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SELECTION OF FUNCTIONAL AND OPERATIONAL REQUIREMENTS FOR THE NEW 13-M DLR KA-BAND GROUND STATION IN WEILHEIM

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INTRODUCTION

Currently, there are several commercial satellite missions worldwide which provide high rate communication services at Ka-band frequencies (18-40 GHz) to various ground-based users. Moreover, commercial geostationary satellite missions slowly begin to use Ka-band frequencies for LEOP (Launch and Early Orbit Phase), TT&C (Telemetry, Tracking and Command) and payload data operations. One of such satellites is ViaSat-1, which is planned for the launch in 2011. At the same time, due to lack of millimeter wave and high data rate systems, future deep space and near-Earth missions are not in a position to downlink scientific data in a full capacity, which limits mission objectives and possible data return. High data return can only be implemented employing higher frequency bands, e.g. Ka-band. Putting in service higher frequencies allows several advantages. For example, Ka-band brings up to 600% link advantage over X-band. In this concern, the Ka-band antenna is an inevitable part of the modern ground station complex, which allows higher data throughput. Today ESA and NASA have already upgraded their Deep Space ground stations to provide Ka-band capability. There are several projects and potential missions which will require Ka-band support in Europe: H2SAT, EDRS, future L2 (Lagrange) and lunar programs, to name a few. These will include IOT (In-Orbit Testing), TT&C services and potentially LEOP. Having this in mind, GSOC has already started the development of a new full-motion 13-m Ka-band ground station, which will simultaneously enable the missions support and research of a new frequency band, including the design of a high data rate modems, rain attenuation models and Fade Mitigation Techniques.

Due to the small wavelength (10-15 mm) of Ka-band signal, the requirements for such ground stations (for front- and back end) in terms of pointing accuracy, acceleration and velocity limits, Doppler shift compensation and the requirements to the specific hardware are very challenging compared to traditional S/X/Ku-band ground stations. This paper describes the most critical requirements partially based on CCSDS recommendations and the needs of future national and European space missions.

The following problems have been addressed: frequency selection; pointing accuracy; angular velocity and acceleration, Doppler shift compensation, rain fade mitigation and link budget.

I. FREQUENCY BAND AND POLARIZATION SELECTION

Access to frequencies is a major concern for all satellite systems. The Ka-Band is foreseen by almost all the satellite and ground station system designers as the most suitable frequency bands for broadband satellite services. Since the future DLR missions will require higher data rates, Ka-band is presently the only available band with the large amounts of available spectrum, which can be implemented today with existing know-how and reasonable investment.
For the fixed satellite communication services there is an ITU frequency allocation in Region-1 (refer to ITU regions) at 28.45-28.94 GHz for uplink and 19.7-20.2 GHz for downlink, which provides about 500 MHz of bandwidth. For the Earth observation data downlink, a frequency band 25.5-27 GHz has been allocated by ITU. There are also several other bandwidths available for various applications in Ka-band. Despite high rain

attenuation in these frequencies and the narrow antenna beamwidth, the Ka-band communication is still efficient due to the higher bandwidth available. Since the exact frequencies for the future missions are not yet defined, the following frequency bands have been selected for implementation within DLR Ka-band ground station antenna system in order to support future missions:

COM-Band:
Downlink: 18.1–21.2 GHz
Uplink: 27.5–31 GHz

EO-Band:
Downlink: 25.5–27.5 GHz
Uplink: 22.55–23.15 GHz

At the moment, the use of a frequency band 22.55–23.15 GHz for space research and Earth observation purposes is still under negotiation between ITU, commercial satellite operators and space agencies.

Due to limited frequency bandwidth available, satellite makes use of multiple polarizations to enhance the communication capacity. During the selection of polarization, the future satellite missions requirements (e.g. H2Sat, EDRS, Hispasat-AG1) and the availability of COTS equipment has been analysed and both - linear and circular polarizations have been selected. However, it was decided not to operate the ground station antenna on both polarisations simultaneously, therefore polarization will be made switchable between linear and circular depending on the mission needs, whereas the switching between two linear polarizations will require a feed rotation of the antenna.

