Journal of Environmental and Engineering Geophysics

March 2020
Volume 25
Issue 1
pp. 153–160
DOI: #10.2113/JEEG19-039

Ground Penetrating Radar Attenuation Expressions in Shallow Groundwater Research

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ABSTRACT

The electromagnetic-wave attenuation coefficient determines the overall resolution and effective penetration depth of ground penetrating radar (GPR) surveys. Despite this relevance to the design of proper GPR surveys, the attenuation expressions are rarely used in the applied shallow groundwater research (SGR) literature. This work examines the status of the attenuation expressions in SGR. For this, 73 GPR case studies (in 47 papers), including some information concerning the attenuation variables and parameters, were selected to build a database. From these, 18 cases (in 10 papers) provided attenuation expressions and only 11 cases (in 4 papers) used those expressions. Two types of expressions were identified, physically based global ones that try to solve a broad (but not complete) range of environmental and field technical conditions, and non-global ones adapted for specific geological environments and resolution needed. The database analysis showed that both global and non-global expressions were used exclusively in low-loss media to report an attenuation range of 0.1–21.5 dB m^{-1} by using common antenna frequencies in the 25–900 MHz range. The range of the attenuation expressions validity in SGR is biased because no surveys in variable-loss heterogeneous media and wider antenna frequency intervals could be compiled. The attenuation database generated seeks to improve the design of GPR surveys in SGR.

INTRODUCTION

Electrical and magnetic properties of geological materials determine the propagation velocity and amplitude of the GPR signal through the subsurface (Neal, 2004; Cassidy, 2009). The exponential reduction of the signal amplitude is expressed by the attenuation coefficient (Neal, 2004; Algeo *et al.*, 2016). The penetration depth of the signal, which is usually expressed by the skin depth (Cassidy, 2009; Lowry *et al.*, 2009), is inversely related to the inherent subsurface attenuation and antenna frequency used (Bano *et al.*, 2000; Neal, 2004; Slater and Comas, 2009). Thus, attenuation determines the overall resolution and effective penetration depth of GPR surveys. Despite the relevance of attenuation to the design of proper GPR surveys (Annan, 2009), numerical expressions are often omitted in the applied SGR literature and, when reported, different expressions with varying degree of mathematical development are found sometimes omitting key approximations. The occasional use of the attenuation expressions may lead to deficient shallow groundwater characterizations in specific hydrogeological contexts.

With the aim to advance in designing proper GPR surveys in SGR, this work: (1) examines the status of attenuation expressions compiled from the applied SGR literature, and (2) shows the range of the attenuation expressions validity in SGR. For this, 73 GPR case studies (in 47 papers), including numerical expressions and additional information concerning the attenuation variables and parameters, were selected to build a database. This work does not intend to introduce new formulations, produce new data, neither to discuss the well-known GPR principles. This work is organized as follows. Section 2 briefly describes the GPR attenuation background. Section 3 presents the data compilation, classifies the attenuation expressions identified, and describes its range of validity in SGR. Section 4 presents the main conclusions.

GPR ATTENUATION BACKGROUND

Formulations describing velocity and attenuation of electromagnetic waves through the geological media have long been well established (*e.g.,* Stratton, 1941). Since GPR emerged as a suitable geophysical technique in the second half of the 20th century (*e.g.,* El-Said, 1956; Holser *et al.*, 1972; Stewart and Unterberger, 1976; Dolphin *et al.*, 1978; Davis *et al.*, 1985; Annan *et al.*, 1988; Olsson *et al.*, 1992), a need arose to determine the attenuation under common environmental and field technical conditions. A number of studies describing some of these advances are cited below.

