Propagation Channel Modeling for LEO Satellite Missions Using Ray-Tracing Simulations

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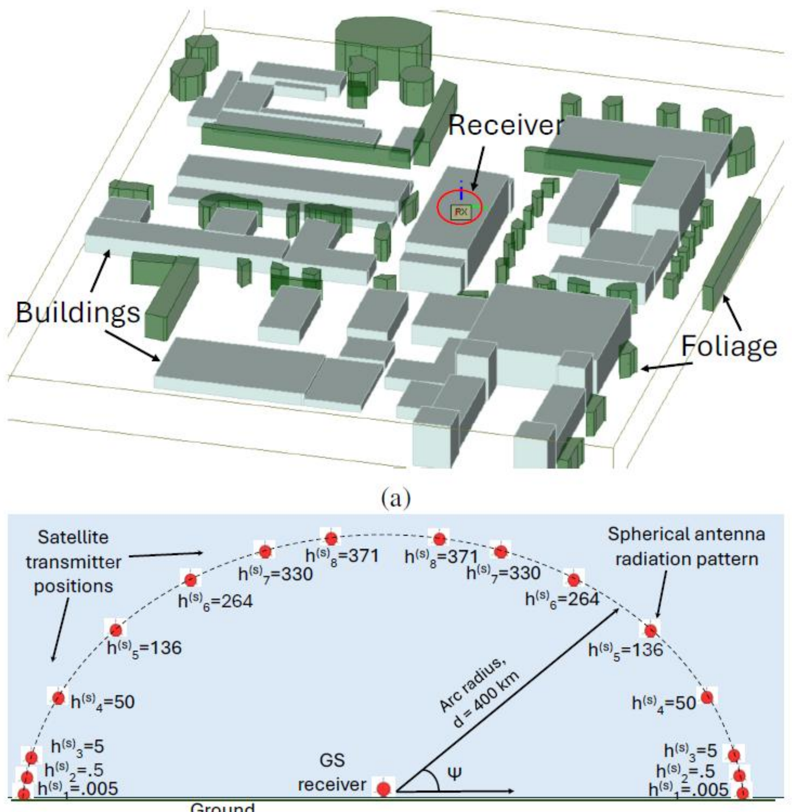
Abstract

This work presents a high-resolution ray-tracing-based channel model for LEO satellite-to-ground links at X-band in a suburban environment. Using Wireless InSite simulations, we develop a parametric model capturing large- and small-scale fading across satellite elevation angles. Large-scale fading accounts for terrain shadowing and environmental factors, benchmarked against the 3GPP NTN model. We also assess link degradation from GS antenna misalignment for single-element and phased-array antennas. Small-scale fading is characterized by shadowed and non-shadowed Rician distributions.
To our knowledge, this is the first elevation-aware X-band channel model integrating ray-traced dynamics, fading, and phased-array misalignment effects.

Introduction

- Most satellite-to-ground models focus on GEO/traditional LEO; small satellites (CubeSats, microsats) are underrepresented.
- Small satellites face short visibility, low antenna gain, weak transmit power, high misalignment risk. X-band increasingly used (good bandwidth, moderate attenuation).
- Gaps in existing models: elevation-dependent fading, site-specific scatterers, phased-array misalignment, weather effects.
- This work: high-resolution, site-specific X-band model for small LEO satellites. Validated via Wireless InSite ray tracing at Aarhus University campus.
- Captures: elevation-dependent fading, weather attenuation (rain > snow > clouds), antenna differences.
- 400 km pass → stronger multipath, larger RMS delay/angle spread than 500 km pass.
- Supports link-budget design, phased-array pointing, and site-specific system planning beyond generic 3GPP/ITU models.

Scenario



(a) Ground station at Aarhus University's Edison Building;

(b) 400 km satellite pass with multiple elevation positions over the GS.

Channel Model

Small-Scale Fading
- MPCs vary with elevation & GS distance.
- Shadowed Rician (low Ψ), Rician (high Ψ), deterministic LOS (no multipath).

RMS-DS & Angular Spreads
- Derived from MPC powers & angles
- Capture delay and spatial dispersion vs. elevation.