II. POINTING AND TRACKING ACCURACY

The most critical ground station antenna loads during tracking of geostationary satellites in Ka-band are wind speed and its direction as well as the elevation angle. Considering low orbiting satellites, loads acting on the ground station antenna, besides the loads mentioned above, additionally depend on the altitude and exact orbit of the satellite, which in turn dictates maximum velocities and accelerations of the antenna system. The last two parameters will be discussed in the next section. As seen from the Fig. 2.1, the wind speed averaged over one year in Weilheim is around 15 km/h, with the high standard deviation of 14.37 km/h. Due to relatively high frequency of the high wind speed occurrences and high availability requirements for the ground station during various mission phases, it was decided to select an operational wind speed requirement for the ground station of 60 km/h, which corresponds to somewhat better than 2σ.

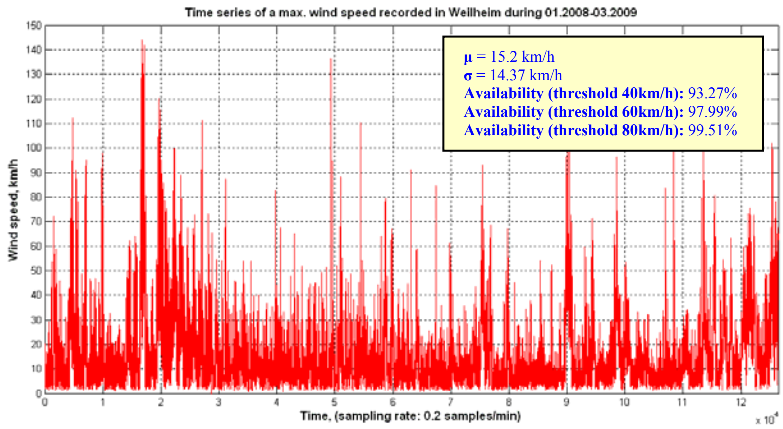


Fig. 2.1 Wind speed time series recorded by DLR weather station in Weilheim during 01.2008- 03.2009.

The pointing and tracking error budget and respective simulations have been performed by the antenna manufacturer and presented during CDR (Critical Design Review), which concluded that 1-σ pointing and tracking loss will not exceed 0.233 dB and 0.254 dB respectively. The following assumptions, representing a geostationary satellite tracking requirements have been considered to obtain the above results:

- Elevation angle: 15 degrees
- AZ speed: 0.01 deg/s
- AZ acceleration: 0.001 deg/s^2
- EL speed: 0.007
- EL acceleration: 0.001 deg/s^2

Unfortunately no further data about the pointing and tracking losses for higher velocities/accelerations are available at the moment. However the values obtained above are considered to be sufficient for tracking of geostationary satellites. Further investigation however required in order to analyze how well the antenna can perform during the IOT and tracking of low orbiting satellites.

III. ANGULAR VELOCITY AND ACCELERATION

Since the antenna considered here has a full-motion capability, it is therefore important to describe the dynamic of the antenna under various loads acting on it to evaluate the required accuracies. Due to a small half power beamwidth (54 mdeg at 30 GHz), it is necessary to provide accurate and precise motion characteristics for the antenna, in order not to loose the contact to the satellite and to be able to perform a first aquisition. For the simulations, azimuth velocity (v_{az}), elevation velocity (v_{el}), azimuth acceleration (a_{az}) and elevation acceleration (a_{el}) were considered to describe a motion in time. These parameters depend mostly on the type of the satellite orbit. For the simulation, a circular orbit with a height of 200 km has been selected, which represents a “worst case” scenario. Table 3.1 shows the antenna parameters which have been used for simulations:

Frequency, f	30 GHz
Antenna diameter, D	13 m
Azimuth velocity, v_{az}	0,015-15°/s
Azimuth acceleration, a_{az}	max. 7,5°/s^2
Elevation velocity, v_{el}	0,006-6°/s
Azimuth acceleration, a_{el}	max. 6°/s^2

Table 3.1 Antenna parameters used for the simulation

The first theoretical notation of the antenna’s motion can be shown in Figure 3.1 (left), where satellite is passing in zenith (over the elevation axis). For simplicity, the rotation of the Earth was not taken into account which leads to a fixed azimuth angle of the antenna. It was observed that the angular velocity and acceleration are both increasing in the beginning of the pass as elevation angle increases. At elevation of approximately 60° the acceleration value reaches its maximum and starts decreasing. The value of the angular velocity reaches maximum as the antenna is pointed to zenith (90°) and the acceleration of the elevation angle is reduced to zero and further gets negative (the antenna begins decelerating). At 120° a braking value reaches maximum level.

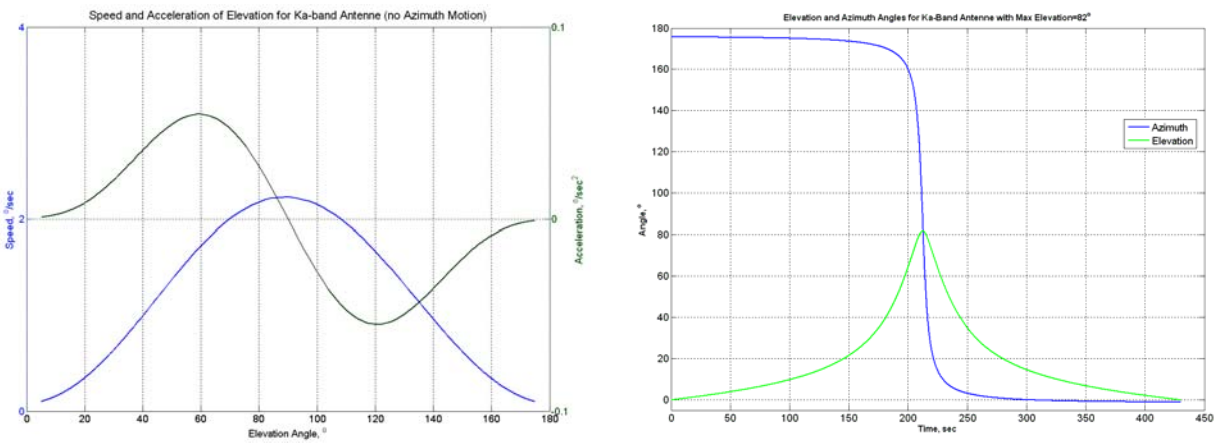


Fig. 3.1 **Left:** Angular velocity and acceleration of elevation angle without azimuth movement. **Right:** Elevation and azimuth angles with elevation angle reaching 82°

In the reality, the azimuth rotation is a part of the antenna's motion, and it cannot be ignored. Since any physical system has its natural limits (in this particular case, the maximum specified azimuth velocity is 15°/s) the antenna will not be able to follow the satellite during the "overhead" passes where the elevation angle is higher than 82°. This can be observed in Figure 3.1 (right) and in Figure 3.2 (left) where the peak value of the angular velocity in azimuth reaches 15°/s. Considering the motion in elevation, which is shown in Figure 3.2 (right), the elevation angular velocity reduces as the elevation increases. The elevation velocity reaches zero as the elevation angle approaches 82° and only after the azimuth rotation the antenna continues its elevation movement again.

