Application of Knife-Edge Diffraction Theory to Optimize Radio Frequency Compatibility On-board a Satellite

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***Abstract*— Modern Earth observation satellites accommodate manifold combinations of Radio Frequency (RF) transmitters and receivers located at various positions on-board the satellite. To minimize the field strength generated by the Tx at the Rx position, one method is to shade the line of sight path by a metallic baffle leading to signal attenuation. This contribution shows the achievable attenuation in practical satellite design and compares the results obtained by field simulations to those obtained by a simplified model (knife-edge diffraction theory). Hereby, knife-edge theory has been expanded by inclusion of angle-dependent antenna gain. Due to the good agreement of the results, knife-edge theory can be used for first-order assessments and parameter studies. This approach minimizes the overall computation time and is currently used to optimize Radio Frequency Compatibility (RFC) on-board the future MetOp Second Generation (MetOp-SG) satellites.**

Keywords- Radio Frequency Compatibility; knife-edge diffraction; baffle attenuation; satellite performance.

I. Introduction

The European MetOp meteorological satellites currenty in orbit will be replaced after 2020 by follow-on satellites with advanced instrumentation. The MetOp-SG will ensure observations until approximately 2040 [1].

After successful finalization of ESA Phase A/B1 study by Airbus Defence and Space, the company has been nominated by EUMETSAT / ESA as prime contractor for the provision of the space segment of MetOp-SG. For this purpose, two satellites (Satellite A and Satellite B) with different scientific instruments are currently developed. Each satellite houses a variety of transmitters (Tx) and instrument receivers (Rx) being sensitive in the RF frequency range. The purpose of the transmitters is to transmit data towards the Earth while ensuring that the instrument receivers are not distorted by the emissions. Although the on-board transmitters are designed to radiate towards the Earth, the field strength around the transmitters is not negligible potentially leading to interference seen by the on-board receivers [2]. Limiting this effect is key to proper performance of the receivers. Reduction of unintended interference power can be achieved by, e.g., sufficiently large distances among transmitters and receivers, optimization of antenna patterns and inclusion of additional baffles to generate a No-Line-of-Sight between Tx and Rx. Figure 1 shows a preliminary model of "Satellite A" together with the positions of an exemplary transmitter radiating in the X-Band towards the Earth, the Microwave Sounder (MWS) instrument receiver, a baffle and the Nadir direction (towards the Earth during flight).

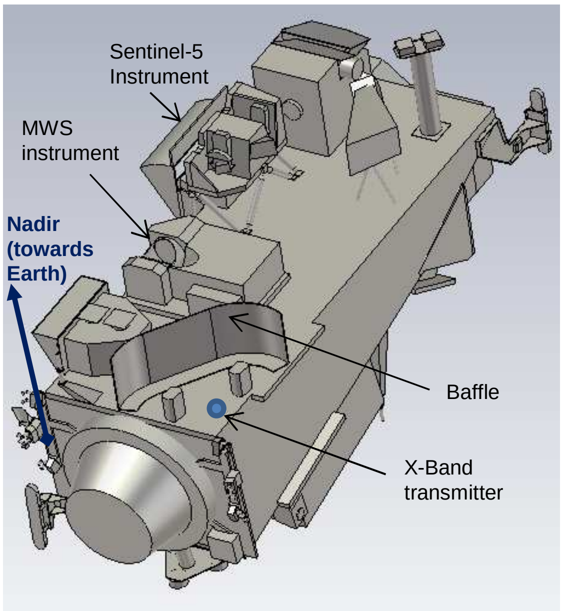

Figure 1. Model of "Satellite A" being part of MetOp Second Generation: Exemplary transmitter and instrument receiver positions

This paper investigates the effect of the baffle on the field strength at the MWS. Hereby, section II presents two general approaches (field simulation and knife-edge diffraction theory) to determine the baffle attenuation. Section III shows an expansion of knife-edge diffraction theory by inclusion of angle-dependent antenna gain and compares the obtained results for the two approaches. Conclusions are given in section IV.