For instance, Lorrain (1991) investigated the radio-frequency holography technique for mapping of fractures in low-conductivity media and provided an *in situ* attenuation database for different geological materials. Turner and Siggins (1994) defined attenuation *vs.* frequency linear functions to deduce the attenuation of radio-waves over typical GPR bandwidths of certain geological materials. As a generalization of the seismic Q parameter, these authors established a new constant Q^* parameter to express the stored-to-dissipated energy ratio. Bano (1996) estimated the attenuation of electromagnetic waves by introducing a frequency power-function for dielectric permittivity in the wave number, which corresponds to a constant-Q model. Xiong and Tripp (1997a,b) modelled the frequency-dependent conductivity and permittivity in the GPR frequency range to express attenuation as positive and negative functions of effective conductivity and effective permittivity, respectively. Carcione (1996) introduced numerical solutions for 2D transverse magnetic waves in order to incorporate wavefield conductivity and permittivity as functions of ground anisotropy and antenna-frequency dissipation in radio-wave modelling.

As a result of this background, the general GPR attenuation formulation has variably been simplified according to the varying electrical conductivity and dielectric permittivity of the specific geological environments and hydrogeological contexts surveyed, and the particular field technical conditions of exploration (Paz *et al.*, 2017).

DATA COMPILATION

A literary data search was conducted to examine the status of the GPR attenuation expressions in the applied SGR. The selection priority was GPR case studies that: (1) mention attenuation; (2) explore at least one-meter depth; and (3) cover enough geological environments determining different hydrogeological contexts. For this, the groundwater-related GPR database prepared by Paz *et al.* (2017) was reanalysed, some reputed technical handbooks (Daniels *et al.*, 2004; Blindow, 2009; Cassidy, 2009; Mavko *et al.*, 2009) were consulted, and several journal papers were added. Finally, 73 cases (in 47 papers), including some information concerning the variables and parameters involved in the attenuation expressions, were selected to build the database included in Table 1. In this database, 18 cases (in 10 papers) provided numerical expressions and only 11 cases (in 4 papers) used those expressions. The information gathered from the selected 73 GPR cases was catalogued according to: 1) geological environments explored; 2) field technical conditions including antenna frequency used and penetrating depth reached; and 3) attenuation variables, parameters, and expressions. This peer-reviewed information was classified into the above three classes and organized as in Table 1.

GPR Attenuation Expressions

Attenuation expressions compiled from the consulted scientific literature (Table 1) are included in Table 2. Below, the definition of physical variables and parameters of the attenuation expressions uses their dimensions instead of SI units or another units system, as in Table 3.

Two types of attenuation expressions can be identified. The first one includes dimensional, physically based global (or pseudo-global) expressions commonly expressed as (*e.g.,* Stratton, 1941; Turner and Siggins, 1994):

$$\alpha = (\mu\varepsilon')^{1/2}\omega\left[\frac{1}{2}\left(\sqrt{1+(\tan\delta)^2}-1\right)\right]^{1/2} \tag{1}$$

as reported in Daniels (2004), Bradford (2007), Cassidy (2007, 2009), and Algeo *et al.* (2016). The second includes non-global, although dimensionally correct, expressions commonly expressed as (*e.g.,* Stewart and Unterberger, 1976):

$$\alpha = (\varepsilon'_r)^{1/2}\frac{1}{c}\omega\left[\frac{1}{2}\left(\sqrt{1+(\tan\delta)^2}-1\right)\right]^{1/2} \tag{2}$$

as reported in Blindow (2009), Lowry *et al.* (2009), and Mukherjee *et al.* (2010).

The term *tan δ* is the dimensionless loss factor (Cassidy, 2009) or loss tangent (Daniels, 2004; Mavko *et al.*, 2009), which is related to the real and imaginary parts of both dielectric permittivity and electrical conductivity as:

$$\tan\delta = \frac{\sigma' + \omega\varepsilon''}{\omega\varepsilon' - \sigma''} \tag{3}$$

At low GPR frequencies, the imaginary part of the electrical conductivity becomes negligible and only the real part is considered (Cassidy, 2009) to express *tan δ* as (*e.g.,* Mavko *et al.*, 2009):

$$\tan\delta = \frac{\sigma}{\omega\varepsilon'} + \frac{\varepsilon''}{\varepsilon'} \tag{4}$$

Table 1 Database of 73 GPR case studies (included in 47 papers) selected from the consulted scientific SGR literature. Data are clustered by geological environments, field technical conditions, and attenuation variables, parameters, and expressions.