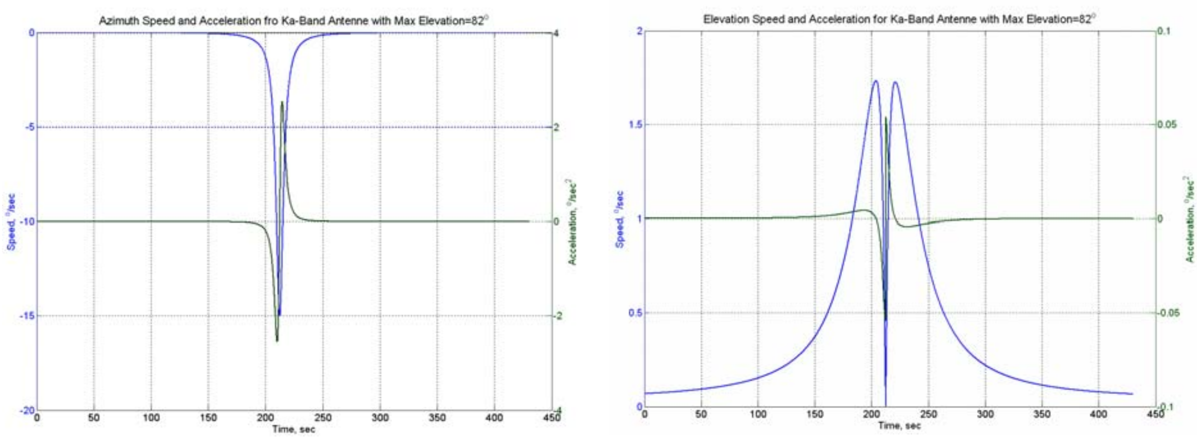


Fig. 3.2 Azimuth (left) and elevation (right) angular velocities and accelerations with Elevation reaching

As it was mentioned above, Ka-band has a small beamwidth. Due to the small beamwidth and limitations of angular velocity and acceleration described above, there will be a "window" during the first acquisition of the satellite (in the beginning of each overhead pass) where the antenna will not be able to follow the satellite due to acceleration limitations. As the angular velocity of the antenna reaches certain level (which corresponds to the angular velocity of the satellite) the antenna will be able to lock and track the satellite further. As an example, let us assume that antenna and satellite established the lock exactly in the midpoint of antenna beamwidth. There is only a half of beamwidth left as a secure interval or margin to loose the lock. The results of such simulation are shown in Figure 3.3.

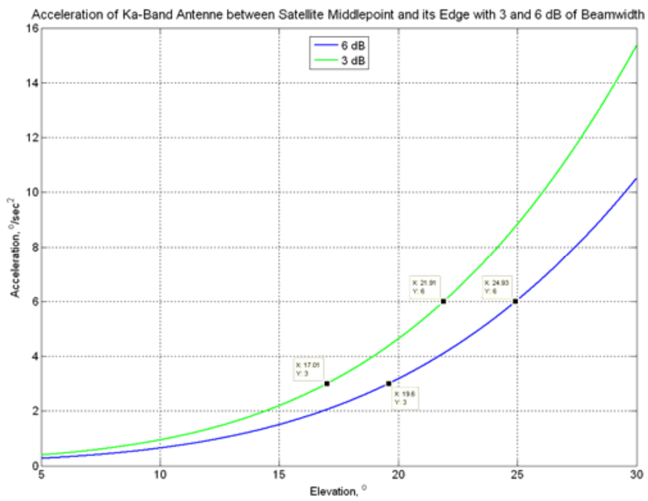


Fig. 3.3 Trade-off between HPBW and acceleration rates

For the case, with the 3-dB-beamwidth and maximum acceleration of 6°/s^2, a lock to the satellite can be easily acquired, if antenna's elevation angle does not exceed 21.91°. For the 6-dB-beamwidth, a lock to the satellite can be easily acquired if antenna's elevation angle does not exceed 24.93°. If acceleration rate would be reduced to 3°/s^2, then the lock could be acquired only within the elevation angle not exceeding 17°.