II. APPROACH TO DETERMINE BAFFLE INFLUENCE

This section assumes a metallic baffle (e.g., wall) between a Tx and a victim Rx to limit undesired signals at the Rx position. The physics of electromagnetic wave propagation at RF frequencies is the reason for an undesired signal still present at the Rx position, albeit strongly attenuated: Signal paths originating from diffraction at the baffle can travel towards the Rx as a result of Huygen's principle. In addition, further signal contributions may originate from reflections or scattering at objects in the vicinity of the Tx and Rx. The principle of this multipath propagation is visualized in Figure 2. Hereby, the shown diffracted path interacts with the baffle directly above the hypothetical Line of Sight path. In general, further diffracted paths are possible with interaction points along the top of the baffle.

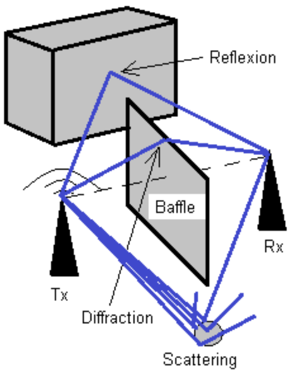

Figure 2. Multipath propagation

Since reflected and scattered paths can carry significant power levels, these contributions should be avoided by a proper design of the baffle (e.g., by an adequate height and an adequate length around the surrounding objects). In this case, the dominant contribution at Rx side only results from the diffraction at the baffle. Due to the physics of diffraction, the interfering signal decreases with steeper diffraction angle (e.g., increased baffle height) and frequency.

The influence of a baffle on the received signal can be determined either by:

- A simplified wave propagation model, e.g., theory of knife-edge diffraction.
- 3D field simulations: A simulation tool solves the corresponding electromagnetic field equations and determines the received field strength at the Rx. This method implicitly takes into account diffraction, reflection and scattering.

A. Analytical Approach by Knife-edge Diffraction

The scenario related to "knife-edge diffraction" is visualized in Figure 3: It assumes a "knife-edge" obstacle between Tx and Rx and shows the diffracted path between Tx and Rx. Hereby, the obstacle subdivides the distance between Tx and Rx into d_1 and d_2. Two cases are possible: In case 1, the upper edge of the obstacle appears at a height $h > 0$ w.r.t. the Line of Sight (LOS). This leads to a "No Line of Sight" (NLOS) scenario. In case 2, the upper edge of the obstacle appears at a height $h < 0$ w.r.t. LOS. This leads to a LOS scenario.

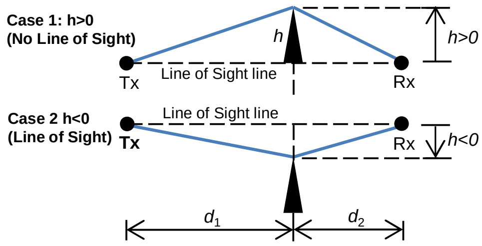

Figure 3. Diffraction at a "knife-edge" for two cases: "No Line of Sight" and "Line of Sight"

According to [3] and [6], the loss induced by the baffle (diffraction loss) is

$$L_{dB} = -20 \cdot \log_{10} |F(v)| \tag{1}$$

with the Fresnel integral

$$F(v) = \frac{1+j}{2} \cdot \int_{v}^{\infty} e^{-j\pi t^2/2} dt \tag{2}$$

and

$$v = h \cdot \sqrt{\frac{2}{\lambda} \cdot \left(\frac{1}{d_1} + \frac{1}{d_2} \right)} \tag{3}$$

where v is the Fresnel-Kirchhoff diffraction parameter and $\lambda = c_0 / f$ is the wavelength of the considered signal. The resulting diffraction loss ("baffle attenuation") as a function of v is plotted below for v = [-5 .. 5] as per [4]:

Figure 4. Diffraction loss of a "knife-edge" versus parameter v [4]

The figure shows the level of the diffracted path in dB relative to freespace which is negative for $v > -0.7$. Hereby, a level of "- x dB" corresponds to an attenuation of "x dB". According to (3), v and h are proportional, hence, $h > 0$ (NLOS) is associated with $v > 0$, yielding a baffle attenuation of at least 6 dB (see graph).

