	
Backhaul Interfaces (non 26 GHz)	Rates (Gb/s) or media (e.g., optical fiber). This backhaul section is optional (if you do not have it)	Shares data lines with other systems at White Sands	

F.2.2.2 *NEN Punta Arenas, Chile*

Table F-15: Characteristics of the PA Satellite Facility 12m Antenna (PA)

	Ground Site Name	26 GHz band downlink	Uplink (for ACM)
Site	Name (country)	Punta Arenas 12m (CL)	
	Agency	NASA	
	Purpose (GEO, Deep Space, LEO?)	Multi-Mission LEO, HEO	
	Operational Date (year)	2020	
	Lat/Long/Altitude	52.9º S 70.8º W	
Antenna	Antenna size (diam. in m.)	12	12 (same antenna as for downlink)
	Gain (dBi)	67.8 dBi	44.8 dBi
	Beamwidth (deg.)	0.07 deg.	0.95 deg.
	G/T (dBK) at zenith and dry conditions	40.4 dBk	EIRP = 66 dBW
	Frequency range (min, max)	20.5 - 27 GHz	2025-2120 MHz
	Mount type (azimuth/elevation or x/y)	3-axis (az, el, 3rd)	3-axis (az, el, 3rd)
	Tracking rate (degrees/sec)	Azimuth: 15°/sec Elevation: 12°/sec Third axis: 5°/sec	Azimuth: 15°/sec Elevation: 12°/sec Third axis: 5°/sec
	Min. elevation angles	0 deg. all azimuth	0 deg. all azimuth
	Horizon mask, if available	TBD	TBD
	Supports overhead passes (yes/no/partially)?	Yes	Yes
	Program tracking and/or autotracking?	Program and autotrack	Program and autotrack
	Polarization	Dual Polarization	RHCP or LHCP
Receiver	Mbaud supported	4 GSPS	< 200 kbps
	Range of frequencies supported	25.5 - 27 GHz	2025-2120 MHz
	Coding and modulation schemes supported	LDPC 7/8 OQPSK	PM, FM or BPSK (currently, no coding supported)
Standards	Standards supported? (IOAG Service Catalog #1: page 10, plus which subsets of RFM and TC S&C are supported, or FTP)	TBD	
Backhaul Interfaces (non 26 GHz)	Rates (Gb/s) or media (e.g., optical fiber). This backhaul section is optional (if you do not have it)	Shares data lines with other systems at White Sands	

F.2.2.3 *NEN Santiago, Chile (AGO)*

Table F-16: Characteristics of the AGO Antenna

	Ground Site Name	**26 GHz band downlink**	**Uplink (for ACM)**
Site	Name (country)	Santiago (CL)	
	Agency	NASA	
	Purpose (GEO, Deep Space, LEO?)	Multi-mission LEO, HEO, GEO, lunar, Lagrange	
	Operational date (year)	2022	
	Lat/long/altitude	33.2º S 70.7º W	
Antenna	Antenna size (diam. in m.)	18 m	18 m (same antenna as for downlink)
	Gain (dBi)	70.5 dBi	49 dBi
	Beamwidth (deg.)	0.04 deg.	0.5 deg.
	G/T (dBK) at zenith and dry conditions	47.9 dB/K @ 10 deg. (Clear Sky)	EIRP = 81 dBW
	Frequency range (min, max)	25.5 – 27.0 GHz	2025-2120 MHz
	Mount type (azimuth/elevation or x/y)	Azimuth/elevation	Azimuth/elevation
	Tracking rate (degrees/sec)	2 deg./sec (slew rate)	2 deg./sec (slew rate)
	Min. elevation angles	5 deg. (typical for operations)	5 deg. (typical for operations)
	Horizon mask, if available	TBD	TBD
	Supports overhead passes (yes/no/partially)?	Limited due to tracking rate	Limited due to tracking rate
	Program tracking and/or autotracking?	Program and autotracking	Program and autotracking
	Polarization	RHCP or LHCP	RHCP or LHCP
Receiver	Mbaud supported	470 Ms/s (max)	100 bps - 1 Mbps
	Range of frequencies supported	25.5 – 27.0 GHz	2025-2120 MHz
	Coding and modulation schemes supported	LDPC 7/8 OQPSK	PCM Encoding, FM or PM FSK, BPSK (currently, no coding supported)
Standards	Standards supported? (IOAG Service Catalog #1: page 10, plus which subsets of RFM and TC S&C are supported, or FTP)	TBD	
Backhaul Interfaces (non 26 GHz)	Rates (Gb/s) or media (e.g., optical fiber). This backhaul section is optional (if you do not have it)	TBD	

F.2.2.4 *NEN Svalbard*

Table F-17: Characteristics of Svalbard Satellite Facility 7.3m Antenna (SG22)

	Ground Site Name	26 GHz band downlink	Uplink (for ACM)
Site	Name (country)	Svalbard Satellite Facility 7.3m (SG22) (NO)	
	Agency	NASA/KSAT	
	Purpose (GEO, Deep Space, LEO?)	Multi-mission LEO, HEO	
	Operational date (year)	2020	
	Lat/long/altitude	78.2321 N 15.4014 E	
Antenna	Antenna size (diam. in m.)	7.3	7.3 (same antenna as for downlink)
	Gain (dBi)	63.5 dBi	44.8 dBi
	Beamwidth (deg.)	.01 deg.	0.95 deg.
	G/T (dBK) at zenith and dry conditions	42.9 dBK	EIRP = 60 dBW
	Frequency range (min, max)	25.5 – 29 GHz	2025-2120 MHz
	Mount type (azimuth/elevation or x/y)	3-axis (az, el, 3rd)	3-axis (az, el, 3rd)
	Tracking rate (degrees/sec)	Azimuth: 15°/sec Elevation: 12°/sec Third axis: 5°/sec	Azimuth: 15°/sec Elevation: 12°/sec Third axis: 5°/sec
	Min. elevation angles	0 deg. all azimuth	0 deg. all azimuth
	Horizon mask, if available	TBD	TBD
	Supports overhead passes (yes/no/partially)?	Yes	Yes
	Program tracking and/or autotracking?	Program and autotrack	Program and autotrack
	Polarization	Dual Polarization	RHCP or LHCP
Receiver	Mbaud supported	4 GSPS	< 200 kbps
	Range of frequencies supported	25.5 – 27 GHz	2025-2120 MHz
	Coding and modulation schemes supported	LDPC 7/8 OQPSK	PM, FM, or BPSK (currently, no coding supported)
Standards	Standards supported? (IOAG Service Catalog #1: page 10, plus which subsets of RFM and TC S&C are supported, or FTP)	TBD	
Backhaul Interfaces (non 26 GHz)	Rates (Gb/s) or media (e.g., optical fiber). This backhaul section is optional (if you do not have it)	TBD	

F.2.3 NOAA

F.2.3.1 Svalbard

Table F-18: Characteristics of the JPSS Ground Segment, Svalbard

	Ground Site Name	26 GHz band downlink	Uplink (for ACM)
Site	Name (country)	Svalbard (Norway)	No uplink available
	Agency	NOAA (hosted by KSAT)	
	Purpose (GEO, Deep Space, LEO?)	LEO (but could support other)	
	Operational date (year)	2015	
	Lat/long/altitude	78.2321 N, 15.4014 E	
Antenna	Antenna size (diam. in m.)	4 m	N/A
	Gain (dBi)		N/A
	Beamwidth (deg.)	0.163 degrees (half power, nominal)	N/A
	G/T (dBK) at zenith and dry conditions	31.8 dB/K	N/A
	Frequency range (min, max)	25.5 – 27.0 GHz	N/A
	Mount type (azimuth/elevation or x/y)	3-axis (EL -3° to +93°, Az ±400°, Third ±181°)	N/A
	Tracking rate (degrees/sec)	10 deg./sec	N/A
	Min. elevation angles	5 deg. (typical for operations)	N/A
	Horizon mask, if available	TBD	N/A
	Supports overhead passes (yes/no/partially)?	Yes	N/A
	Program tracking and/or autotracking?	Autotracking	N/A
	Polarization	Right-hand circular (RHCP)	N/A
Receiver	Mbaud supported	300 Ms/s (150 Ms/s w/ convolution coding TBD: Others may also be available	
	Range of frequencies supported	25.5 – 27.0 GHz	
	Coding and modulation schemes supported	OQPSK, Convolutional rate ½, K=7 with Reed-Solomon (223, 255) TBD: Others may also be available	
Standards	Standards supported? (IOAG Service Catalog #1: page 10, plus which subsets of RFM and TC S&C are supported, or FTP)	TBD	
Backhaul Interfaces (non 26 GHz)	Rates (Gb/s) or media (e.g., optical fiber). This backhaul section is optional (if you do not have it)	Shares data lines with other systems at location	

F.2.3.2 Fairbanks

The characteristics of the Fairbanks antenna are the same as for the antenna at Svalbard (see Table F-18Table F-17). The antenna is located at: 64.9722N, -147.4975E.

F.2.3.3 *McMurdo*

There are two antennas at McMurdo, each with the same antenna characteristics as the antenna at Svalbard (see Table F-17). The antennas are located at: -77.8369N, 166.6674E.

