Line of sight power variation in the air to ground channel

Nicolas Schneckenburger, Thomas Jost, Dmitriy Shutin, and Uwe-Carsten Fiebig
Institute of Communications and Navigation, Deutsches Zentrum für Luft- und Raumfahrt (DLR), Germany

***Abstract*—The paper investigates the variation of the received line-of-sight power due to ground multipath propagation for the L-band air to ground radio channel. Within, both theoretical as well as results taken from flight trial measurements are presented.**

In theory, ground multipath propagation leads to periodic amplification and attenuation of the received line-of-sight power. Measurement data presented within the paper confirms that in general, the variation can be well modeled by introducing an additional ground multipath component. Nevertheless, in reality strong signal variations do not appear as often as expected, i.e. the reflection off the ground is strongly attenuated.

Two main reasons can be identified attenuation. First, ground multipath propagation can be blocked by nearby buildings, terrain features or vegetation. Second, a rough ground surfaces causes the incident radio waves to be reflected in all directions. This effect is called scattering and results in only a small portion of the power being received at the aircraft.

I. INTRODUCTION

The Communication Navigation and Surveillance (CNS) infrastructure in civil aviation is currently undergoing a major innovation process to allow higher traffic levels and more efficient flight operations.

On the communication side, new ground based systems are being developed to replace the analog very high frequency (VHF) voice link [1]. As for navigation, in the future pilots in civil aviation will mainly rely on global navigation satellite systems (GNSS). Nevertheless, ground based radio navigation systems will still play a vital role as alternative positioning navigation and timing (APNT) systems in the future navigation infrastructure. APNT systems are used as backup in case the primary satellite based navigation infrastructure becomes unavailable [2], [3]. Both ground based communication and navigation systems are assigned to use the L-band frequency range. In order to guarantee reliable communications between ground and air and allow for accurate positioning, it is crucial to understand and model the propagation characteristics of the air-to-ground (A2G) radio channel [4]. Hereby, multipath propagation plays a major role, as it can degrade both communication and navigation performance [5], [6].

A multipath component (MPC) arises, when part of the emitted signal is reflected via one or more reflection points towards the receiver. Hereby, we distinguish between two types of multipath propagation: lateral multipath propagation, i.e. reflections of buildings or objects, and ground multipath propagation. Lateral multipath propagation can produce MPCs with a delay able to introduce a range estimation error [7]. In contrast to that, reflections off the ground usually have a very short delay. The resulting constructive or destructive interference of the MPC with the direct line-of-sight (LoS) propagation path leads to an attenuation or amplification of the latter. Hereby, the attenuation of the received LoS power is of great interest, as it has a direct impact on the performance of both communication and navigation systems.

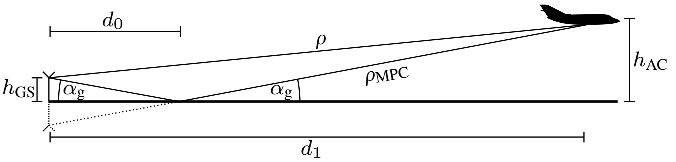

Fig. 1. Schematics of ground multipath propagation. For simplicity we assume a flat surrounding around the ground station antenna.

In this contribution, we focus on ground multipath propagation causing a variation, i.e. amplification or attenuation, of the received LoS power. The analysis of the ground multipath propagation is based on a theoretical analysis as well as on measurement data collected in 2013 by DLR [7]. Therefore, in Sec. II we begin by describing the theoretical background of ground multipath propagation and its influence on the received LoS power. In Sec. III we compare the theoretical results with measured LoS receive power. Sec. IV deals with the modeling of the effects of ground multipath propagation. The paper is concluded in Sec. V with a discussion of the obtained results and an outline of future work.

II. THEORETICAL BACKGROUND OF GROUND MULTIPATH PROPAGATION

By a ground MPC we define a reflection with a short delay relative to the LoS propagation path. Because of the short relative delay, the ground MPC can interfere with the LoS propagation path. The reflection points of such MPCs usually lie on the ground surface surrounding the ground station[1].