		Geological environment[a]			Field technical conditions[b]		Attenuation variables, parameters, and expressions[c]						
ID	**Site**	**GE1**	**GE2**	**GE3**	**AN**	**PD**	ε_r'	ε_r''	σ	α	**AE**	**US**	**Reference**
1	Saint-Lambert-de-Lauzon	c			100				0–14				Bélanger *et al.* (2010)
2	Canadian Forces Base Borden	c			200		6–30						Bevan *et al.* (2003)
3	MADE site, Mississippi	c			50				0–0.12				Bowling *et al.* (2005)
4	Samford Ecological Research Facility			a	200						a	n	Algeo *et al.* (2016)
5	Sottomarina, Venice Lagoon	b			400				0.67–1000				Calgaro *et al.* (2000)
6	Baharya Road	d			0.11,0.087,0.84		7.56						El-Said (1956)
7	Abu Aweigla	d			0.087,0.077		5.66						El-Said (1956)
8	Bells Creek plain	a			100		5–22.5			4.3–8.7			Ezzy *et al.* (2006)
9	Bares	b			250				0.3–3000	2.9			Gómez-Ortiz *et al.* (2009)
10	Gabes		a		1500		1–44		4–112				Lambot *et al.* (2008)
11	Allequash wetland	d			25		40.7–73.5		1.8–10		b	n	Lowry *et al.* (2009)
12	Sardon			a	200		5–27		1.25–4				Mahmoudzadeh *et al.* (2012)
13	Sardon			a	200		4–27		0.5–20				Mahmoudzadeh *et al.* (2010)
14	Lake Georgetown 1		a		50	17.5–132.3	6.3–7.6	0.07–0.6		4.6–0.6	b	y	Mukherjee *et al.* (2010)
15	Lake Georgetown 1		a		200	9.3–46.4	6.2–7.3	0.05–0.3		8.6–1.7	b	y	Mukherjee *et al.* (2010)
16	Lake Georgetown 1		a		400	4.7–23.2	6.2–7.2	0.04–0.2		17.2–3.4	b	y	Mukherjee *et al.* (2010)
17	Lake Georgetown 1		a		500	3.7–18.6	6.2–7.1	0.04–0.2		21.5–4.3	b	y	Mukherjee *et al.* (2010)
18	Lake Georgetown 2		a		50	37.3–63.8	7.1–10.3	0.4–2.3		2.2–1.2	b	y	Mukherjee *et al.* (2010)
19	Lake Georgetown 2		a		200	9.3–16.0	6.7–8.9	0.2–1.0		8.6–5.0	b	y	Mukherjee *et al.* (2010)
20	Lake Georgetown 2		a		400	4.7–7.8	6.6–8.6	0.2–0.6		17.2–10.0	b	y	Mukherjee *et al.* (2010)
21	Lake Georgetown 2		a		500	3.7–6.4	6.6–8.4	0.2–0.5		21.5–12.6	b	y	Mukherjee *et al.* (2010)
22	Horstwalde	c			100		5–35						Schmelzbach *et al.* (2011)
23	Said Abdullah shrine	d			500		7.9–8.4						Seger and Nashait (2011)
24	Altona Flat Rock		b		50,100				138–1640				Tsoflias and Becker (2008)
25	Ulaanbaatar	c			100		4–14						Nakashima *et al.* (2001)
26	Hatfield		b		100				2–10				Binley *et al.* (2002)
27	Eggborough		b		50,100				25–35				Binley *et al.* (2002)
28	Hatfield		b		100				5–20				Binley *et al.* (2001)
29	Eggborough		b		50					17.4–0.9			Cassiani and Binley (2005)
30	Boise	c			200		3–51		0.55–1.13				Clement *et al.* (2006)
31	Boise	c			250		10–16		1–10				Ernst *et al.* (2007)
32	US Department of Energy, Hanford	c			250		4–81						Kowalsky *et al.* (2005)
33	Rio Claro			a	50				11–23				Porsani *et al.* (2004)
34	Nazaré	b			270		6						Conyers *et al.* (2013)
35	Przemęt, Obra valley	c			100	6.3–8.1							Słowik (2014)
36	Przemęt, Obra valley	c			250	6.3–8.0							Słowik (2014)
37	Przemęt, Obra valley	c			500	2.3–5.2							Słowik (2014)
38	Przemęt, Obra valley	c			100	1.3–2.5							Słowik (2014)
39	Przemęt, Obra valley	c			250	0.9–2.5							Słowik (2014)
40	Przemęt, Obra valley	c			500	1.0–2.1							Słowik (2014)
41	Solec, Obra valley	c			100	2.5–4.1							Słowik (2014)
42	Solec, Obra valley	c			250	2.7–3.8							Słowik (2014)
43	Solec, Obra valley	c			500	1.5–2.1							Słowik (2014)
44	Solec, Obra valley	c			100	2.0–3.0							Słowik (2014)
45	Solec, Obra valley	c			250	1.8–2.7							Słowik (2014)
46	Solec, Obra valley	c			500	1.3–1.8							Słowik (2014)
47	Obrzańskie Lake, Obra valley	c			100	1.7–3.5							Słowik (2014)
48	Obrzańskie Lake, Obra valley	c			250	2.2–4.0							Słowik (2014)
49	Obrzańskie Lake, Obra valley	c			500	1.3–3.0							Słowik (2014)
50	Sidi Chennane			b	40		9		1.3–10				El Assel *et al.* (2011)
51	Thassos Island		a		300		6	0.01	1	0.77			Grandjean and Gourry (1996)
52	Thassos Island		a		900		6	0.01	1	1			Grandjean and Gourry (1996)
53	Altona Flat Rock site		b		100		7–80		10–1000		c	n	Talley *et al.* (2005)