Appendix G Space Link Design

G.1 *Example Link Budget in the 26 GHz Band*

Table G-1: Example of a Link Budget for 26 GHz

Blocks	**Example @ 600 km altitude; f = 26 GHz**			§	Link Budget assumptions
	Elevation angles =	5 deg.	27.5 deg.		
	Contact time above elev. angle =	100.0%	20.3%		
1) Space segment	**Output power_tx [dBW]**	10.00	10.00	1	With 10 W high power ampl.
	Output back-off [dB]	-0.3	-3.5	2	5 deg.: 8PSK; 27.5 deg: 64APSK
	O/B losses [dB]	-0.70	-1.20	3	waveguides, …
	OB pointing losses [dB]	-0.1	-0.1	4	
	O/B antenna diameter [m]	0.1	0.1	5	10 cm => 8.1 deg. 3 dB beam
	O/B antenna gain [dBi]	26.1	26.1	6	parabolic & effic.= 0.55
	EIRP [dBW]	34.98	31.31	7	= Tx - loss + AntGain (in dB)
2) Free space	d =distance Sat.- G/S (km)	2,329	1,140	8	d at 5 and 27.5 deg. elev.
	Free space loss [dB]	-188.1	-181.9	9	=(4π*d/λ)2 @ 26 GHz
	Atmospheric attenuation [dB]	-9.1	-1.7	10	99.5 % in Svalbard (ITU)
3) Ground station	Antenna diameter [m]	6.3	6.3	11	D; eff= 0.65; Bm3dB= 0 deg.
	Ground antenna gain [dBi]	62.82	62.82	12	= eff*(π*D/λ)2
	Antenna pointing loss [dB]	-1.0	-1.0	13	Pointing impact
	Radome losses [dB]	-2.0	-2.0	14	In some locations
	Mismatch losses [dB]	-0.1	-0.1	15	Additional losses
	Total gain ground antenna [dB]	59.72	59.72	16	= SUM (gain - losses) in G/S
	Tsys [K]	546	361	17	With propagation @ Svalbard
	Tsys [dBK]	27.37	25.57	18	10*log(Tsys)
	G/T [dB/K]	32.35	34.15	19	Gain - Tsys - losses (in dB)
Noise eq.	Boltzmann_K [m2 kg s-2 K-1]	-228.60	-228.60	20	=10*log(1.38×10-23)
4) Rates	**R** = Symbol rate [Mbaud]	300	300	21	Symbol rate (1 channel)
	Channel symbol rate [dB Hz]	-84.8	-84.8	22	log (R)
	ModCod efficiency [symbol/bi	2.37	5.39	23	5 deg.: 8PSK + 4/5 code 27.5 deg.: 64APSK + 9/10 code
	Bit data rate [Mb/s] (1 chanel)	**711**	**1,618**	24	Data rate = R * ModCod_eff (1 channel)
5) Modulation & receiver	Losses in the receiver [dB]	-0.30	-1.00	25	Implementation and modulation losses (Tx, Rx)
	Non-linear modulatation distortion [dB]	-0.88	-2.31	26	5 deg.: 8PSK + 4/5 code 27.5 deg.: 64APSK + 9/10 code
	Es/No (received) [dB]	12.80	22.40	27	Es/No @ receiver
	Es/No (required) [dB]	9.09	19.05	28	5 deg.: 8PSK + 4/5 code 27.5 deg.: 64APSK + 9/10 code
	Es/No (margin) [dB]	**3.71**	**3.35**	29	**Typical mission req. > 3 dB**

The link budget example above takes as basic assumptions:

- Frequency = 26 GHz or wavelength of 1.15 cm
- Satellite altitude = 600 km
- Svalbard ground station with minimum elevation angle of 5 degrees and 99.5% link availability
- Link budget for one channel (500 Mbaud) and one polarization, but it is possible to increase the data rate by a factor of 4 (two channels, two polarizations)

The main equation that has been applied is:

$$Margin = \left(\frac{Es}{No}\right)_{received} - \left(\frac{Es}{No}\right)_{required} = \frac{EIRP \cdot L_{sp} \cdot}{K \cdot R_{symbol}} \cdot \left(\frac{G}{T_{sys}}\right) \cdot L_{Rx} - \left(\frac{Es}{No}\right)_{in-given-CodingModulation}$$

where Es is the energy per symbol (or carrier power divided by symbol rate R) received (over normalized noise (No)). This is a function of several parameters that are compared in Table G-2 to a typical X-band link:

Table G-2: Comparison of Parameters between 26 GHz and X-band

Parameter	Comparison to X-band
EIRP (equivalent isotropically radiated power) by the satellite (It is the sum of onboard output power, onboard losses and onboard antenna gain.)	Significantly higher at 26 GHz mainly due to steerable antenna (30 dBi) compared to typical 6 dBi in isoflux antennas. Steerable antennas may also be used at X-band, in which case the difference is less.
Lsp (space losses = $(\lambda / 4 \pi d)^2$ (d = distance satellite to ground, λ = wavelength)	9.5 dB (i.e., 20*log(3)) higher in 26 GHz band (same geometry, but ratio of 3 in wavelength)
Lat (atmospheric attenuation losses)	Many dB higher at 26 GHz, where there is high dependency on ground station. Main problem is high variability. It is less than 2 dB in X-band.
R = Symbol rate or (C / Es) at the receiver There is a direct relationship to bit data rate for each set of coding and modulation.	6 dB higher in 26 GHz due to the availability of 4 times more bandwidth - plus whatever advantage comes from increased EIRP.
G/T: Ground antenna gain (G) and its system temperature (Tsys)	Higher than in X-band: Gain could be higher given the smaller wavelength, but Tsys is higher at 26 GHz due to propagation.
Lrx: Receiver and modulation losses	No big difference because it depends mainly on the modulation. High-order modulations can be used in both 26 GHz and X-band.
Es/No (required) It is a function of coding and modulation.	The required Es/No does not depend on the frequency.

In order to calculate the link budget margin, each Es/No received needs to be compared to the required Es/No required for a given coding and modulation. The example of Table G-1 shows that the achievable margins are very high (> 10dB) even for the worst case at 5-degree elevation. This implies that:

- Data availability in Svalbard could be even higher than the proposed 99.5% in this example
- Stations with higher atmospheric attenuation than Svalbard can also be considered
- More efficient coding/modulation schemes, which need higher energy, could be considered to increase the data rate
- Or some other system parameters (e.g., transmitted power or size of the antennas) could be relaxe

We also took the same input parameters from the link budget in Table G-1 to calculate the power flux density (PFD) in Table G-3. This example shows that there is a lot of margin compared to the ITU regulations.

Table G-3: Example of a Power Flux Density Budget for 26 GHz

		5 deg.	27.5 deg	§	Assumptions
PFD	d [km]	2329	1140	30	d = distance Satellite to G/S
	EIRP [dBW]	34.98	31.31	31	= Tx - Loss + AntGain (in dB)
	PFD - [dBW/m2]	-103.4	-100.8	32	=EIRP / $4\pi*d^2$
	R (Symbol Rate) [Mbaud]	300	300	33	Symbol Rate
	Bandwidth [MHz]	375	375	34	= R * (1.25 roll-off) ;
	PFD [dBW/m2/MHz]	-129.1	-126.6	35	= PFD / Bw (MHz)
	ITU PFD [dBW/m2/MHz]	-115.0	-105.0	36	ITU requirement
	PFD Margin [dB]	14.1	21.6	37	Margin must be > 0

G.2 *Key Tradeoffs*

The key tradeoffs are highly influenced by the two key system parameters that reduce considerably the margin with respect to X-band due to:

- Higher atmospheric losses (easily > 10 dB at 26 GHz wrt X-band) in a given station: this is reflected in the Lat and Tsys parameters.
- Higher symbol rates allowed by the availability of 4 times more bandwidth in the 26 GHz band

The factors above can be compensated by:

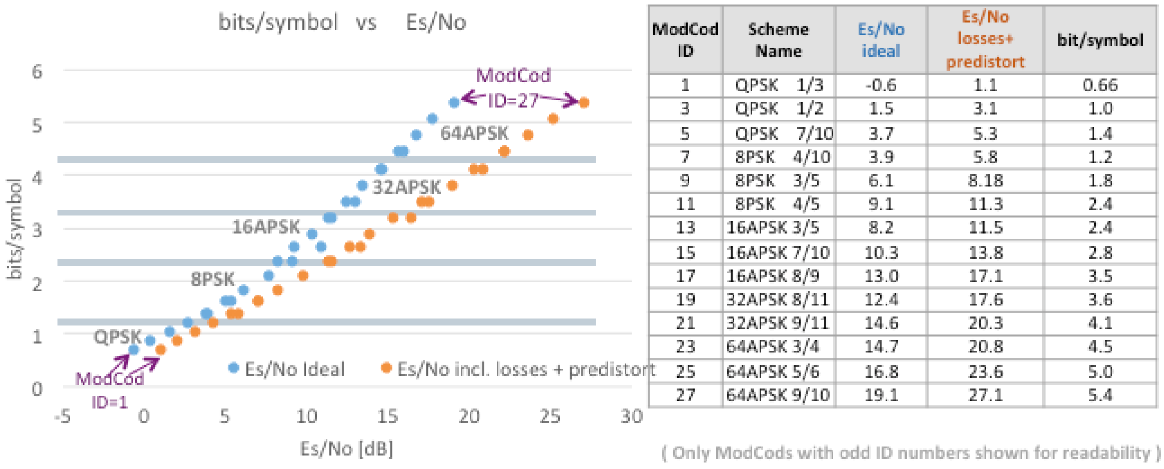
- Increasing the EIRP, and the most suitable way to do it is by using a steerable antenna. A small 15-cm dish gives a 30-dBi gain with a 5-degree beam width at 3 dB. This gain allows to have very reasonable power consumption in the onboard system.
- Increasing the gain of the ground antenna, which depends on the square of the diameter size or 6 dB if we double that diameter. The example above (6 m diameter) shows that ground antennas do not need to be very big.
- Use of advanced coding and modulation schemes that not only support VCM/ACM, but they are also optimized (very close to Shannon) and offer a few dB gains with respect to the traditional convolution + Reed Solomon encoding.

G.3 Example of VCM Coding and Modulation Capabilities

G.3.1 Multiple Codes and Modulations

The figure below depicts the relationship between data rate efficiency in [bit/symbol] and energy efficiency in terms of Es/No for the 27 ModCods from the CCSDS 131.2-B-1 standard used in this study. All these codes and modulations can be implemented in a single integrated circuit component. One key constraint is that only one ModCod can be used within a given CCSDS frame, but these standards offer the possibility to signal to the decoder that the following CCSDS frame will come with a new ModCod.