Fig. 1 shows the schematic of ground multipath propagation. The ground MPC with a propagation path length ρ_{MPC} interferes with the LoS path. The result is an amplification or attenuation of the latter. Using the ground distance d_1 between ground station and aircraft

$$d_1 = \sqrt{\left(\rho^2 - \left(h_{\mathrm{AC}} - h_{\mathrm{GS}}\right)^2\right)}, \tag{1}$$

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[1] Theoretically, the reflection point may also lie on a building, if the resulting MPC has a short relative delay. Apart from a shorter life time of such a MPC, which is caused by the limited dimensions of a building compared to the ground plane, its characteristics are identical to a ground reflection. We therefore do not differ between the two cases.

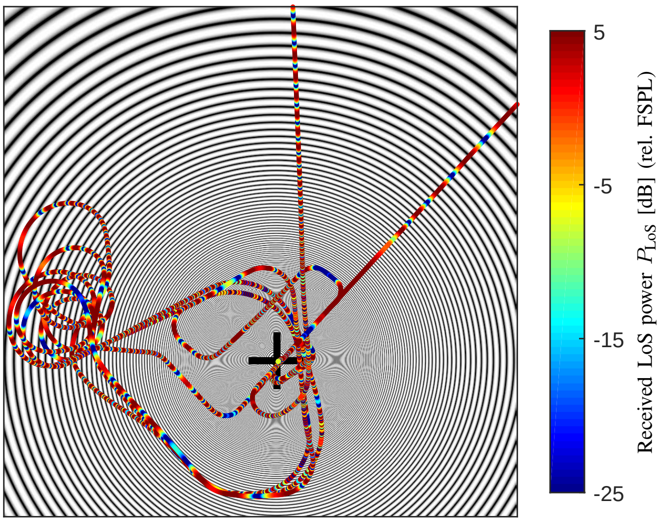

Fig. 2. Variation of the received LoS power P_{LoS} due to ground multipath propagation (area size: $100\,\mathrm{km} \times 100\,\mathrm{km}$). The gray background shows the theoretical received LoS power P_{LoS} for an aircraft flying at a constant altitude of $h_{\mathrm{AC}} = 10\,\mathrm{km}$ AGL. The colored line marks the received power for a flight track conducted in 2013. During the flight the altitude changes between 0 and $10\,\mathrm{km}$ AGL. The ground station position is marked by a black cross.

ρ_{MPC} is given as

$$\rho_{\mathrm{MPC}} = \sqrt{\left(d_1^2 + (h_{\mathrm{AC}} + h_{\mathrm{GS}})^2\right)}. \tag{2}$$

By applying basic trigonometry, the grazing angle α_{g} is calculated as

$$\alpha_{\mathrm{g}} = \tan^{-1} \frac{h_{\mathrm{AC}} + h_{\mathrm{GS}}}{d_1} \tag{3}$$

and the distance between ground station and the ground reflection point d_0 is

$$d_0 = \frac{h_{\mathrm{GS}}}{\tan \alpha_{\mathrm{g}}}. \tag{4}$$

Depending on the path length difference $\Delta\rho_{\mathrm{MPC}} = \rho_{\mathrm{MPC}} - \rho$ divided by the carrier wavelength λ_c, the ground MPC interferes either constructively or destructively with the LoS propagation path. The result is an amplification or attenuation of the latter.