The above graph can be approximated, e.g., by the following piecewise function [5]:

$$L_{dB} = \begin{cases} -(6+9\cdot v-1.27v^2) & \text{if } 0\le v\le 2.4 \\ -(13+20\cdot \log_{10}(v)) & \text{if } v>2.4 \end{cases} \quad (4)$$

Note that above equation is the good one compared to a sign error related to $1.27v^2$ in [5].

To quickly determine the "baffle attenuation", the approach is to determine v by (3) and then to apply (4) for the obtained v. Example: For d_1 = 1.5 m, d_2 = 1.5 m and f = 8.2 GHz (X-Band), Figure 5 visualizes the "baffle attenuation" as a function of h.

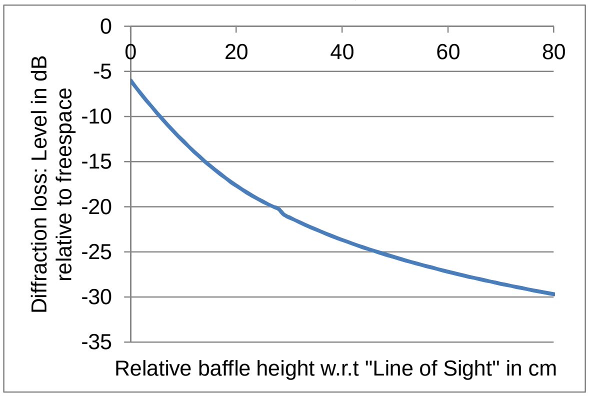

Figure 5. Diffraction loss of a "knife-edge" versus h assuming d_1 = 1.5 m, d_2 = 1.5 m and f = 8.2 GHz

The result reveals that the attenuation is very sensitive to the height. This behavior is due to the small wavelength which is only 3.7 cm in the considered case.

The other way around, the theory of knife-edge diffraction reveals that the baffle attenuation in X-Band frequency range can be improved significantly by only slightly increasing the baffle height. In practice, constraints on the height are given by the required field of views of the transmitters and instruments.

B. Simulation based approach (CST field simulation)

An approach based on solving electromagnetic field equations has the following advantages:

- Result available for any baffle geometry (not only for simple objects like a "knife-edge")
- All wave propagation phenomena implicitly taken into account (e.g., also reflection and scattering), not only diffraction as in the "knife-edge model"
- Environment (surrounding structure) can be taken into account

A well suited approach for satellite engineering is to use the simulation software "Microwave Studio" from the company CST. This tool has, e.g., also been used by Airbus Defence and Space to assess EMC/RFC for MTG satellites.

To determine the baffle attenuation, a dipole antenna is placed at the transmitter position and oriented in a way that the radiation towards the receiver position is maximized. The electric field strength in dB(mV/m) at a victim receiver is first simulated without baffle (reference, including Line of Sight path) and then with baffle. In both cases, the surrounding satellite structure is taken into account. The difference of the electric field strength in dB(mV/m) corresponds to the baffle attenuation in dB.

To obtain the simulation results reported in this paper, the integral equal solver based on Multi Level Fast Multipole Method (MLFMM) has been used. MLFMM is a technique based on the same principles as the traditional "Method of Moments" (MoM), but applicable to models of significantly larger electrical size. Given the geometrical dimensions of typical Earth observation satellites, simulations at frequencies as high as (roughly) 30 GHz can be performed applying this numerical technique. Higher frequencies (smaller wavelengths) require a mesh size which results in increased memory demand and simulation time. Should the need arise to overcome that constraint for practical limitations (e.g., memory size), the satellite structure can be restricted to a representative volume encompassing the Tx and Rx positions.