Note that spectral efficiency expressed here in bits/symbol, which is the product of the modulation order by the coding ratio, increases at the expense of needing higher energy per symbol per normalized noise (Es/No). This is aggravated (orange curve) with the need of higher losses and pre-distortion with higher modulations. Several codes ranging from 1/3 up to 9/10 are available per modulation. The discontinuities in the curve come when changing modulation, from QPSK to 8PSK, and so on up to 64-APSK.



ModCod ID	Scheme Name	Es/No ideal	Es/No losses+ predistort	bit/symbol
1	QPSK 1/3	-0.6	1.1	0.66
3	QPSK 1/2	1.5	3.1	1.0
5	QPSK 7/10	3.7	5.3	1.4
7	8PSK 4/10	3.9	5.8	1.2
9	8PSK 3/5	6.1	8.18	1.8
11	8PSK 4/5	9.1	11.3	2.4
13	16APSK 3/5	8.2	11.5	2.4
15	16APSK 7/10	10.3	13.8	2.8
17	16APSK 8/9	13.0	17.1	3.5
19	32APSK 8/11	12.4	17.6	3.6
21	32APSK 9/11	14.6	20.3	4.1
23	64APSK 3/4	14.7	20.8	4.5
25	64APSK 5/6	16.8	23.6	5.0
27	64APSK 9/10	19.1	27.1	5.4

(Only ModCods with odd ID numbers shown for readability)

Figure G-1: Data Rate over SNR/bit for 27 ModCods

Note the logarithmic scale in the increase of Es/No [dB] required to increase spectral efficiency. Table G-4 translates it into the linear scale. A gain in data rate by a factor of 8 requires almost 400 times more energy, which corresponds to 26 dB. In the case of using steerable antennas, the difference between horizon and zenith is about 20 dB in Svalbard (more in less dry ground stations), which can be wisely used to use higher efficient modulation and codes at high elevation angles.

Table G-4: Ratio between ModCods and Data Rates

ModCod ID	Modulation - code	Es / No [dB]	Es/ No [linear]	bits/ symbol	Data rate @ 100 MSy/s	Data rate @ 500 MSy/s
# 1	QPSK - Cod 1/3	1.1 dB	1.3	0.67	66.7 [Mb/s]	333 [Mb/s]
# 27	64APSK- Cod 9/10	27.1 dB	508	5.4	540 [Mb/s]	2700 [Mb/s]
Ratio		26 dB	397	8.1		

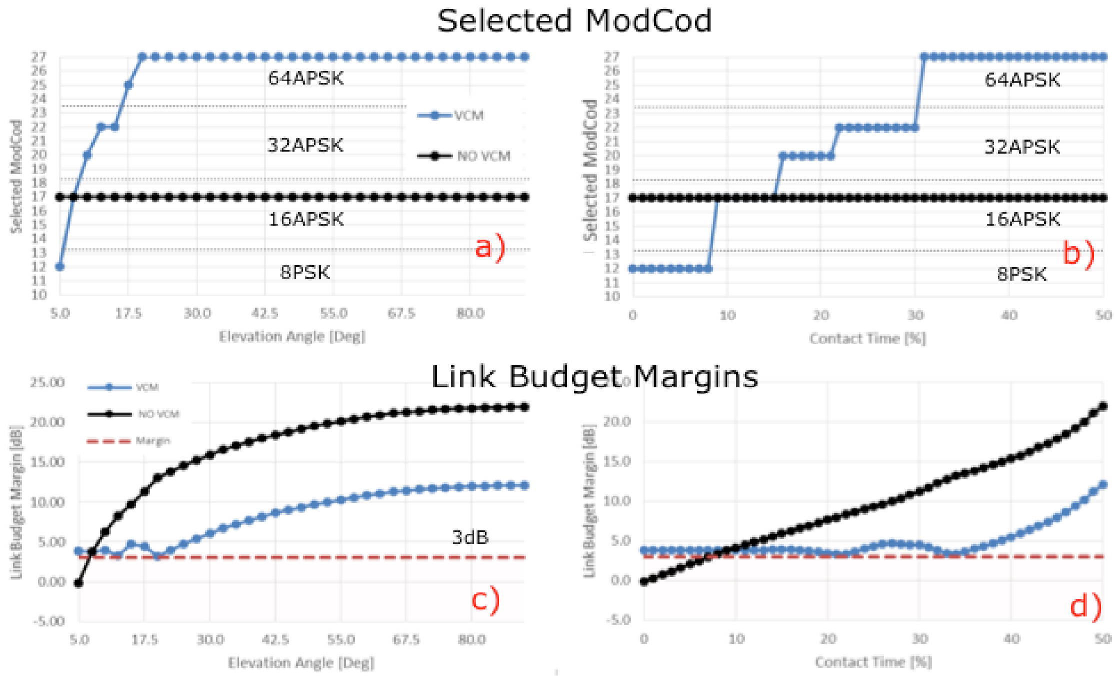
Table G-5 shows the signal variation just due to the geometry.

Table G-5: Ratio between Horizon and Zenith

Elevat. angle [deg]	Distance satellite - G/S [km]	Free space loss [dB]	Atmosp. loss in Svalbard in [dB]	Total [dB]
5 deg.	2,329	188.1	9.1	197.2
90 deg.	600	176.3	1	177.3
Ratio		11.8 [dB]	8.1 [dB]	19.9 [dB]

G.3.2 VCM versus without VCM

Thus far, we considered an instantaneous data rate. This section builds up from the link budget in Table G-1 and the equation in section G.1, by an iterating algorithm that evalutes the link budget every 2.5 degrees of ground elevation angle, and by choosing the highest ModCod with the condition of maintaining at least 3 dB link margin, as shown in the figure below, where the sub-figures on the left and on the right have the same information, but with a different stretching of the horizontal axis.



Append Figure G-2: Comparison between VCM (blue) and No-VCM (black) for a) Selected ModCod over Elevation Angle and b) over Contact Time in Svalbard; c) Link Budget Margin over Elevation Angle and d) over Contact Time

The simulations were carried for different elevation angles, but in practice, what is also relevant for the final data throughput is the contact time. Note that only up to 50% of contact time, corresponding to zenith or 90-degree elevation, is shown, given that the 50% to 100% would be symmetrical. Subfigure c) and d) show the link budget margin and highlight how the VCM algorithm optimizes the margin.

For the no-VCM scenario (in black), a constant ModCod providing the best overall data transmission was selected, at the expense of unnecessary high levels of link budget margin at high elevation angles, as shown in the two bottom figures, and potential break of the communication at very low elevation angles. In this example, the VCM algorithm changes the ModCod during the contact time from a low-level 8PSK to a high 64APSK in 4 steps while the no-VCM maintains a fixed 16-APSK mod for the duration of the overpass.

Figure G-3 shows the data throughput achieved, which corresponds to the integration of instantaneous data rate explained in G.3 over contact time in Svalbard where an average contact of 560 seconds has been considered. Note that VCM already enables a successful contact between the satellite and the ground station at a much lower elevation. Without VCM the selected ModCod, the connection would not be established for 20% of the contact time (approx. 10deg or 2 minutes). The limit on the right is presented with two numbers: the data throughput [Gbit] in the whole contact time, and also as equivalent average data rate value in [Gb/s], which is a more intuitive value, after dividing the data throughput by the total average contact time (i.e. 560 seconds in Svalbard for a 600-km altitude satellite with a polar orbit).

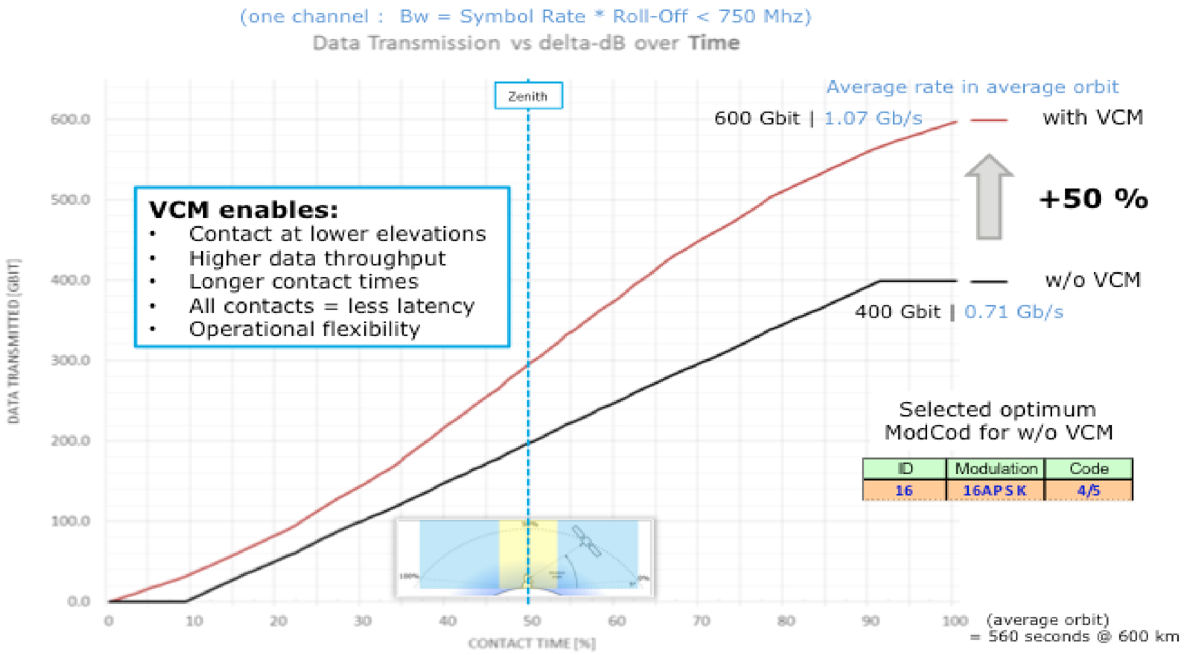


Figure G-3: Resulting Data Transmission in comparison between VCM and without VCM for one channel at 300 MSymbol/s

Overall and assuming one channel with a symbol rate of 300 Msymbol/s, the VCM-enabled transmission achieves a total data throughput of 600 Gbit, which equates to 1.07 Gbit/s average data rate (or average of 3.6 bits/symbol, see bit/symbol ranges in Figure G-1), while the no-VCM only achieves around 400 Gbit or 0.71 Gbit/s (i.e. 2.4 bits/symbol for 16APSK and 4/5 coding). So for this case, VCM allows for an increase of 50% of total data transmission. VCM allows the more efficient usage of downlink margins.