A. Theoretical variation of the received LoS power

Fig. 2 shows the variation of the received LoS power P_{LoS} due to ground multipath propagation. Hereby, we assume a ground antenna height of $h_{\mathrm{GS}} = 23\,\mathrm{m}$, a flat surrounding around the ground antenna, and perfectly reflecting ground surface. The power is normalized to free space path loss (FSPL) to allow an analysis independently from the distance between ground station and aircraft. The ground station location is marked by a black cross. The brightness of the gray background represents the amplification (light) or attenuation (dark) of the LoS path due to ground multipath propagation. Hereby, we assume the aircraft to be at a constant altitude of $h_{\mathrm{AC}} = 10\,\mathrm{km}$ above ground level (AGL). The colored line represents the theoretical received LoS power P_{LoS} for a flight track of the 2013 measurements [7]. During the flight the altitude changes between 0 and $10\,\mathrm{km}$ AGL. Thus, the locations of the fades for an altitude of $10\,\mathrm{km}$ AGL (gray) do usually not coincide with the fades for the conducted flight track (colored).

In both cases, the received LoS power P_{LoS} varies between $6\,\mathrm{dB}$ and total attenuation, depending whether the ground MPC interferes constructively or destructively with the LoS propagation path.

From Fig. 2, we observe that for an aircraft flying at a constant altitude, the variation of the received LoS path power appears in a circular shape. With increasing distance between ground station and aircraft ρ, the frequency of the received LoS power variation decreases. An aircraft experiences longer periods where the LoS path is received at a very low power level. Similarly, decreasing the antenna height h_{GS} also lowers the frequency of the received LoS power variation (not shown in Fig. 2).

We may get very unfavorable situations, if an aircraft flies on a circle around the ground station. In that case the fades of the received LoS power P_{LoS} can last for a very long duration.

It is important to note that Fig. 2 shows the received LoS power variation under assumption of a flat, perfectly reflecting surface surrounding the ground station. The power of the ground MPC can be severely attenuated as described in Sec. II-B. The resulting variation of the received LoS is then significantly decreased. Therefore, Fig. 2 is to be understood as an upper bound on the received LoS power variation due to a single ground MPC.

B. Ground MPC Power

The degree of amplification or attenuation of the received LoS signal depends on the power of the ground MPC received at the aircraft. Additional to the FSPL, the ground MPC can be attenuated mainly in two ways. First, its propagation path can be blocked or attenuated by buildings, terrain features or vegetation. In the case of strongly attenuated ground multipath propagation, the resulting variation of the received LoS power P_{LoS} is only very minor or not detectable.

Second, the ground MPC can be attenuated at the reflection point on the ground. The ratio between the incident and reflected amplitude is expressed by the reflection coefficient Γ. The magnitude of Γ strongly depends on the material of the ground, the grazing angle and the roughness of the ground surface.

The reflection coefficient Γ for a vertically polarized wave for different smooth ground surface materials against the grazing angle α_{g} has been presented in [8], [9]. Based on the given reflection coefficients Γ, the upper and lower limit for received LoS power P_{LoS} can be calculated as

$$|1 - \Gamma|^2 < P_{\mathrm{LoS}} < |1 + \Gamma|^2 \tag{5}$$

Fig. 3 shows the maximum amplification and attenuation of the LoS received power due to a single ground MPC depending on the material of the reflecting ground surface and grazing angle α_{g}. The upper and lower limits are reached, if the ground

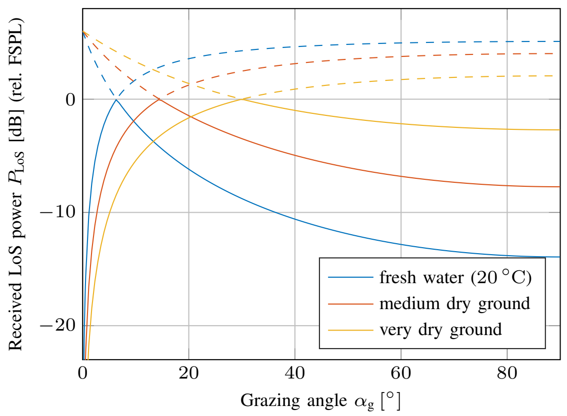

Fig. 3. Upper (dashed line) and lower (solid line) limit for the received power P_{LoS} of the LoS path due to a single ground MPC. The reflection coefficients for the different ground surfaces and grazing angles α_{g} are taken from [8], [9]. We assume a carrier frequency of 1 MHz.