MPC Clustering
- MPCs form spatial–temporal clusters.
- DBSCAN detects clusters, labels weak MPCs as noise.

Large-Scale Fading
- Attenuation from path loss, hardware, misalignment, atmosphere.
- Weather impact: rain > clouds > snow.
- Misalignment modeled as gain loss vs. boresight.

$$P^{(\mathrm{RX})}(\Psi, d)\ [\mathrm{dB}] = P^{(\mathrm{coh})}(\Psi, d) - L^{(\mathrm{hd})} - L^{(\mathrm{am})}(\Delta\phi, \Delta\theta) - L^{(\mathrm{atm})}$$

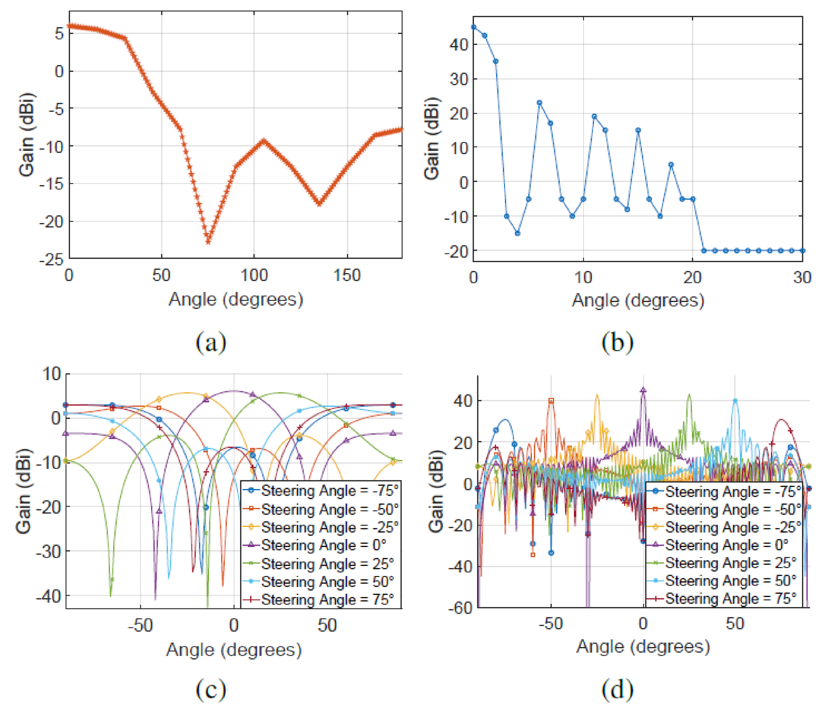
Ray-Tracing & 3GPP Profile
- Wireless InSite with GS at Aarhus Univ.
- Compared with 3GPP NTN profiles:
  TDL-A (NLOS, $\Psi < 10°$)
  TDL-B (shadowed LOS, $10°$–$15°$)
  TDL-C (clear LOS, $\Psi \geq 15°$)

Antenna Gain Filtering
- Rays captured with spherical pattern.
- Mapped to real antenna patterns via spatial filtering.
- Gains adjusted for azimuth–elevation & misalignment.