IV. DOPPLER SHIFT

The signal transmitted from and to the satellite is subject to a Doppler shift that results from motion of the satellites as well as the movement of the ground station due to Earth rotation. The received signal therefore has frequency:

$$f_r = f_t \pm f_d = f_t \pm \frac{v_r f_t}{c} \tag{1}$$

where f_t is the transmitted frequency, f_d is the Doppler shift, and v_r is the relative velocity of the satellite relative to the receiver. Note that the Doppler shift is affected by whether the satellite is approaching or receding, which results in the ambiguous $\pm$ sign [1].

Since DLR since a long time incorporated coherent 2-way ranging, the equation (1) can be written in the different form, where the Doppler shift:

$$f_d = \pm \frac{2 v_r f_t}{c} \tag{2}$$

Substituting the frequencies and velocities, one gets the value of $\pm$ 675 kHz for LEO satellites, $\pm$ 900 kHz during perigees of Launch and Early Orbit Phases (LEOP) and $\pm$ 1800 kHz for the Deep Space fly by perigees.

Since existing tracking receivers at DLR are specified to maintain the maximum search range of $\pm$ 500 kHz, it was important to select a new type of digital tracking receiver which is able to maintain the search range of $\pm$ 1500 kHz to support Ka-band missions. An Automatic Frequency Control (AFC) will automatically keep a resonant circuit tuned to the frequency of an incoming radio signal. When AFC enabled, the receiver will track +/-1500 kHz from the programmed center frequency to compensate for Doppler shift. DSP based processing samples the input spectrum and adjusts the center frequency accordingly.

V. ATMOSPHERIC ABSORPTION AND RAIN FADE MITIGATION

It is well known that the radio signals of frequencies above 10 GHz all suffer from various limiting effects such as rain and gaseous attenuation, scintillation and depolarization, which affect the satellite links significantly. These time varying random weather events, like rain and clouds, increase the moisture in the atmosphere and consequently a noise temperature and the attenuation. The major attenuation contribution at Ka-band frequencies is a rain fade, which seriously affects the link availability. To deal with this problem in a long term, there are various rain attenuation models, which have been developed by different authors. Most of these models are able to predict the stochastic fluctuation of the rain attenuation based on the long-term statistics, which are successfully used within the systems where a large fixed link margin is employed. However, the technology limitations combined with the cost efficiency requirements (e.g. power and bandwidth) do not allow using static margin systems, and push towards the implementation of adaptive control schemes, called Fade Mitigation Techniques (FMT), in general. Depending on the needs, one of the following FMTs could be selected:

- Power Control
- Adaptive Waveform
- Diversity

Since no attenuation measurements have been done in Weilheim, the ITU's long-term rain attenuation statistics have been analyzed to determine the amount of rain fading for different availabilities in Weilheim. Link availability is essentially the percentage of time that the available rain fade margin is not exceeded. For the 99.9% availability performance the attenuation can easily exceed 15 dB. This can lead to huge and unpractical antenna designs if the fixed rain margin is employed. Figure 5.1 illustrates the results of rain attenuation prediction using ITU-R model for different rain availabilities at 30 GHz (as an example of the uplink frequency) at Weilheim region for the rainfall rate of about 40mm/h [2].