III. COMPARISON OF FIELD SIMULATIONS W.R.T. KNIFE-EDGE THEORY

On Satellite A, the radiation of the X-Band transmitter towards the MWS instrument is reduced by a baffle. Figure 6 visualizes a part of the satellite structure including the phase center of the transmitter (modeled as a dipole) radiating at 8.2 GHz, the baffle as well as the MWS victim receiver. Hereby, two Rx positions ("Position 1", "Position 2") are considered, where "Position 2" corresponds to the center of the MWS reflector plate. The figure also shows the position of the Sentinel-5 instrument.

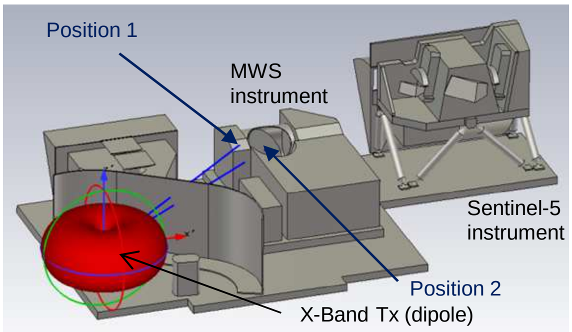

Figure 6. Part of the structure of Satellite A (dipole Tx)

The figure also indicates the LOS directions between Tx and the two Rx positions. The electric field strengths are simulated with the CST software for two scenarios:

- "without baffle"

- “with baffle”.

Results are presented below:

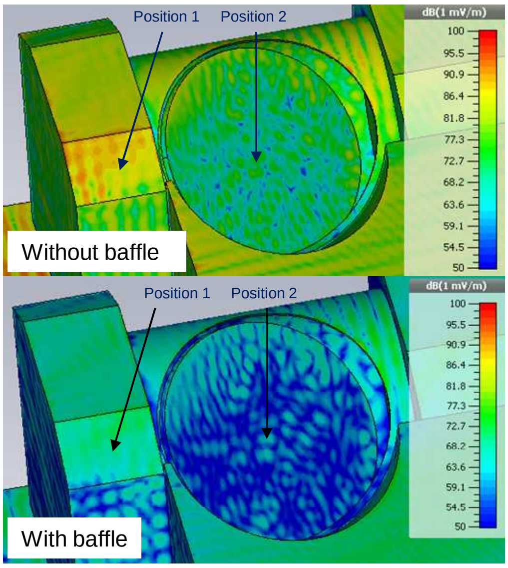

Figure 7. Simulated field strength at MWS assuming radiating dipole; f=8.2 GHz

Observation:
Position 1: The case “Without baffle” reveals a field strength of 90 ± 1 dBmV/m”. The case “With baffle” reveals 72 ± 1 dBmV/m. Hence, the difference is 18 dB.
Position 2: The case “Without baffle” reveals a field strength of ≈ 77 dBmV/m”. The case “With baffle” reveals ≈ 64 dBmV/m. Hence, the difference is 13 dB.

In a second step, the attenuation is estimated by applying the theory of knife-edge diffraction. As explained in the section on knife-edge theory, the baffle subdivides the theoretical LOS path into two distances (d_1, d_2) and a relative height h of the baffle.
For “Position 1”, the values are: d_1 = 1.07 m, d_2 = 1.08 m, h = 0.16 m. Assessment at f = 8.2 GHz yields an expected baffle attenuation of 17.2 dB while 18 dB has been simulated by CST software according to the previous figure. This shows a good agreement between simplified theory and CST simulations. Assessment for “Position 2” (d_1 = 1.05 m, d_2 = 1.43 m, h = 0.218 m) at f = 8.2 GHz yields an expected baffle attenuation of 18 dB while 13 dB has been simulated by CST software. This behavior can be explained as follows: In contrast to “Position 1”, “Position 2” does not enable a path directly diffracted at the baffle towards the receiver position. The signal can arrive at “Position 2” only via multiple interactions, hence, the knife-edge diffraction theory based on a single baffle is not applicable.