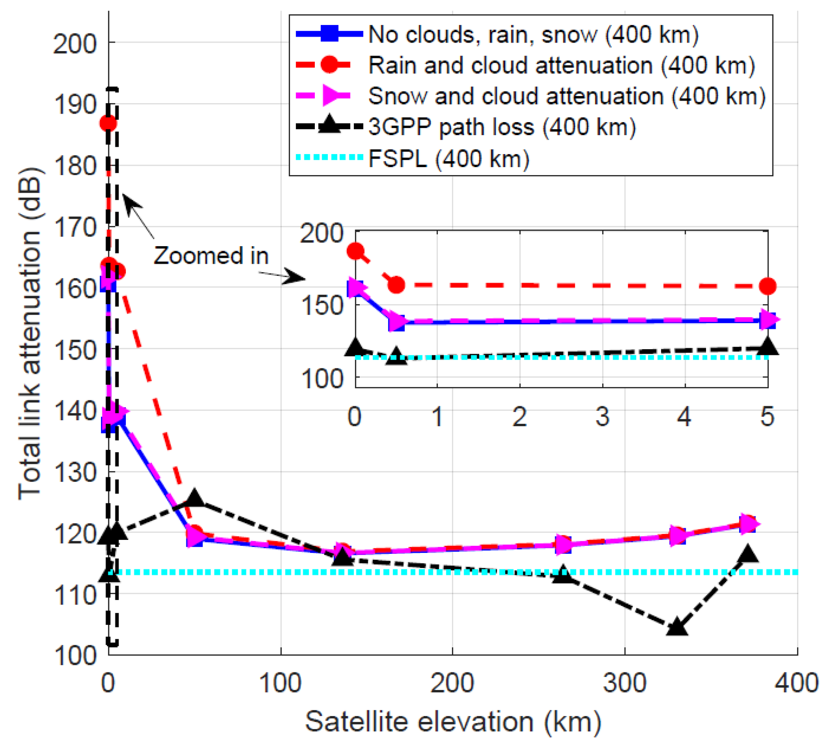
Results

Parameters for simulations.

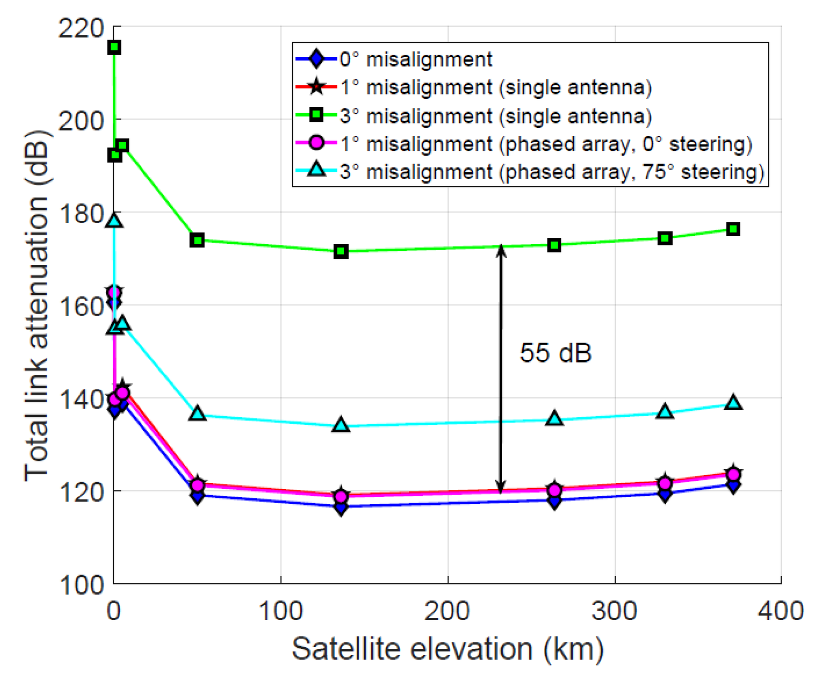
Parameter	Parameter value
Center frequency, f_c	10 GHz
Antenna radiation pattern	Spherical
Antenna polarization	Left hand circular
Transmit power, $P^{(\mathrm{TX})}$	30 dBm
Permittivity of ground	3.5
Permittivity of scatterer structure	5.31
Height of GS (RX), $h^{(\mathrm{GS})}$	23 m
Maximum height of the satellite above GS, $h^{(\mathrm{s})}_{\max}$	$\{400, 500\} - .023$ km
Foliage	Dense deciduous tree
Polarization-dependent attenuation constant, β	3 dB
Rain height, $h^{(\mathrm{R})} = h^{(\mathrm{S})}$	5 km
Effective radius of the earth, R_e	6371 km
Rainfall and snow rate, $\{R_{.01},\ S\}$	{32, 4} mm/h
Rain attenuation coefficient, $k^{(\mathrm{rn})}$	0.0363
Rain attenuation coefficient, ϵ	1.095
Specific attenuation constant for clouds and snow, $\{k^{(\mathrm{cl})},\ k^{(\mathrm{sn})}\}$	{0.072, 0.004}
Clouds thickness, T	1.5 km
Liquid water density, M	0.35 g/m^3
Hardware and fixed atmospheric attenuation, $\{L^{(\mathrm{hd})},\ L^{(\mathrm{fx})}\}$	{1.5, 1.5} dB



Antenna patterns: (a) Satellite single-antenna, (b) GS single-antenna, (c) Satellite 3×3 phased array (multi-angle), (d) GS 60×60 phased array (multi-angle).