Table 1 Continued.

		Geological environment[a]			Field technical conditions[b]		Attenuation variables, parameters, and expressions[c]						
ID	**Site**	**GE1**	**GE2**	**GE3**	**AN**	**PD**	ε_r'	ε_r''	σ	α	**AE**	**US**	**Reference**
54	Bissen Quarry test site, Sturgeon Bay		a		200		1–80		0.7–1				Tsoflias *et al.* (2001)
55	La Soutte test site, Vosges Mountains			a	100				0.3–30				Sailhac *et al.* (2009)
56	Fuel tank, Tuba City	c			100		2–4						Benson (1995)
57	Rock Canyon, Provo	c			100		2.5						Benson (1995)
58	Thur River field site	c			100				3–5				Doetsch *et al.* (2012)
59	Thur River	c			250		10–25		2–30				Klotzsche *et al.* (2013)
60	Krauthausen	c			200		8–24		10–40				Gueting *et al.* (2015)
61	Boise Hydrogeophysics Research Site	c			250		9–18		0.1–100				Yang *et al.* (2013)
62	Wielkie Błoto	c			250				5.2–52				Zurek *et al.* (2015)
63	nd	b			225		2.7	0.3	0.9–76	6	a	y	Cassidy (2007)
64	Opabin Moraine	c			50				0.03–1				Langston *et al.* (2011)
65	Freemont Pass, Colorado	c			900						c	n	Bradford *et al.* (2009)
66	Lionhead Mountain, Montana	c			1000		1.4–1.6	0.007–0.016			c	n	Bradford *et al.* (2009)
67	Opabin Moraine	c			50				0.01–1				Muir *et al.* (2011)
68	nd			a	120					7			Turner and Siggins (1994)
69	Victorio Peak, New Mexico		a		25		9			0.4			Dolphin *et al.* (1978)
70	Saskatchewan		c		100	20	5–6			1–0.1	c	n	Annan *et al.* (1988)
71	Cote Blanche Salt Dome		c		440	622					b	n	Stewart and Unterberger (1976)
72	Sandia/Tech VZ site, New Mexico		c		100	7–12				16.5–2.6	c	y	Chang *et al.* (2004)
73	Boise Hydrogeophysics Research Site		c		70	4.5–19	4.6		3.1	6.1–1.8	c	y	Tronicke *et al.* (2004)