G.4 VCM Multi-parametric Study

G.4.1 VCM Symbol Rate and ΔdB Variation

This section provides an analysis of variable data rates that has been carried out with two key set of parameters:

- ΔdB is the deviation with respect to a baseline gain, where gain (G) is the sum of output power of the transmitter, $G_{\text{On-Board}}$ antenna and $G_{\text{On-Ground}}$ antenna.We chose these parameters because they are constant and do not depend on propagation conditions, ground station and elevation angle for a steerable antenna. ΔdB = 0 dB for the baseline gain is defined in Table G-7.
- Symbol rate (R), which leads to instantaneous data rate when multiplying R by the modulation order (e.g., 6 in 64-APSK), and code rate (e.g., at R=100 Msymbol/s, with 64-APSK and a 9/10 code, the data rate is 540 Mbit/s, (see Table G-4). Symbol rates are fixed for a given mission, so that the same RF chain filters can be used.

A python script was used on top in order to iterate the link budget calculation sheet in Table G-1, with variations of symbol rate and ΔdB. The first step was to vary ΔdB between -9 dB and +9 dB with respect to the baseline in Table G-6, while keeping the symbol rate constant at 300 MS/s. The detailed results of this iterative process are presented in Figure G-4, where it can be seen that the baseline case matches the values anticipated in Figure G-3. As to be expected, lower ΔdB reduces achievable data transmission capacity and higher ΔdB increases it.

Table G-6: Baseline Definition

FIXED	PARAMETERS
Orbit	600 km
Svalbard G/S	99.5% avail.
Frequency	26 GHz

VARIABLE PARAMETERS

	Symbol rate	**300** MS/s
Onboard	OB antenna gain (with 10 cm diam.; 0.55 eff.)	**26.1 dBi**
	Transmission power (10 W SSPA)	**10 dBW**
On ground	OG antenna gain (with 6.3 m diam.; 0.65 eff.)	**62.8 dBi**

ΔdB = 0 dB

Table G-7 below also summarizes the achievable average data rates, and what would be needed if just one of the several parameters that contribute to ΔdB had to be changed. In short, increasing requirements may lead to a marginal increase in data throughput, but it is also possible to relax requirements, especially for small satellites not requiring the 1 Gb/s.

Table G-7: Requirements for 9dB Increase or Decrease

	ΔdB -8 dB (as for no-VCM)	**ΔdB =0 dB (Baseline)**	**ΔdB +9 dB**
Power transmitted	1.6 W	10 W	80 W
Onboard antenna diameter	0.04 m	0.1 m	0.28 m
On-ground antenna diameter	2.5 m	6.3 m	18 m
Average data rate with VCM	0.71 Gb/s	1.07 Gb/s	1.3 Gb/s

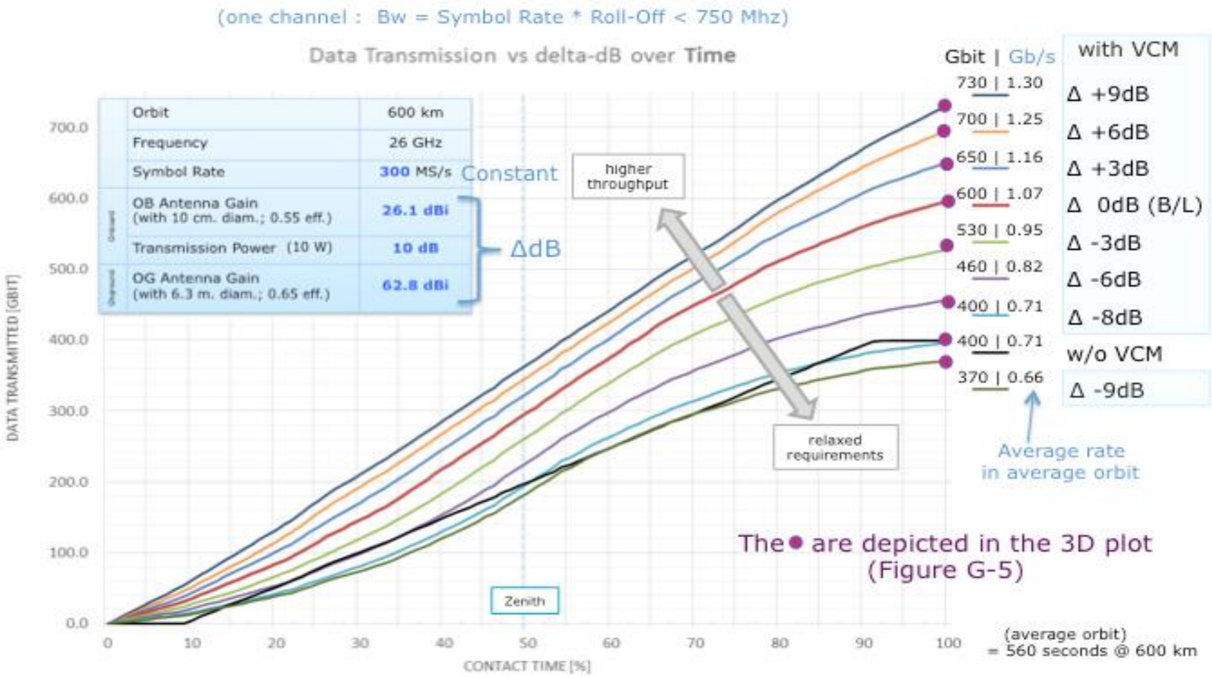


Figure G-4: Variation of ΔdB and Resulting Data Transmission Rates

G.4.2 Full Variation of Both Parameters

Figure G-5 shows the result of the parametric study varying both symbol rate as well as Δ-dB and the resulting average data rate. The curve with constant symbol rate (300 MS/s) corresponds to the final points of Figure G-4.

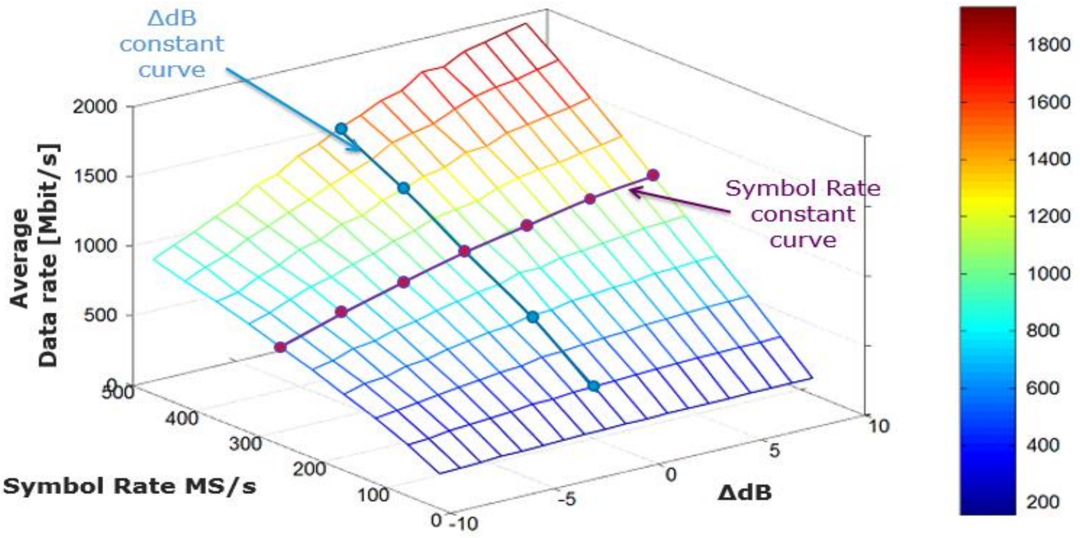


Figure G-5: Symbol Rate vs Delta-dB vs Average Data Rate Solution Space

One can also see in Figure G-5 that the gradient changes depending on the combination of Δ-dB and symbol rate. This gets even clearer if we project the data in isometric form as in the Figure G-6, and can be very helpful to determine whether priority should be given to increase ΔdB or to increase the symbol rate in order to increase the final average data rate.