Next, the radiation pattern of the transmit antenna is replaced by the measured characteristics of the physical X-Band antenna which is a helix antenna. Figure 8 visualizes the 3D pattern as well as the antenna gain as a function of elevation angle Θ.

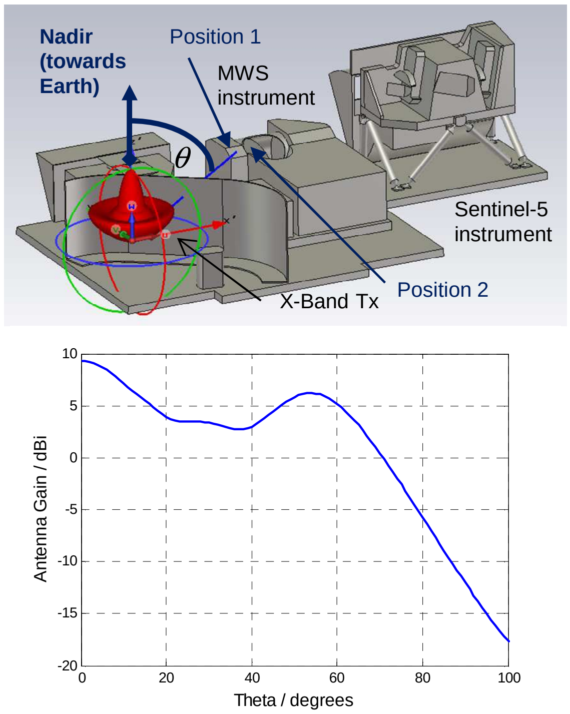

Figure 8. Scenario involving real antenna pattern

For the analysis, “Position 1” is considered. The CST simulation as per Figure 9 reveals: The case “Without baffle” leads to a field strength of 80.8 ± 1 dBmV/m” while “With baffle” leads to 70.8 ± 1 dBmV/m. Hence, the difference caused by the baffle is 10 dB.

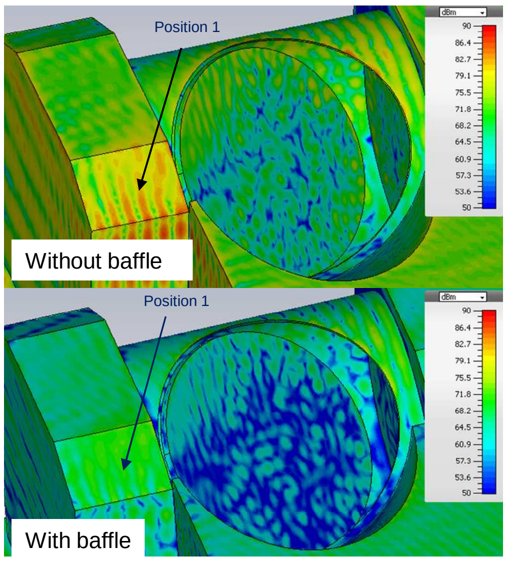

Figure 9. Simulated field strength at MWS assuming real antenna pattern; f=8.2 GHz

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The question arises if this value of 10 dB attenuation can be predicted by the knife-edge diffraction theory. To do so, the angle-dependent antenna data has been incorporated into the knife-edge diffraction theory. The approach is described hereafter:

First, the elevation angle is determined under which a propagation path leaves the transmitter. Figure 10 shows the principal scenario:

- A dotted line indicates the propagation path in LOS direction which is present in absence of the baffle. The associated elevation angle is Θ_1.
- In presence of a baffle, a path originating from diffraction appears at an angle $\Theta_2 < \Theta_1$. Hereby, the interaction point with the baffle is inside the plane defined by the Nadir direction and the LOS direction.