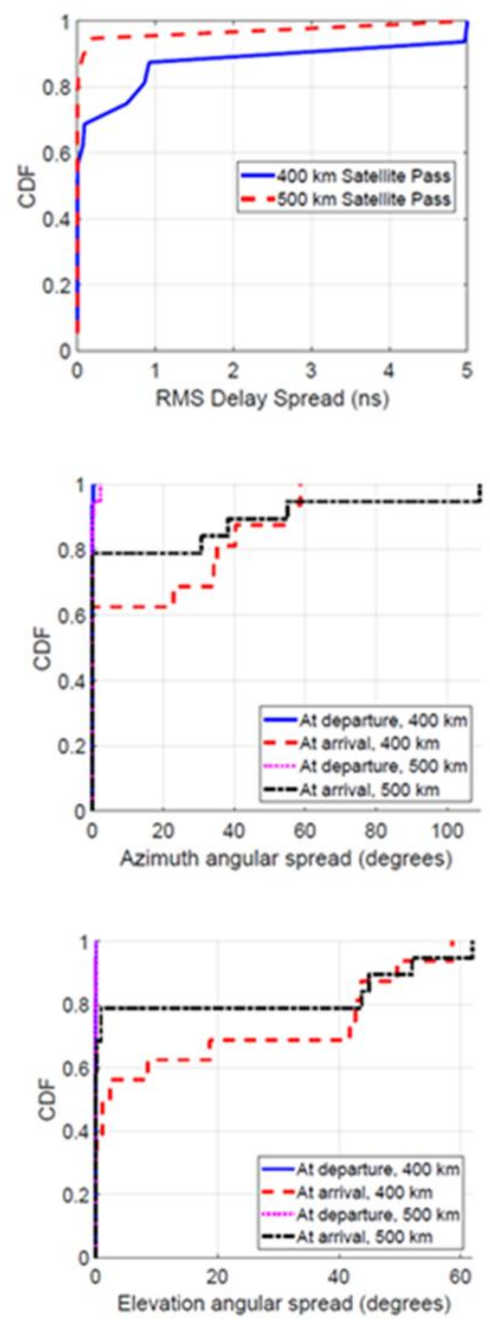


Total link attenuation for a 400 km satellite pass under varying weather conditions compared with 3GPP NTN model and FSPL.



Total link attenuation for a 400 km satellite pass and antenna misalignment (0°, 1°, 3°) for single-antenna and phased array.

Results (Cont.)



MPC delay and angular spreads (azimuth and elevation) vs. satellite elevation for 400 km and 500 km passes.

400 km Satellite Pass				500 km Satellite Pass			
Elev. (km)	# of MPCs	K-factor	# of clust.	Elev. (km)	# of MPCs	K-factor	# of clust.
0.005	2	0.007	0	0.005	2	0.005	0
0.5	3	0.11	1	0.5	2	0.087	0
5	2	2.26	0	10	2	0.77	0
50	2	52.94	0	75	1	–	0
136	2	210.36	0	150	1	–	0
264	4	53.50	1	250	1	–	0
330	3	168.73	1	330	2	158.53	0
371	3	82.21	1	400	2	142.79	0
–	–	–	–	480	2	197.02	0
–	–	–	–	500	9	119.93	2

MPC, cluster counts, and K-factor vs. satellite elevation for 400 km and 500 km passes (clear weather, aligned beams).

Conclusions and Future Work

- Significant link attenuation at low elevations due to shadowing and rain at X-band.
- GS antenna patterns and misalignment affected losses for single and phased-array setups.
- Small-scale fading modeled via single path, shadowed Rician, and Rician distributions.
- 400 km pass showed more MPCs/clusters and larger RMS delay/angular spreads than 500 km.
- **Future work:** adaptive MODCOD selection using synthetic geometries and empirical elevation-dependent link/channel statistics.

Acknowledgements

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