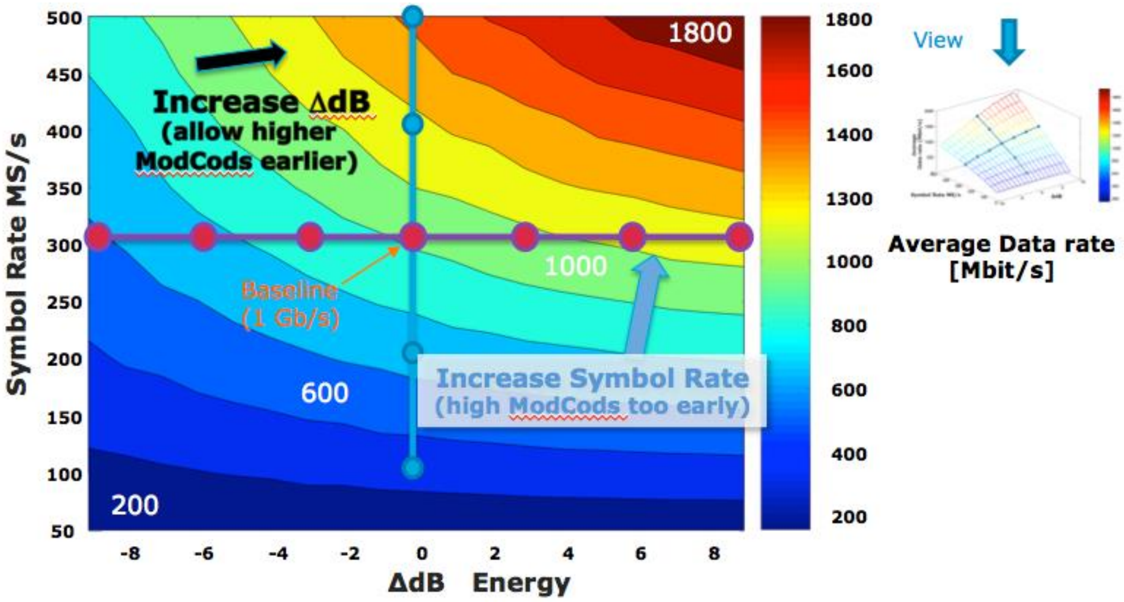


Figure G-6: Isometric View of Parameter Space

The two examples with blue and black arrows in Figure G-6 show how to interpret this information:

- At the bottom-right side, the Δ-dB (with larger antennas, transmission power) is high, which allows to start the communication with ModCod 20 (see blue curve in Figure G-7 and the highest efficient (64APSK) ModCods is already in use with low elevation angles. Therefore, the most efficient way to increase data throughput is to increase symbol rate.
- At the top-left corner, the Δ-dB is low, which means that the highest efficiency (64 APSK) is only used for a very small contact time (see black curve in Figure G-7). Therefore, an increase in Δ-dB would help to get the black curve below closer to the blue curve and will result in higher overall data throughput. As a reminder, overall data throughput is directly related to the surface under Figure G-7, since it is defined as the integral over contact time of the instantaneous data rates.

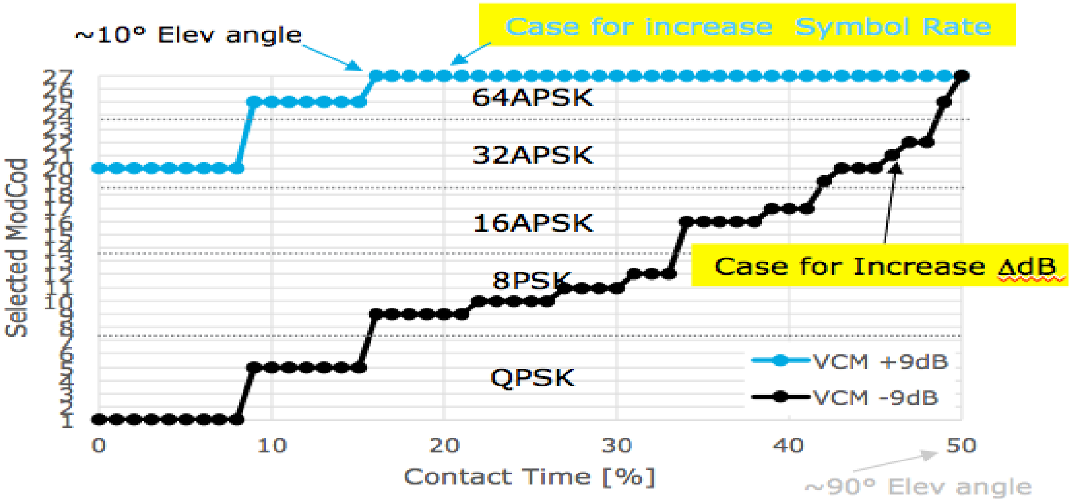


Figure G-7: Example of ModCods Used in Different Conditions

Note that this graph is only correct for the chosen base parameters (Svalbard, orbit height), and each mission shall iterate this analysis.

G.4.3 Maximum Speed Achievable

In the example and Figures in section G.4.2 it can be seen that the maximum average data rate that can be achieved is in the order of 1.9 Gb/s for one channel operating at 500 Msymbol/s, which fits well in less than half of the available bandwidth (1500 MHz). Hardware exists from some manufacturers supporting channels with 500 Msymbol/s. For this reason it would be possible to consider two channels per polarization and also dual polarization when using high-gain antennas.

Appendix G-8: Example of Maximum Data Rate Achievable

	Average VCM	Peak (64-APSK Code 9/10)
Data rate (1 channel @ 500 MS/s)	1.9 [Gb/s]	2.7 [Gb/s]
Bit/symbol (1 channel)	**3.8 [bit/symbol]**	**5.4 [bit/symbol]**
Data rate (2 channels x 2 polarizations)	7.6 [Gb/s]	10.8 [Gb/s]

G.4.4 Range of Parameters Affecting the Link Budget

Table G-9 shows a coarse view of parameters affecting the link budget. It can be seen that while some parameters will not have a big impact (e.g., satellite altitude), others determine the feasibility of the system (e.g., the onboard antenna gain). In blue, the parameters that contribute to ∆dB and in red the symbol rate driving the multi-parametric analysis in earlier sections. Their range variation confirms their importance in the link budget.

Table G-9: Example of Range of Parameter Affecting the Link Budget in Svalbard

	High range [dB]	Low range [dB]	Range [dB]	
OB Tx power	18.5	10.0	**8.5**	TWT (70W) vs SSPA (10 W)
OB antenna gain	30	6	**24.0**	High gain (15 cm diam.) vs. isoflux
Free space losses	185.9	189.6	3.8	400 km vs 800 km altitude @ 5-deg. elev.
Atmosph. losses	6.30	9.10	2.8	7.5 vs 5-deg. elev. angle
OG antenna gain	69.1	57.1	**12.0**	13 m G/S vs 3.25 m G/S
Req. Es/No + backOff	1.1	27.1	26.0	QPSK - Cod 1/3 vs 64APSK - Cod 9/10
Symbol rate (R)	80.0	87.0	**7.0**	100 Msym/s vs 500 Msym/s (potential for 1000 Msym/s)
Min. elev. angle impact	218.2	224.6	6.4	10 [deg.] vs 5 [deg.] elev. ang @ Svalbard for free space losses + attenuation + Tsys
Range [dB]			84.4	Not all combination of parameters are possible

G.5 Example with Onboard Isoflux Antenna

High-gain antennas can be used in three configurations:

- With mechanically steerable antennas, with implications on reliability
- Steering the whole satellite during data transmission with a fixed antenna; this may imply not using the observing instrument at given times

- Electrical steering, which may not be cheap and has complications to the receiver due to possible phase jumps

All these options may not be attractive to small satellites, which may want to use the classical isoflux steerable antennas. Table G-9 provides an example of link budget that shows the following:

- A high-gain ground station (e.g., a 15-meter diameter) is needed
- Minimum elevation angle may need to be higher than 5 degrees
- Moderate data rates need to be considered: a few hundred Mb/s (> 470 Mb/s above the 15-degree elevation in the example below)

On the other side, VCM is definitely the enabler factor since it provides the adaptability and its performance (required Es/No) is very close to the Shannon limit, which allows to gain a few dBs with respect to other classical coding approaches.

Table G-10: Example of a Link Budget for 26 GHz with Isoflux Antenna

Blocks	Example @ 600 km altitude ; f = 26 GHz				Link Budget
	Elev. Angles =	5 deg.	15 deg.	§	assumptions
	Contact time above Elev. Angle =	100.0%	47.5%		
1) Space Segment	**Output Power_Tx (dBW)**	10.00	10.00	1	with 10 W High Power Ampl.
	Output Back-off (dB)	-0.3	-0.3	2	5 deg: QPSK ; 15 deg: 8PSK
	O/B losses (dB)	-0.50	-0.70	3	Waveguides, …
	OB pointing losses (dB)	-0.1	-0.1	4	
	O/B antenna diam. (m)	0.1	0.1	5	Isoflux 10 cm possible
	O/B Antenna Gain (dBi)	6.0	6.0	6	Parabolic & Effic.= 0.55
	EIRP (dBW)	15.08	14.87	7	Tx - Loss + AntGain (in dB)
2) Free space	d =distance Sat.- G/S (km)	2,329	1,626	8	d at 5 and 15 deg.elev.
	Free Space Loss (dB)	-188.1	-185.0	9	$=(4\pi*d/\lambda)2$ @ 26 GHz
	Atmospheric attenuation (dB)	-9.1	-3.4	10	99.5 % in Svalbard (ITU)
3) Ground Station	Antenna Diameter (m)	15	15	11	D ; eff= 0.65 ; Bm3dB= 0 deg
	Ground Antenna Gain (dBi)	70.36	70.36	12	$= eff*(\pi*D/\lambda)2$
	Anten. Pointing loss (dB)	-1.0	-1.0	13	Pointing impact
	Radome losses (dB)	-2.0	-2.0	14	In some locations
	Missmatch losses (dB)	-0.1	-0.1	15	Additional Losses
	Total Gain Ground Antenna (dB)	67.26	67.26	16	= SUM (Gain - Losses) in G/S
	Tsys (K)	546	432	17	with propagation @ Svalbard
	Tsys (dBK)	27.37	26.35	18	10*log(Tsys)
	G/T (dB/K)	39.89	40.90	19	Gain - Tsys - Losses (in dB)
Noise Eq.	Boltzmann_K (m2 kg s-2 K-1)	-228.60	-228.60	20	=10*log(1.38×10-23)
4) Rates	R = Symbol rate (Mbaud)	200	200	21	Only 1 Channel
	Channel Symbol Rate (dB Hz)	-83.0	-83.0	22	log (R)
	ModCod efficiency (symbol/bit)	0.71	2.37	23	5 deg: QPSK + 1/3 code 15 deg: 8PSK + 4/5 code
	Bit data rate (Mb/s) (1 channel)	**142**	**474**	24	= R * ModCod_eff
5) Modulation & Receiver	Losses in the receiver (dB)	-0.20	-0.30	25	Implementation and modulation losses (Tx, Rx)
	Non-linear modulat. distortions (dB)	-0.69	-0.88	26	5 deg: QPSK + 1/3 code 15 deg: 8PSK + 4/5 code
	Es/No (received) (dB)	2.48	11.82	27	Es/No @ Receiver
	Es/No (required) (dB)	-0.64	9.09	28	5 deg: QPSK + 1/3 code 15 deg: 8PSK + 4/5 code
	Es/No (Margin) (dB)	**3.12**	**2.73**	29	**Typical mission req. > 3 dB**

G.6 Conclusion

For the design of an efficient downlink budget, which uses VCM, the above graph can be used as a guideline to optimize the design and find an optimal balance between system parameters.