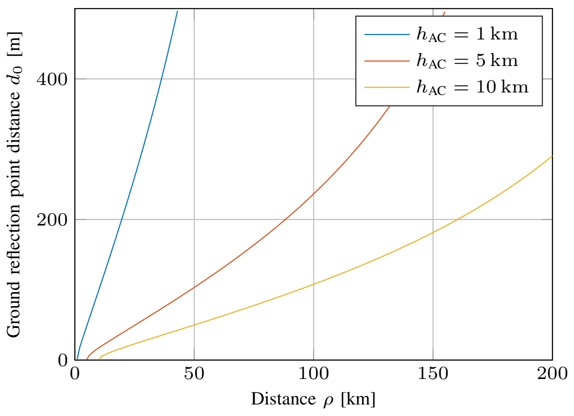

Fig. 4. Distance between the ground station and ground reflection point d_0 for different aircraft altitudes h_{AC} (AGL) versus distance between ground station and aircraft ρ.

MPC either constructively or destructively interferes with the LoS path.

We observe a strong dependence on the grazing angle α_{g} and the material of the reflecting ground surface. The angle at which the LoS is not influenced, e.g. about 6.3° for fresh water, is called Brewster angle [10]. For grazing angles α_{g} above the Brewster angle, wetter surfaces can lead to a more significant change of the received LoS power P_{LoS}. Nevertheless, independently from the ground material the received power of the LoS path can experience large variations. For very shallow grazing angles, i.e. α_{g} approaching 0°, almost the entire power is reflected, i.e. total reflection appears. Thus, the LoS path can either be completely attenuated or its power amplified by 6 dB.

It is important to note, that Fig. 3 assumes a smooth ground. Depending on the roughness of the reflecting surface, the incident electromagnetic waves are not reflected in a single direction, but rather scattered in all directions [10]. Scattering can decrease the reflected power of a ground MPC to a degree at which the received LoS power P_{LoS} does not experience any variation.

C. Lifetime of a ground MPC

As described in Sec. II-B, depending on the material and roughness of the ground surface, the received LoS power P_{LoS} may experience large variations. The lifetime of a strong ground MPC depends on how long its ground reflection stays within the boundaries of a well reflecting area[2]. Thus, the distance between ground station and the ground reflection point d_0 and especially its change for a moving aircraft is of interest for the lifetime of a ground MPC.

Fig. 4 shows the distance between the ground station and ground reflection point d_0 versus the distance between ground station and aircraft ρ. Fig. 4 is generated for different aircraft altitudes h_{AC}. From Fig. 4 we observe that the distance between reflection point and ground station d_0 changes very slowly for an increasing ρ.

Assume a small area of well reflecting material, e.g. concrete of size 100 m × 100 m. We also assume an aircraft at an altitude of $h_{\mathrm{AC}} = 5$ km AGL, starting from a distance of $\rho = 50$ km and flying on a straight course at a speed of 500 km/h away from the receiver. In that case, the reflecting area will lead to a strong ground MPC visible for roughly 10 min. As areas of that or bigger size often exist in all kind of environments, especially airports, the influence of ground multipath propagation can persist for a long time. Note, that if the aircraft is flying on a different course, e.g. circularly around the ground station, a strong ground MPC may be received for even a longer time from an area of the size mentioned above.

III. MEASURED RECEIVED LOS POWER

In this section we present results on the received LoS power P_{LoS} based on flight trials DLR conducted in 2013 [7]. The measurements were performed using a bandwidth of 10 MHz at a carrier frequency in the L-band (970 MHz). In the theoretical results presented in Sec. II we assume a flat, perfectly reflecting ground surface. In contrast to that, during the flight trials the ground antenna is located in a significantly more complex environment. The environment consists of large and small hangar buildings, as well as civil infrastructure, such as office buildings, and large open spaces of either grassy or concrete surface. The overall terrain features small hills and larger forest areas.