[a] Categories defined as in Paz *et al.* (2017), as GE1—Pliocene to Quaternary soft porous media as: a) coastal fluvial, estuarine, and lacustrine formations; b) coastal and inland sand bars and dunes; c) inland alluvial, colluvial, and fluvio-glacial formations; and d) inland endorheic lacustrine formations including oases in drylands. GE2—Cambrian to Tertiary permeable hard sediments as: a) carbonates; b) weathered and fissured siliciclastic; and c) evaporites. GE3—Precambrian to Tertiary low-permeability rocks and sediments as: a) weathered and fissured crystalline formations; and b) weathered marls.

[b] AN—antenna centre frequency used, MHz. PD—prospecting depth, m.

[c] Original magnitude of variables and parameters of the attenuation expressions, as ε_r'—real part of the relative dielectric permittivity [–]; ε_r''— imaginary part of the relative dielectric permittivity [–]; σ— electrical conductivity [mS m^{-1}]; α—attenuation [dB m^{-1}]. AE—attenuation expressions type, as: (a) global; (b) non-global; and (c) other particular non-global adapted for specific non-magnetic and low-loss geological media. US—use of the attenuation expression on work, yes (y) or no (n).

nd—no data.

In low electrical conductivity geological media, *tan δ* can be expressed as (*e.g.,* Daniels, 2004; Cassidy, 2009):

$$\tan\delta \approx \frac{\sigma'}{\omega\varepsilon'} \tag{5}$$

and in dry and relatively low-loss geological media as (*e.g.,* Bano, 1996; Daniels, 2004):

$$\tan\delta = \frac{\varepsilon''}{\varepsilon'} \tag{6}$$

Different simplifications of non-global expressions for specific non-magnetic and low-loss geological media were identified in the consulted scientific literature (Annan *et al.*, 1988; Chang *et al.*, 2004; Tronicke *et al.*, 2004; Neal, 2004; Talley *et al.*, 2005; Bradford, 2007; Bradford *et al.*, 2009). They are considered a particular subtype of non-global expressions as in Table 2, for instance expressed for low-loss media as:

$$\alpha = \frac{\sigma}{2}\left(\frac{\mu}{\varepsilon}\right)^{1/2} \tag{7}$$

Range of the Attenuation Expressions Validity in SGR

Equations (1) and (2) differ in their first terms $(\mu\varepsilon')^{1/2}$and $(\varepsilon_r')^{1/2}/c$, respectively, while their equal second terms represent the general expression of the dimensionless loss tangent. The term $(\mu\varepsilon')^{1/2}$ relies on the absolute magnitude of variables μ and ε' while the term $(\varepsilon_r')^{1/2}/c$ relies on the relative magnitude of ε_r' and the normalization of ω by *c*. Expressions such as Eq. (1) cover a theoretically wider range of environmental and field technical conditions, whereas expressions such as Eq. (2), although dimensionally correct, are approximations that cannot be reproduc-

Table 2 Attenuation expressions compiled from the consulted scientific SGR literature for different environmental and field technical conditions of the GPR survey.