The benefits of VCM-enabled data transmissions can be summarized as:

- Optimal use of energy with respect to the Shannon channel theoretical limit thanks to the advanced coding standards used in VCM (see Appendix I)
- Operational flexibility that enables contacts at very low elevations that otherwise would not be possible
- Higher data throughput, by wisely using link margins in low elevation angles to establish the contact, but also in high elevation angles to use more efficient ModCods delivering more bits per symbol

VCM, with its flexibility, can support average data rates that go between very few hundreds of Mb/s up to almost 2 Gb/s average data rate.

A multi-parametric analysis has been presented that allows to optimize gain (e.g., in onboard transmitter, and high-gain onboard and on-ground antennas) versus symbol rates, which need to be fixed for a given mission so that the same RF chain (e.g., filters) can be used. An approach based on a gradient-method is proposed in order to determine an optimal selection of these parameters.

Beyond the scope of this appendix, the natural extension of the pre-programmed VCM (i.e. off-line and based on atmospheric statistics) is ACM, where the selection of ModCods will be done on the ground (i.e. with real propagation measurements in real time) and then sent with an uplink to the onboard transmitter to adapt the ModCods accordingly. This real-time factor will allow the data downlink to operate with optimal ModCods in each instant.

Appendix H Atmospheric Propagation (Data and Models)

This appendix covers aspects related to propagation such as:

- Why is propagation important (reasons and implications)?
- Why is it ground-station specific?
- What knowledge do we have?
- What is missing (e.g., data, models)?
- How to get the missing items?

In any communication system, the quality of the signal at the ground station receiver determines the achievable performance and link availability. The signal quality is often affected by signal propagation between transmitter and receiver, in the form of signal attenuation and other effects (e.g., signal phase and/or polarization changes).

The total attenuation along a path is an integral parameter of the link budget that depends on the radio link frequency and the distribution of the atmospheric components (oxygen, vapor, clouds, precipitation, all highly variable in time and space) at the ground station site and along the signal path. At 26 GHz, the propagation attenuation is higher and more variable than that at X-band (many dB) with respect to:

- Time (daily and short-scale fluctuations, and seasonal)
- Local climatology
- Link elevation angle (EA)

Propagation is particularly critical in the 26 GHz band due to its vicinity to the water vapor absorption peak at 22 GHz and rain attenuation.

For LEO-to-ground communications, ground station location plays a key role in the atmospheric propagation attenuation concerns due to the local weather and elevation angles. Locally, dryer locations are preferred due to their lack of precipitation. Many studies and analyses have been done for GEO-based systems to characterize different climatological conditions for optimum ground station location placement for those systems, but the same is not true for LEO-based systems. The interesting aspect for LEO-based systems is the variable and long signal paths, especially at low elevation angles.

In general the atmospheric attenuation between satellite and ground station can vary between 2 dB and 50 dB at very low elevation angles, depending on the link availability and station location. In addition to link attenuation due to absorption and hydrometeor scattering, the power of the received signal can be affected also by atmospheric refractive effects like the scintillation due to atmospheric turbulence, multipath, ray bending and defocussing. These effects increase at lower elevation angles, can depend also on the type of ground along the path (e.g., land or sea) and are characterized by fast variations in time and space. Other effects such as depolarization are due to the non-spherical shape of atmospheric hydrometeors (i.e., rain drops, ice crystals and snowflakes). This produces an additional loss of the signal and the interference between orthogonal polarization channels (in the case of dual-polarization systems). Also, the atmosphere emits a large amount of thermal radiation, which increases the overall noise in the radio receiver. Since LEO satellites are fast-moving objects, the elevation angle at any location changes continuously over time, changing the signal propagation distance, which imposes additional dynamics on propagation conditions.

All of these factors may result in differences of more than 20 dB signal attenuation when comparing the signal over zenith to the signal at a low elevation angle.

Given the complexity of the phenomena, the statistical distribution of all this propagation parameters must be estimated using a statistical approach which needs experimental data for both model development and testing. For additional information see the propagation references in Appendix B (*ITU-R*, [n.d]; *COST 255*, 2002; *Castanet,* 2008; and *Allnutt*, 2011).

For further analysis of low elevation angle effects, consider Figure H-1, which illustrates the attenuation at different elevation angles for ground stations at Svalbard (arctic region), and Maspalomas (mid-latitude) and the cumulative contact time percentage at the different elevation angles.

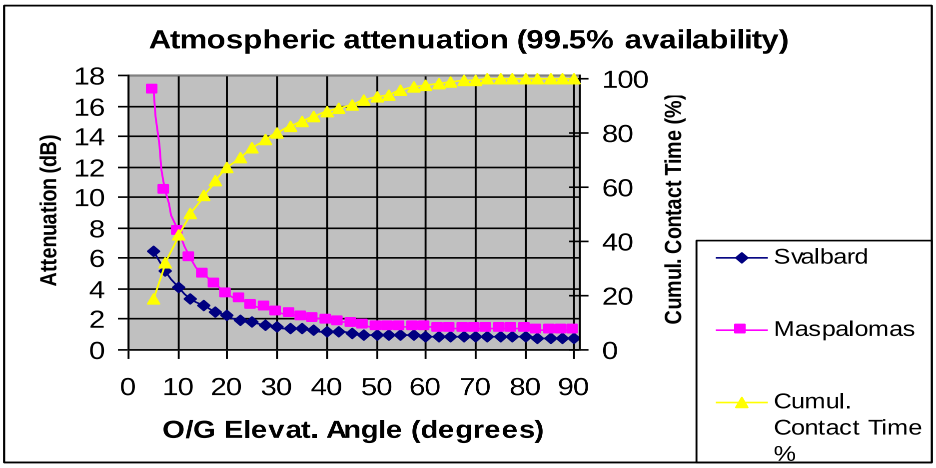


Figure H-1. Contact Time Analysis at Low Elevation Angle

Note that about 40% of the typical contact time occurs at low elevation angles, between 5 and 10 degrees. Thus, a significant portion of the contact occurs at the low elevation angles making the system susceptible to the worse propagation effects, for most of the contact time. Recent propagation measurements performed at Isfjord Radio, Svalbard at Ka-band at 3-degree elevation confirmed the occurrence of long and slow deep fades due to the combination of multipath effects with scintillation, cloud and gaseous attenuation (see *Rytir* 2015).

As an example of the attenuation magnitude at these low elevation angles, Table H-1 shows the predicted propagation attenuation for 5-degree elevation angle for varying ground station locations and compares it with X-band, for similar availability.

Table H-1: Signal Attenuation at Low Elevation Angle

Ground station location	Attenuation at 26 GHz-band (dB)	Attenuation at X-band (dB)
Svalbard (arctic region)	7	2
Maspalomas (mid-latitude)	17	
Tropical regions	> 40	
Availability	99.5%	99.8%

These attenuation values indicate that polar areas, which have the greater contact time, also have much better propagation conditions. For example, most of the Arctic basin receives less than 250 mm of precipitation per year, qualifying it as a desert. Seasonal distributions of attenuation show improvements of the margin up to approximately 2 dB with respect to the annual distribution. Table H-1 data have been derived with past ITU-R recommendations. New ITU-R recommended and considered models will permit the global prediction of annual and monthly distributions of gas, cloud and rain attenuation with higher accuracy and spatial resolution (ref ITU-R P WP3J 2016). On this basis link budget analyses can be refined with respect to earlier results to improve the definitions of system margins.

In any case, considering the required system margin and the overall link budget figures, the experimental characterization of 26 GHz propagation effects at high latitudes is critical for accurate design and control of direct-to-ground systems. Future work in this area might include:

- Identification of different precipitation types (i.e., wet snow, rain, hail and ice)
- Characterization of the propagation path for LEO dynamics for mitigation techniques like ACM or ground terminal antenna diversity

Unfortunately, current channel models have been derived from data collected in propagation campaigns primarily at mid-latitudes with geostationary satellites, although some data exists for low elevation angles with GEO satellites. Their applicability to a system using LEO orbits is quite questionable, especially for what concerns signal dynamics for non-GEO satellites, propagation under low elevation angles and for the climatic conditions of high latitudes. The lack of measurements can be addressed through the development of advanced physical simulators (i.e., a time synthesizer) of space and temporal variations of the atmospheric channel fed by Numerical Weather Prediction (NWP) (*Martellucci*, 2009 and *European Centre for Medium-Range Weather Forecasts Products,* [n.d.], and SISTAR, a correlated space-time tropospheric attenuation simulator developed in coordination between ONERA and CNES [Jeannin 2013]), and also by ground remote sensing and Earth observation data. A number of Atmospheric Numerical Simulators (ANS) have been developed by ESA in recent years for Earth observation and deep space exploration missions (Castanet 2015, Marzano 2015). The MetOP-SG project have already used one of these ANS to validate adopted margins for the EO Ka Band DDL (EUMETSAT 2015). However, each one of these techniques can have limitation in terms of spatial and temporal resolution and coverage area (*Rosello*, *et al*., 2012). Therefore, in-situ measurements under low elevation angles observed from beacons in non-GEO and GEO satellites and ground radiometers shall be considered to validate and test models. At the moment results from propagation campaigns in Alaska (NASA ACTS beacon campaign in Fairbanks) and Svalbard (NASA radiometric measurements and ESA/Telenor beacon campaign) have been used to evaluate the model accuracy at high latitudes. Other campaigns using geostationary satellites are ongoing in Svalbard (Svalsat with Thor-7 and Telenor with KaSAT).