Fig. 5 shows the received LoS power P_{LoS} based data from flight measurements [7]. About 100 min of measurement data is visible in Fig. 5. Large banking angles can lead to a significant attenuation of the received LoS power P_{LoS} due to shadowing by the airframe. As we are not interested in those effects, we exclude data points where the aircraft is banking strongly (absolute roll angle above 5°).

From Fig. 5 we can identify several regions in which the attenuation of the LoS path is most likely caused by a ground MPC. Especially, when the aircraft is flying circularly around

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[2] Hereby, we assume that the ground MPC is not blocked.

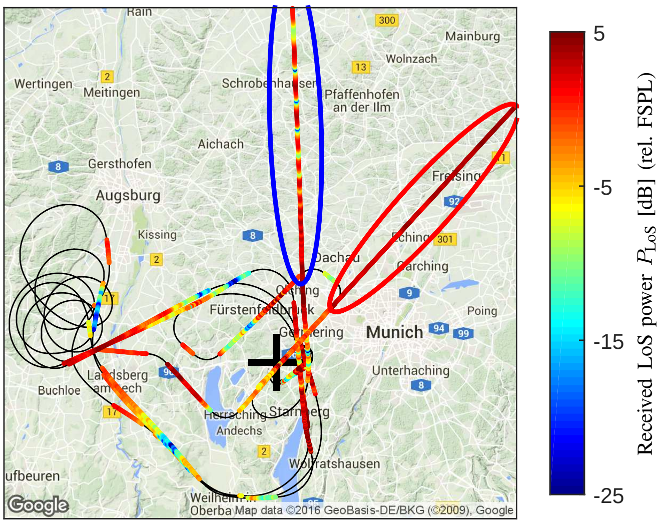

Fig. 5. Received LoS power P_{LoS} based on measurements from [7] (area size: 100 km × 100 km). Data points, where the aircraft is banking are excluded. The ground station position is marked by a black cross (Map: ©Google).

the ground station, fades of the received LoS power P_{LoS} lasting longer than 30 s can be observed (compare Fig. 2). In those situations, the measured received LoS power is attenuated by more than 20 dB.

However, in contrast to Fig. 2, the measured received LoS power does not always experience strong variations. The most plausible explanation is that the ground MPC is strongly attenuated. Therefore, it is not able to attenuate the LoS propagation path.

As described in Sec. II-B, the attenuation can be due to blockage by the terrain or a weakly reflecting or rough ground surface. Good examples for strong and weak ground MPCs are the two straight parts of the flight tracks top right corner of Fig. 5, marked in blue and red, respectively. While flying on the course north marked in blue, the measured received LoS power P_{LoS} undergoes strong and periodic oscillations. When flying on a north-east course marked in red, the measured received LoS power P_{LoS} experiences almost no variation.

A good explanation of this behavior can be found in Fig. 6, in which the two flight tracks are shown on an photograph as observed from the ground station position. No buildings exist in the direction of the blue flight segment, so the ground MPC can arrive at the aircraft unimpeded. In case of the red flight segment, the ground MPC is most likely blocked by the underlying building. Other segments of the flight in which no variation of the received power is observed can usually be explained similarly using a photograph like Fig. 6.

Overall, we can conclude, that strong variations in the received power can be observed during the measurements. This effect is attributed to ground multipath propagation. Nevertheless, a strong ground MPC is very often not present. The ground MPC may be strongly attenuated during its reflection off the ground or completely blocked by surrounding buildings or terrain.

Fig. 6. Flight tracks of the blue and red segment from Fig. 5 as seen from the antennas point of view.