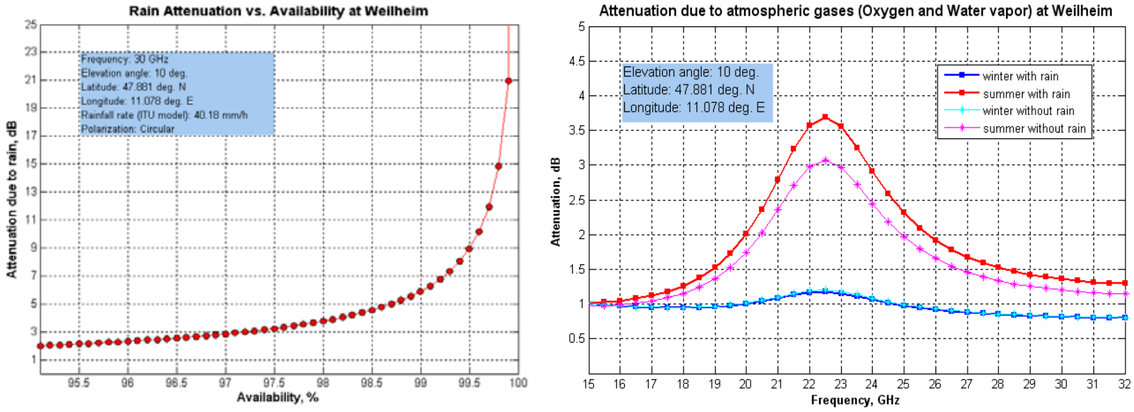
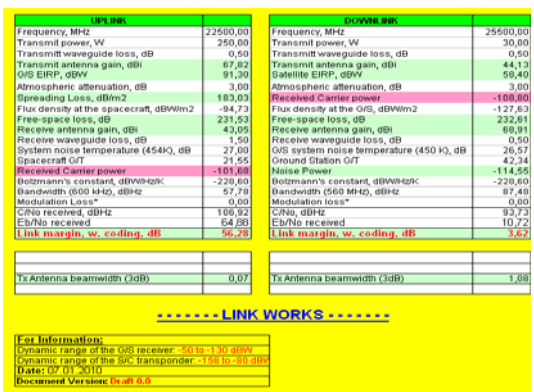


Fig. 5.1 **Left:** Rain attenuation vs. availability at Weilheim Ground Station at frequency 30 GHz. **Right:** Season dependent gaseous attenuation (with and without rain) vs. frequency at Weilheim Ground Station with availability of 98% [2]

As the output of the above model suggests, about 1.5 dB of margin has been included into the link margin to compensate for the gaseous attenuation during IOT (In-orbit Test) measurements of Hispasat-AG1 satellite. In order to guarantee successful IOT of the satellite transponders, it is important to know exact variation of the attenuation in real time during measurements. For this reason, Ka-band radiometer or satellite beacon receiver is inevitable part of any IOT which is performed in frequencies above 10 GHz. In this particular case, single frequency Ka-band radiometer operating on 31.65 GHz frequency will be made available, which means that one has to use frequency scaling techniques in order to obtain the attenuation values at lower frequencies. The frequency scaling techniques are clamed to be 0.2 dB accurate [3]. During the other missions, high attenuation effects of rain will be either compensated with the uplink power control or by means of variable coding and modulation (VCM) schemes which could adapt the link parameters (code, data rate, modulation) depending on the elevation angle and rain intensity. VCM technique is presently under consideration by CCSDS and is a good candidate to be implemented as a standard.

VI. LINK BUDGET

The main drivers for defining size and RF-parameters of the Ka-band Antenna at DLR were the requirements of upcoming In-orbit Tests of geostationary satellites and high rate data downlink from future near Earth Missions (e.g. Moon Orbiter). The In-orbit Test of a newly launched satellite must determine the post-launch conditions of the orbiting satellite and any damage that may have occurred to its subsystems during the launch. These requirements are met by measuring the condition of the satellite's communication and telemetry subsystems, and determining their usability in the satellite's operational environment [4].