Modeling issues that should be addressed are:

- Characterization of the radio-climatology of high-latitude regions
- Propagation effects that occur/increase at low elevation angles (scintillation, multipath)
- Seasonal, monthly diurnal statistics
- Assessment of the confidence interval of the propagation predictions
- Assessment of the distribution of system outages in time and spatial direction
- Modeling of site diversity
- Atmospheric radio channel modeling (synthetic time series generator)
- The capability to generate design and control parameters for an adaptive system (e.g., VCM or ACM)
- Use of ground radiometric techniques for the calibration of 26 GHz EO DDL payload (e.g., METOP-SG IOT/IOV and monitoring during operations)

To achieve these objectives, additional activities that should be considered include:

- Development of physical/statistical simulators of atmospheric propagation parameter on a LEO satellite(s). The simulator shall be based on use of Numerical Weather Prediction data and can be used for system simulation, control of a fade mitigation system (e.g., VCM), adaptation of a global model to specific areas, model development/improvement. At the moment these tools have been developed and used for preliminary system analyses but they need to be validated with real measurements.
- Performing a propagation campaign by measuring a 26 GHz beacon transmitted from a non-GEO satellite (preferably LEO or MEO) to assess the dynamical properties of attenuation on this type of links for at least one year. At the moment activities for developing the space and ground segment for this type of campaign do not exist, but there is a confirmed program for it. On the other hand, the recent development of Ka-band SatCom non-GEO constellation (03B) makes it possible to perform measurements on MEO orbits as an intermediate step between the GEO and LEO missions. The ESA Telecom workplan includes a project for a MEO campaign in 2018.
- Performing a long-term propagation campaign by measuring at high-latitude a 26 GHz beacon transmitted from a geostationary satellite to assess the impact of propagation at low elevation angles (e.g., scintillations and multipath effects) and the radio climatic characteristics of arctic regions for a long-term campaign (2 to 5 years). Ongoing ESA projects in collaboration with NASA are addressing this objective (see ESA 2015, Nessel 2016 and Tjelta 2015) for a 3-year period, but additional support will be needed to achieve the 5-year goal.

In conclusion:

- Propagation characteristics depend on the location of the ground station and its meteorological conditions (e.g., precipitation, temperature, etc.)
- The 26 GHz band is much more sensitive to atmospheric effects than the X-band, especially at very low elevation angles
- New propagation measurements, with higher spatial and temporal resolution and coverage, are needed for each ground station that take into account two different type of contributions:
    - One related to the dynamics between the LEO satellite and the ground station
    - One related to the atmospheric dynamics
- Data models will be refined as more propagation measurements become available

Appendix I Interoperability and Standards

I.1 Interoperability and Standards Overview

Traditionally, telecommunication networks use a variety of standard interfaces and protocols to ensure reliable delivery of data, voice, video and other services. One of the primary benefits of such telecommunication standards is to enable interoperability among different service providers through common protocols that exchange data and support end-to-end service across different networks. Another benefit is to enable multiple vendors to develop products and systems that can interoperate.

Communications in the space domain, including links using the 26 GHz band, follow this practice, often using standards tailored for the space link and ground link characteristics of space mission architectures. Figure I-1depicts the reference architecture applicable to this study. Using this architecture, the IOAG developed two catalogs (see section I.2) that define a set of common services that can be offered by space communication networks using a set of space data interoperability standards. These services use CCSDS standards for the space internetworking services, space link services, and cross-support services. The primary difference in these services when using 26 GHz as compared with more typically used frequencies is with the space link interface, which is discussed in section I.3. Cross-support services are connections between space communication network ground nodes and terrestrial user mission nodes, and there are no functional differences when using 26 GHz. However the increased bandwidth enabled by use of the 26 GHz band requires increased bandwidth for the terrestrial links (see section I.4). Although there is nothing unique about space internetworking services as a result of using 26 GHz, these emerging internetworking services provide additional capabilities that may be offered in the future by space communication networks (see section I.5).

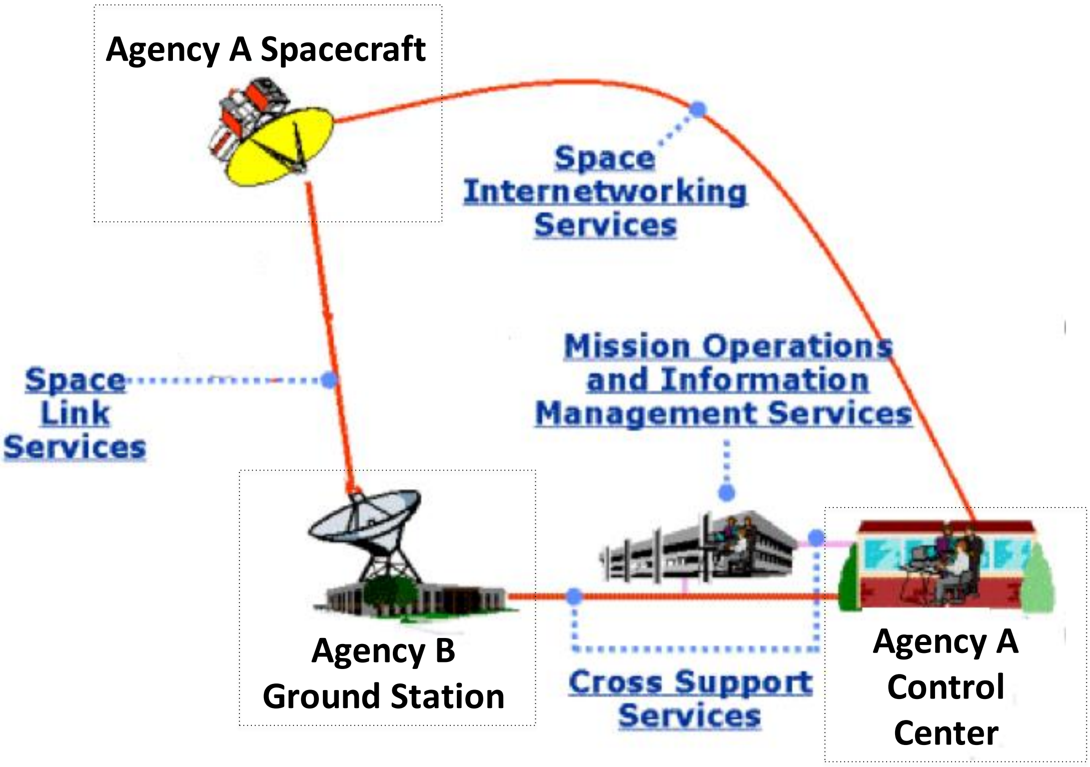


Figure I-1: Reference Architecture

I.2 IOAG Service Catalog

To promote the ability of space agency communication networks to provide cross support to space missions, the IOAG developed the IOAG service catalogs (*Interagency Operations Advisory Group*, 2010b, 2011) that describe the cross support services that will be provided by the ground tracking assets operated by the IOAG member agencies. Service Catalog 1 defines a service as "a self-contained function, which accepts one or more requests and returns one or more responses through a well-defined, standard interface. A service does not depend on the context or state of other services or processes (although it may utilize other services via their interfaces). Services are specified from the user's point of view, i.e., in terms of 'what it provides' rather than 'how it is performed' or 'what does the job.' Therefore, a service is solely specified in terms of its behavior and performance without reference to a particular implementation."

The IOAG Service Catalog 1 is structured into "core" and "extended" services with the understanding that "core" services will be implemented by all IOAG agencies, while "extended" services will be considered for bilateral cross support. The services defined in the two IOAG service catalogs are associated with service groups and are further specified by specific CCSDS space link and cross-support service standards. The services groups are:

- Forward data delivery: The transport of data from a mission operations center to a mission spacecraft, where such data may be spacecraft commands, software uploads or other types of data used onboard spacecraft
- Return data delivery: The transport of data from a mission spacecraft and a mission (or science) operations center, where such data may be spacecraft telemetry or collected science data

- Radiometric data: The delivery of radiometric data measured by the spacecraft or network ground or space station, where such data is used for navigation (location) determination

The standards used to support these services are associated with each of the interfaces as illustrated in Figure I-1, and are described in the following sections.

I.3 Space Link Services

A space link interconnects a spacecraft with its ground support system or with another spacecraft. Agencies' new generations of space missions require telemetry capabilities beyond current technologies. These new needs include higher data rates, better link performances, better performing ranging systems, together with lower cost, mass and power and higher security.

More specifically, the space link services concentrate on layers 1 and 2 of the Open Systems Interconnection (OSI) protocol stack, namely RF and modulation, channel coding, and the data link layer. These layers interact with each other, and new methods to address channel conditions through varying or adapting the modulation and coding are now emerging, as described in section I.3.3.

I.3.1 Space Data Link Layer

There are different ways to provide the space data link layer using several distinct CCSDS standards, but they are not specific to the 26 GHz band. Available data link standards for return data delivery in the 26 GHz band include:

- CCSDS *TM Space Data Link Protocol*, CCSDS 132.0-B-2
- CCSDS *AOS Space Data Link Protocol*, CCSDS 732.0-B-3

High-rate communications, as enabled by 26 GHz systems, could benefit from new space data link features beyond those offered in the existing AOS standard, such as additional flexibility to support larger frame sizes that have not yet been standardized. CCSDS is working on a unified space data link protocol.