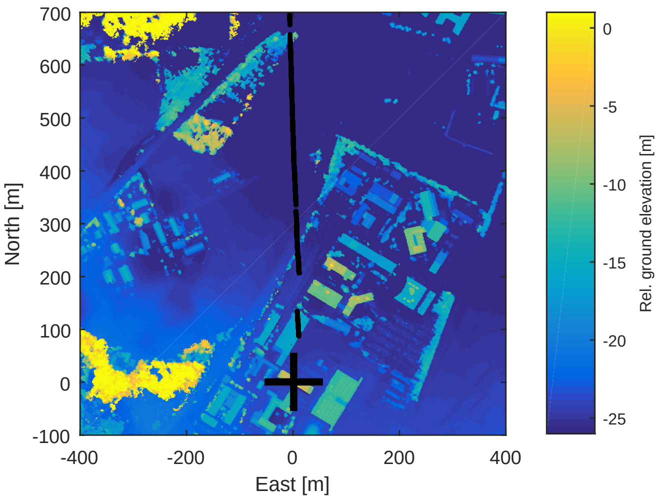

Fig. 7. DEM of the area surrounding the ground station antenna. The elevation is given relative to the ground station antenna. The track of the ground reflection point for the presented flight segment is marked in black.

IV. MODELING OF RECEIVED LoS POWER

In the previous section Sec. III, results on measured received LoS power P_{LoS} over a long duration are presented. In this section, we determine, if we are able to predict the variation of the received LoS power P_{LoS}. The modeling serves two reasons. First, we can verify that a measured variation of the received LoS is really caused ground multipath propagation. Second, modeling of the ground multipath propagation is an integral part, when developing an A2G channel model. A qualitative analysis of how well the measured LoS power variation can modeled is of great interest.

As described in Sec. II, we represent the ground multipath propagation by single ground MPC. The result is a model with two propagation paths [10]. The ground station antenna is located at a very complex environment, featuring different buildings and terrain. Therefore, to calculate the ground station antenna height h_{AC} over the ground plane for a given point, it is necessary to employ a digital elevation model (DEM) [11]. Fig. 7 shows the elevation of the ground, relative to the ground station antenna. From Fig. 7, we can identify several high

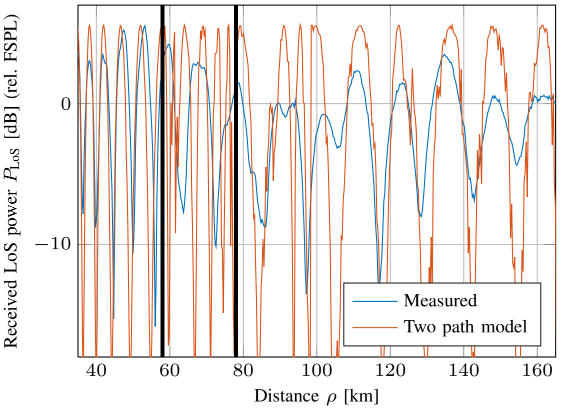

Fig. 8. Measured and predicted received LoS power P_{LoS}. For the prediction we assume a reflection coefficient $\Gamma = 0.9$.

buildings and other terrain features. Thus, a ground reflection point lying on the roof of such a building will effectively reduce the ground antenna height h_{AC}.

Using the DEM and the formulas described in Sec. II, we are able to model the ground multipath propagation. The estimated ground reflection point is shown in Fig. 7. Fig. 8 presents the results for both the measured and estimated received LoS power P_{LoS}. As we do not have precise information about the reflection coefficient Γ of the different ground surfaces, we assume $\Gamma = 0.9$. During the investigated segment the combined antenna gain (ground and aircraft antenna) is expected to be roughly between $-3\,\text{dBi}$ and $0\,\text{dBi}$.

From Fig. 8 we observe that the two path model is able to qualitatively predict the variation of the received LoS power P_{LoS}. Nevertheless, the exact power level depends on the reflection coefficient Γ of the ground as well as the gains of the employed antennas. As exact values for those parameters are often hard to estimate, an offset in the received power is likely.