UPLINK	
Frequency, MHz	22500,00
Transmit power, W	250,00
Transmitt waveguide loss, dB	0,50
Transmit antenna gain, dBi	67,82
G/S EIRP, dBW	91,30
Atmospheric attenuation, dB	3,00
Spreading Loss, dB/m2	183,03
Flux density at the spacecraft, dBW/m2	-94,73
Free-space loss, dB	231,53
Receive antenna gain, dBi	43,05
Receive waveguide loss, dB	1,50
System noise temperature (454K), dB	27,00
Spacecraft G/T	21,55
Received Carrier power	-101,68
Bolzmann's constant, dBW/Hz/K	-228,60
Bandwidth (600 kHz), dBHz	57,78
Modulation Loss*	0,00
C/No received, dBHz	106,92
Eb/No received	64,88
Link margin, w. coding, dB	**56,28**
Tx Antenna beamwidth (3dB)	0,07

DOWNLINK	
Frequency, MHz	25500,00
Transmit power, W	30,00
Transmitt waveguide loss, dB	0,50
Transmit antenna gain, dBi	44,13
Satellite EIRP, dBW	58,40
Atmospheric attenuation, dB	3,00
Received Carrier power	-108,80
Flux density at the G/S, dBW/m2	-127,63
Free-space loss, dB	232,61
Receive antenna gain, dBi	68,91
Receive waveguide loss, dB	0,50
G/S system noise temperature (450 K), dB	26,57
Ground Station G/T	42,34
Noise Power	-114,55
Bolzmann's constant, dBW/Hz/K	-228,60
Bandwidth (560 MHz), dBHz	87,48
Modulation loss*	0,00
C/No, dBHz	93,73
Eb/No received	10,72
Link margin, w. coding, dB	**3,62**
Tx Antenna beamwidth (3dB)	1,08

- - - - - - - LINK WORKS - - - - - - -

For Information:
Dynamic range of the G/S receiver: -50 to -130 dBW
Dynamic range of the S/C transponder: -158 to -80 dBW
Date: 07.01.2010
Document Version: Draft 0.0

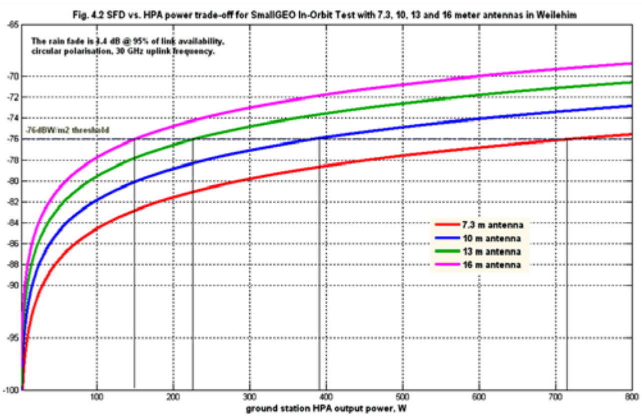


Fig. 6.1 **Left:** Link budget for Lunar Exploration Orbiter. **Right:** Antenna size vs. transmit power.

Since the effective transmit power of available COTS high power amplifiers in Ka-band at the moment is limited to 250 W, it was important to select right antenna diameter. The Figure 6.1 (Left) shows the link budget calculation for Lunar Exploration Orbiter which required for high rate data (200 Mbps) downlink on the slant range of 400,000 km from the Earth. One should not forget that Moon exhibits additional noise to the antenna looking to the Moon of around 200 Kelvin which weakens the link significantly [5]. On the other side, the IOT of the Hispasat-AG1 satellites requires -76 dBW/m^2 of the SFD (Saturated Flux Density) on the satellite antenna input, which is also challenging value. The trade off between antenna size and available high power amplifiers for the rain availability of 95% and circular polarisation is shown on the Figure 6.1 (Right). Therefore the requirements of IOT and Moon Orbiter were decisive parameters in defining 13-m Ka-band antenna at DLR.

VII. CONCLUSION

This paper demonstrated the importance of simulations and analysis related to the Ka-band antenna dynamics during the early phase of requirements specification. The paper therefore, carries important information for those entities, which plan to design, integrate and/or operate Ka-band ground station antenna in their facilities. The most critical parameters to keep tracking during the design and planning are therefore pointing and tracking accuracies, acceleration and velocity limits (in azimuth and elevation), Doppler shifts and rain attenuation (including scintillation and depolarisation).

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