Expression [a]	Geological environment [b]	Antenna frequency, MHz	Expression type [c]	Expression was used?	Reference
$\alpha = 8.686\omega\sqrt{\frac{\mu\varepsilon'}{2}\left(\sqrt{1+(\tan\delta)^2}-1\right)}$ [d]	Coastal and inland sand dunes	225	a	yes	Cassidy (2007)
$\alpha = \omega\sqrt{\frac{\mu\varepsilon}{2}\left(\sqrt{1+\frac{\sigma^2}{\omega^2\varepsilon^2}}-1\right)}$	Weathered and fissured crystalline formation [e]	200	a	no	Algeo *et al.* (2016)
$\alpha = \frac{2\pi}{\lambda_0}\sqrt{\frac{\varepsilon'}{2\varepsilon_0}\left(\sqrt{1+\left(\frac{\varepsilon''}{\varepsilon'}\right)^2}-1\right)}$	Evaporites, salt-rock formation	440	b	no	Stewart and Unterberger (1976)
$\alpha = \frac{\omega}{c}\sqrt{\frac{\varepsilon'_r}{2}\left(\sqrt{1+\left(\frac{\sigma+\varepsilon''_r\varepsilon_0\omega}{\varepsilon'_r\varepsilon_0\omega}\right)^2}-1\right)}$	Inland endorheic lacustrine formation	25	b	no	Lowry *et al.* (2009)
$\alpha = 40\frac{\omega}{c}\sqrt{\frac{\varepsilon'_r}{2}\left(\sqrt{1+\left(\frac{\varepsilon''_r}{\varepsilon'_r}\right)^2}-1\right)}$ [f]	High-permeability carbonates	50, 200, 400, 500	b	yes	Mukherjee *et al.* (2010)
$\alpha \approx \frac{\omega\sqrt{\varepsilon}}{2c}\tan\delta$	Evaporites, salt-rock formation	100	c	no	Annan *et al.* (1988)
$\alpha \approx \frac{1}{2}\sqrt{\frac{\mu_0}{\varepsilon_0}}\frac{\sigma}{\sqrt{(\varepsilon/\varepsilon_0)}}$	Inland fluvial formation	100	c	yes	Chang *et al.* (2004)
$\alpha \approx \frac{\sigma}{2}\sqrt{\frac{\mu}{\varepsilon}}$	Inland fluvial formation	70	c	yes	Tronicke *et al.* (2004)
$\alpha \approx \frac{\sigma}{2}\left(\frac{\mu}{\varepsilon}\right)^{1/2}$	Weathered and fissured siliciclastic	100	c	no	Talley *et al.* (2005)
$\alpha \approx \left(\frac{\mu_0}{\varepsilon'}\right)^{1/2}\frac{\varepsilon''\omega}{2}$	Inland fluvio-glacial formation	900, 1000	c	no	Bradford *et al.* (2009)

[a] Notation for variables and parameters, as in Table 3.

[b] Description follows the categories defined by Paz *et al.* (2017).

[c] Expressions such as: a) global, b) non-global, and c) other particular non-global adapted for specific non-magnetic and low-loss geological media.

[d] 8.686 is the Np m^{-1} to dB m^{-1} attenuation conversion factor, as in Blindow (2009).

[e] Geological formation deduced from regional geological maps; the uppermost weathered level reaches 40% clay content.

[f] 40 is a specific dimensionless conversion factor.

Table 3 Notation, definition, and dimension for attenuation variables and parameters used.

