Electromagnetic Wave Propagation in Precipitation Media and its Applications in: Radar Remote Sensing, Earth-Satellite Links, and Terrestrial Telecommunication

Propagation des ondes EM et précipitations : Applications en télédétection Radar, Satellite et télécommunication

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Résumé / Abstract

If the propagation of electromagnetic waves in 'free-space' is taken as a standard reference, the corresponding wave propagation through precipitation filled media can experience several physical effects: wave attenuation, phase shifts exceeding the ones due to free-space propagation delay, change of polarisation state (so-called wave depolarisation), dispersion over the signal bandwidth, scintillations, and the addition of radiometric noise. These effects, in turn, are capable of significantly impairing the quality, strength, and even the character of information carrying radio signals. As one might expect, the named propagation effects are strongly dependent on the frequency of the EM-waves and the nature (hydrometeor type, particle size distribution) of the precipitation medium.

In view of the fact that link-budgeting of wireless signals is deemed to include the influence of these propagation effects and their resulting impairment, the assessment of such effects, and the constraints they set, has become a challenging issue for propagation scientists and engineers. The need to estimate or account for propagation effects in precipitation media arises in several scenarios: terrestrial microwave links, earth-satellite links, active and passive remote sensing, and, contrary to popular opinion, even in mobile communications. The inclusion of higher frequencies, well beyond 10 GHz, and higher bandwidths well into the GHz region has only exacerbated the problem. At this juncture, it is perhaps instructive to ask which types of precipitations may generate propagation effects more significantly than others. Generally, wet precipitation media, i.e. the media containing wet hydrometeors such as raindrops or wet sleet or wet hail, contribute to propagation effects far more strongly than their corresponding dry counterparts such as snowflakes, dry hail and powdery snow. As it turns out, the modelling and simulation of the various propagation effects arising from wave propagation in diverse media is a daunting task that demands an interdisciplinary mix of atmospheric physics, EM-scattering, systems engineering, and propagation science. In view of the broadness of this field and its inherent complexity, the present state-of-the-art offers maximum insight into the propagation effects due to one of the most frequent contributors: the rain medium! Fortunately (less so when you are holidaying!), rain is also one of the most prevalent wet precipitations across the globe and, therefore, for practical purposes, the most relevant medium when it comes to the estimation and assessment of propagation effects in wireless communications, remote sensing, and GNSS applications. A review of the propagation properties of rain and the signal distortions it generates will therefore constitute the main theme of this contribution. Quantitative and qualitative features of such rain induced impairments will be illustrated using real and simulated data. Also, the most established physical models of these propagation effects will be critically reviewed against the future needs. .

Briefly, the main features to be addressed in this spirit will be: signal attenuation, and precipitation-induced-phase-shifts. Both features, which underlie the various named propagation effects, will be considered in dependence of polarisation and frequency. At this stage, the reader might ask: what are the physical mechanisms that lead to such effects? The origin of signal attenuation may be found in the losses incurred by the 'travelling wave' due to absorption and scattering by raindrops. Both features can be physically accounted for by the imaginary part of the complex forward scattering amplitude of raindrops (assuming exp(jωt) harmonic time-dependence phasors). Similarly, the origin of phase shifts may be found in the real part of the complex forward scattering amplitude that ultimately leads to an increase in the refractive index of the rain medium. The fact that the complex forward scattering amplitude depends on the electrical size (measured with respect to the effective wavelength) and the dielectric constant of the raindrop accounts for the strong frequency dependence of the propagation effects in rain. Now it remains to be seen why the rain media is capable of generating polarisation dependent attenuation, phase shifts and depolarisation. The root cause of these unique features lies in the scattering anisotropy of raindrops that have non-spherical shapes. Contrary to the popular belief that raindrops have a 'tear drop' shape, the true shape of raindrops is more like oblate spheroids with their minor axis parallel to the gravity vector. This shape anisotropy and overall alignment of rain hydrometeors leads to different values of refractive indices along the horizontal and vertical polarisations. It is worth noting that this anisotropy of rain media only came to light with the advent of microwave links and weather radars! A noteworthy application of this polarisation dependence is the assessment of co-to-cross-polar-discrimination in polarisation diversity systems.

At this stage, the reader might ask: what are the typical magnitudes of such propagation effects in rain? Not unexpectedly, the magnitudes of propagation effects depend not only on the frequency and the complex dielectric constant of the raindrops but also on the so-called raindrop-size-distribution function. This elusive quantity poses a major challenge in the field of radar and radio meteorology. Keeping these factors in mind, qualitatively it may be stated that rain attenuation is capable of leading to a total fall-out of earth-satellite and terrestrial links. In remote sensing, however, an entire sensor-data-take, for example, a SAR image may be rendered unusable. A detailed quantitative treatment of these effects will be a subject of the presentation and the full paper. Nevertheless, in this regard, we can afford the reader a brief glimpse on the matter with the help of the following table.

Rainrate	**Specific Attenuation [dB/km]**		
[mm/hr]	**L-Band**	**C-Band**	**X-Band**
2.5	< 0.001	< 0.01	0.05
0.5	< 0.001	0.05	0.3
20	< 0.01	0.2	2.0
150	0.1	1.0	6.0

Table 1: Rain Attenuation (dB/km) in dependence of frequency bands and rainrate

A detailed discussion will acquaint the reader with the corresponding properties at higher frequencies. Also, examples of phase shifts, attenuation and polarisation dependent behaviour of wave propagation in rain will be illustrated with measurements made by weather radars. This feature will also bring into fore the nearly forgotten application of weather radars, namely, their function as a versatile tool for obtaining and estimating propagation effects in precipitation media of all kinds, not just rain. Finally, the issue of multiple scattering will raised and its importance in generating radiometric noise and cross-polar power will be elucidated.

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