While the ground reflection point is located on the metal roof of the neighboring hangar ($\rho < 58\,\text{km}$), the variations of the modeled received LoS power P_{LoS} match the measurements. After passing over the roof, the reflection point moves over a parking lot ($58\,\text{km} < \rho < 78\,\text{km}$). During that time, the model does not match the measurements very well. The mismatch is best explained by the very complex ground surface, which features cars, several trees, and other uneven surfaces. Especially the parking lot may have looked very different during the time the DEM was generated, compared to the day the measurements were performed. Later, the reflection point is located on open fields ($78\,\text{km} < \rho$). Here, the two path model generally shows a very good match for the measurements.

Overall, we can conclude, that in a case of a strong variation of the received power, the fades of the received power can be very well predicted using a two path model. However, only a part of the entire surface around the transmitter produces a ground MPC visible at the aircraft. Thus, to model ground multipath propagation for the entire ground station environment, we can define areas on the ground producing a ground MPC visible at the aircraft. This method allows a very simple description of the complex ground station environment with respect to ground multipath propagation.

V. CONCLUSION AND OUTLOOK

In this contribution we analyzed ground multipath propagation and its effect on the received LoS power in the A2G channel.

Both theory and measurements show that ground multipath propagation can lead to a significant variation of the received LoS power. Strong fades of the received LoS power exceeding $-20\,\text{dB}$ and lasting over $30\,\text{s}$ were observed. Nevertheless, during the measurements a strong MPC is not always present. Very often the ground MPC may be strongly attenuated during its reflection off the ground or completely blocked by surrounding buildings or terrain.

At locations, where a strong ground MPC exists, the resulting variation of the received LoS power can usually be modeled very well using a two path model. However, due to the complex ground station environment of the measurements, a DEM has to be employed.

Future work will be focused on the development of a geometry-based stochastic channel model (GSCM) of the A2G channel. Hereby, the modeling of the ground multipath propagation is an integral part. As results in this paper indicate, a ground station environment can be described by areas on the ground producing a ground MPC visible at the aircraft.

REFERENCES

[1] M. Schnell, U. Epple, D. Shutin, and N. Schneckenburger, "LDACS: Future Aeronautical Communications for Air-Traffic Management," *IEEE Commun. Mag.*, vol. 52, no. 5, pp. 104–110, 2014.

[2] S. Lo, Y.-H. Chen, P. Enge, B. Peterson, and R. Erikson, "Distance Measuring Equipment Accuracy Performance Today and for Future Alternative Position Navigation and Timing (APNT)," in *ION GNSS+*, (Nashville (TN), USA), 2013.

[3] W. Pelgrum, K. Li, M. Smearcheck, and F. van Graas, "eDME architecture development and flight-test evaluation," in *ION GNSS+*, (Nashville (TN), USA), 2012.

[4] D. W. Matolak, "Air-ground channels and models: Comprehensive review and considerations for unmanned aircraft systems," in *Proc. IEEE Aerospace Conference*, (Big Sky (MT), USA), 2012.

[5] J. Proakis, *Digital Communications*. Boston, MA: McGraw-Hill, 4th ed., 2010.

[6] P. Misraand and P. Enge, *Global Positioning System: Signals, Measurements, and Performance*. Lincoln (MA), USA: Ganga-Jamuna Press, 2nd ed., 2011.

[7] N. Schneckenburger, D. Shutin, T. Jost, M. Walter, T. Thiasiriphet, A. Filip, and M. Schnell, "From L-Band Measurements to a Preliminary Channel Model for APNT," in *ION GNSS+*, (Tampa (FL), USA), 2014.

[8] ITU-R, "Recommendation P.527-3: Electrical characteristics of the surface of the earth," tech. rep., 1992.

[9] ITU-R, "Report P.1008-1: Reflection from the surface of the Earth," tech. rep., 1990.

[10] J. D. Parsons, *The Mobile Radio Propagation Channel*. Wiley, 2nd ed., 2000.

[11] L. Zhilin, C. Zhu, and C. Gold, *Digital Terrain Modeling: Principles and Methodology*. Boca Raton, FL: CRC Press, 2004.