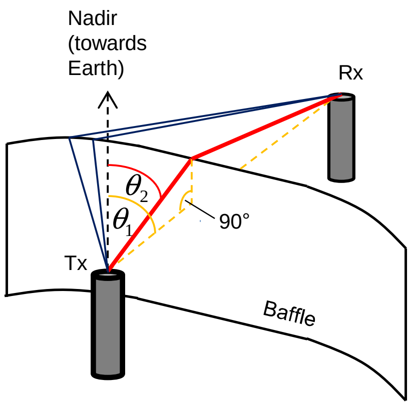

Figure 10. Principal scenario involving diffracted paths

For "Position 1", the elevation angles and the associated antenna gain according to Figure 8 are:

- Θ_1 = 89.9 deg, associated with a gain of -12.5 dBi.
- Θ_2 = 82.4 deg, associated with a gain of -7.3 dBi.

Hence, the diffracted path runs along a direction with higher gain when compared to the LOS direction. Therefore, it is expected that the influence of the baffle is lower compared to the dipole case. The expected attenuation by insertion of the baffle corresponds to the result of the dipole, corrected by the delta antenna gain, hence, the expected value is 17.2 dB – ((-7.3) - (-12.5)) dB = 12 dB.

For comparison, 10 dB attenuation has been determined using the CST simulation software. Limited differences in the result can be explained, e.g., by

- Multipath propagation:
  While above consideration assumes only one diffracted path, further diffracted paths are possible along the top of the baffle. These additional paths occur out of the plane which is defined by Nadir direction and LOS direction. Possible additional paths are already visualized in the left part of Figure 10. In principle, all paths have to be weighted by the angle-dependent antenna gain and then summed up. As the knife-edge theory does not predict multiple paths and the associated elevation angles, only weighting of the diffracted path "in-plane" is possible. A more complex channel model which predicts multiple paths and allows for insertion of an angle dependent antenna gain is Ray-tracing [7]. A disadvantage of this technique is however increased computational time.
- Baffle geometry:
  The baffle geometry differs from the ideal "knife-edge theory" as the baffle is bended and the distance between Tx and baffle differs along the baffle.
- Approximation of Fresnel integral :
  Equation (4) is only an approximation of (1).

To verify the effect of baffles on-board the MetOp-SG satellites prior to launch, early measurements are envisaged in the frame of ground testing. These so-called mock-up tests will use transmitters and receivers with representative antenna pattern as well as a relevant part of the satellite structure.

A similar approach using an adapted knife-edge model is shown in [8] which considers the channel between a train and a satellite including a knife-edge obstacle that models structural elements on the roof of the train. In [8], classical knife-edge theory is expanded by only one antenna gain (the "train antenna gain") whereas the present contribution takes into account both the characteristics of the transmitter and the receiver.

Finally, a general remark is given w.r.t. field predictions when involving antenna patterns: The radiation pattern of a transmit antenna differs between the near-field and the far field where far field conditions are achieved at distances of $d > d_{min} = 2\,D^2 / \lambda$ (D = antenna dimension). When using a far field antenna pattern in above approach, the distance between the transmit antenna and the baffle has to be at least d_{min} (fulfilled in above consideration).

IV. Conclusions

On-board a satellite, strong decoupling between a transmitter and a victim receiver can be achieved by a baffle of adequate height and length so that the strongest propagation path results from diffraction at the top of the baffle.

The height of the baffle shall be large enough to

- realize NLOS between Tx and Rx (and hence, a diffracted path towards the Rx)

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- avoid reflexions at, e.g., high objects in the vicinity of Tx and Rx

The length of the baffle shall be large enough to avoid reflexions at objects next to the baffle which could carry significant power towards the Rx.

To determine the baffle attenuation for such a properly designed baffle, two methods have been studied: 3D field simulations and knife-edge diffraction theory (based on a single baffle), expanded by information on antenna gain. It has been shown that the results agree well when the diffracted path can travel directly into the Rx as per Figure 10 (no multiple diffraction). Hence, the simplified theory helps to quickly assess the baffle influence prior to starting time-consuming simulations. This approach is currently applied by Airbus Defence and Space to ensure radio frequency compatibility on the future MetOp-SG satellites.

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