I.3.2 Modulation and Coding

The RF modulation and coding provides the interface in the space-to-ground link. This is the physical layer of the OSI stack. The CCSDS Radio Frequency and Modulation Systems standard, *Radio Frequency and Modulation Systems--Part 1: Earth Stations and Spacecraft,* CCSDS 401.0-B-26, defines two modulations for the space research (SR) service (near-Earth) in the 26 GHz band, specifically GMSK and baseband filtered OQPSK. The formats for use by the Earth Exploration Satellite Services (EESS) (near-Earth) in the 26 GHz band are identified in the "TM synchronization and channel coding" standards; the CCSDS is considering the following modulations for the LEO-to-ground data downlink at 26 GHz: OQPSK, 8-PSK, 16-APSK, 32-APSK, and 64-APSK. Choice of a modulation depends on a mission's data throughput needs and system constraints. Linearity, phase noise and group delay could become issues at high order modulations and for very high data rate systems; however, such considerations are not unique to 26 GHz. Mitigation techniques (e.g., equalization and pre-distortion filtering) to alleviate these issues exist and should be considered.

Regarding coding, CCSDS has developed or references several coding standards that can be used for space-to-ground link communication. *TM Synchronization and Channel Coding,* CCSDS 131.0-B-2, defines a set of convolutional, block and low-density parity check (LDPC). This standard is being updated to introduce LDPC slicing in chapter 8 and is starting the agency review. In addition to this standard, the CCSDS approved a set for serially concatenated convolutional turbo coding (SCCC) defined in *Flexible Advanced Coding and Modulation Scheme for High Rate Telemetry Applications*, CCSDS 131.2-B-1 and another set in the *CCSDS Space Link Protocol over ETSI DVB-S2 Standard*, CCSDS 131.3-B-1, that uses a family of codes including BCH and LDPC codes. As with other space link elements, the coding is not unique to 26 GHz systems; however, system designers need to consider factors such as high data rates and signal propagation when selecting the appropriate coding and associated parameters (e.g., code block sizes).

I.3.3 Variable Coding and Modulation (VCM) and Adaptive Coding and Modulation (ACM)

As discussed in the study report, VCM and ACM could be part of the space link services and are not specific to use of 26 GHz. Three standards exist that include or will include some of the functionality necessary to support VCM and ACM operations at the lower ISO OSI layers. These standards are:

- Flexible Advanced Coding and Modulation Scheme for High Rate Telemetry Applications, CCSDS 131.2-B-1
- CCSDS Space Link Protocol over ETSI DVB-S2 Standard, CCSDS 131.3-B-1
- TM Synchronization and Channel Coding. The future CCSDS 131.0-B-3 will incorporate chapter 8 dedicated to LDPC slicing to be used in combination with the modulations defined in 401.0-B-26 reccomendation 2.4.23. Usage of codes in 131.0-B for VCM/ACM needs the integration foreseen in the CCSDS 431.1-M-1 Magenta Book under preparation.

In regards to VCM operations, the core CCSDS modulation and coding standards, CCSDS 401.0-B-26 and CCSDS 131.0-B-2 when integrated by CCSDS 431.1-M, could also be utilized to support VCM operations since such a VCM service can be “scheduled” prior to actual operation. Unlike VCM operations that can use pre-planned schedules and configurations, ACM mechanisms for implementing the necessary feedback between the transmitting and receiving sites need to be considered.

A magenta book, which defines the recommended practice for using variable coded modulation (VCM) together with any CCSDS recommended channel codes is under preparation for future publication. This is the Variable Coded Modulation Protocol CCSDS 431.0-M-1 magenta book.

I.4 Cross-support Services

The cross-support services define what data exchanges are required at various cross-support interface points and how those services are exposed, scheduled and used by organizations that want to confederate their infrastructure in order to execute a mission.

For example, the space link extension (SLE) CCSDS recommendations (the CCSDS 91x. series) provide the protocols used to achieve this interoperability in the ground link, regardless of the space-to-ground frequency chosen. The data rates that are currently achieved with SLE are on the order of a few and even hundreds of Mbps with high reliability.

I.5 Space Internetworking Services

The IOAG has addressed space internetworking and international interoperability on the network layer (see IOAG, Recommendations on a Strategy for Space Internetworking, IOAG.T.RC.002.V1). Interoperability today by ground stations is characterized as shown in Figure I-1 with the ground station only playing the role of a bent pipe (or simple forwarding) at frame level (or at the data link layer) and transferring the data over the ground via cross-support services in accordance with IOAG Service Catalog 1.

The space internetworking services deal with communication services and protocols that are independent of specific space-to-ground link technology and frequencies (as a lower layer bound) and independent of application-specific semantics (as an upper bound). Such space internetworking services cover essentially the network through application layers of the OSI reference model. Space links at 26 GHz do not require any new internetworking functionality, except for accommodation of the likely higher data volumes.

Traditionally, communication was based on the direct exchange of packets without further application layer support for additional data structures like files. However, spacecraft operations are becoming more and more file-based and there is a tendency to separate protocol layers more clearly. For the future, a transition to a networked architecture potentially based on disruption/delay tolerant networking (DTN) is envisaged in accordance with IOAG Service Catalog 2.

The CCSDS File Delivery Protocol (CFDP) standard (CCSDS File Delivery Protocol [CFDP], CCSDS-720.7-B-4) defines a protocol for bi-directional (forward and return) transfer of files between entities on the ground and in space, taking the special environmental constraints into account like potential interrupted visibility under severe propagation conditions. CFDP defines a fully elaborated set of options for reliable and unreliable file transfer mainly based on negative acknowledgments. In addition, CFDP includes file management services to control the remote file stores and allows routing of files over multiple intermediate waypoints.

In a DTN architecture, CFDP could be used as an application layer protocol while the bundle protocol (BP) (see CCSDS Bundle Protocol Specification, CCSDS 734.2-R-1) would provide store-and-forward capabilities and the Licklider transmission protocol (LTP) (see Licklider Transmission Protocol (LTP) for CCSDS, CCSDS 734.1-R-2) could provide reliability on (delayed/disrupted) point-to-point links.

The propagation impairments in space links may cause undesired corruption of files or other data units, so using the DTN architecture would allow retrieval of the complete file or data units, and extend the transfer over several ground stations, as represented in Figure I-1.

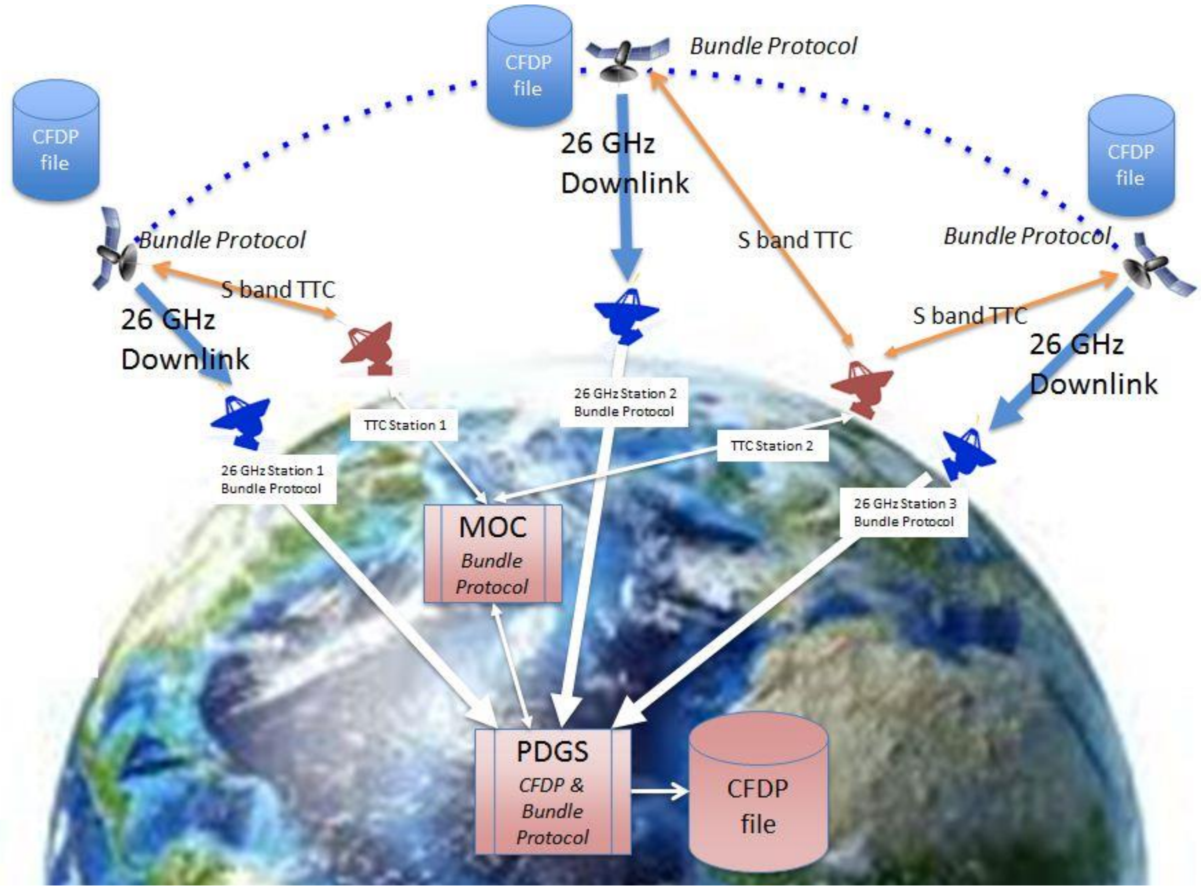


Figure I-1. Internetworking Using DTN Architecture. Different TTC Stations Close the BP at S-band when Overlapping with 26 GHz. TTC Stations Need to be Collocated with Receiving 26 GHz Stations for ACM.