Notation	Definition	Dimension	Equation [a]
Greek alphabet			
α	electromagnetic-wave attenuation	$[\mathrm{L}^{-1}]$	(1,2,7)
ε	dielectric permittivity of the medium	$[\mathrm{I}^2\ \mathrm{T}^4\ \mathrm{M}^{-1}\ \mathrm{L}^{-3}]$	(7)
ε'	real part of ε	$[\mathrm{I}^2\ \mathrm{T}^4\ \mathrm{M}^{-1}\ \mathrm{L}^{-3}]$	(1,3,4,5,6)
ε''	imaginary part of ε	$[\mathrm{I}^2\ \mathrm{T}^4\ \mathrm{M}^{-1}\ \mathrm{L}^{-3}]$	(3,4,6)
ε_r	relative ε	[–]	(–)
ε'_r	real part of ε_r	[–]	(2)
ε''_r	imaginary part of ε_r	[–]	(–)
ε_0	dielectric permittivity of free space	$[\mathrm{I}^2\ \mathrm{T}^4\ \mathrm{M}^{-1}\ \mathrm{L}^{-3}]$	(–)
μ	magnetic permeability	$[\mathrm{I}^{-2}\ \mathrm{T}^{-2}\ \mathrm{M}\ \mathrm{L}]$	(1,7)
μ_0	magnetic permeability of free space	$[\mathrm{I}^{-2}\ \mathrm{T}^{-2}\ \mathrm{M}\ \mathrm{L}]$	(–)
σ	electrical conductivity of the medium	$[\mathrm{I}^2\ \mathrm{T}^3\ \mathrm{M}^{-1}\ \mathrm{L}^{-3}]$	(4,7)
σ'	real part of σ	$[\mathrm{I}^2\ \mathrm{T}^3\ \mathrm{M}^{-1}\ \mathrm{L}^{-3}]$	(3,5)
σ''	imaginary part of σ	$[\mathrm{I}^2\ \mathrm{T}^3\ \mathrm{M}^{-1}\ \mathrm{L}^{-3}]$	(3)
ω	angular frequency, as $2\pi f$	$[\mathrm{T}^{-1}]$	(1,2,3,4,5)
λ_0	electromagnetic wave wavelength in free space	[L]	(–)
Latin alphabet			
c	electromagnetic wave velocity in free space	$[\mathrm{L}\ \mathrm{T}^{-1}]$	(2)
f	wave frequency	$[\mathrm{T}^{-1}]$	(–)
tan δ	loss factor or loss tangent	[–]	(1,2,3,4,5,6)

[a] (–) for intermediate variables, and for those solely described in the text and in Table 2.

ible in all environmental and field technical conditions. Expressions such as Eq. (7) are simplified non-global expressions for specific non-magnetic and low-loss geological media.

Dimensional, physically based global (or pseudo-global) expressions such as Eq. (1) were enunciated in two case studies (in two papers) surveying low-loss geological media (Cassidy, 2007; Algeo *et al.*, 2016) but just Cassidy (2007) used the expression (Table 1; Table 2). Non-global expressions such as Equation (2) were reported in ten cases (in three papers) surveying low-loss geological media (Stewart and Unterberger, 1976; Lowry *et al.*, 2009; Mukherjee *et al.*, 2010) but just Mukherjee *et al.* (2010) used the expression in eight cases. Finally, simplified non-global expressions such as Equation (7) were included in six cases (in five papers) surveying non-magnetic and low-loss geological media (Annan *et al.*, 1988; Talley *et al.*, 2005; Bradford *et al.*, 2009) but just Chang *et al.* (2004) and Tronicke *et al.* (2004) used the expressions in two cases (Table 1; Table 2). All these attenuation expressions were introduced to explore low-loss geological media by using antenna frequencies in the

50–900 MHz range (Table 1; Table 2). The specific rationale to use each expression and antenna frequency was justified only by Stewart and Unterberger (1976), Annan *et al.* (1988), and Tronicke *et al.* (2004) in three cases.

It is well known that a wide range of antenna frequencies is desirable to explore different hydrogeological processes occurring in variable-loss heterogeneous media at different spatial scales and depths. As described above, overall resolution and antenna centre frequency are inversely related. Thus, in non-magnetic and low-loss media, higher frequencies are desirable to define small-scale geometries and hydraulic behaviours in the uppermost vadose zone. Lower frequencies are advisable to define aquifer geometry and hydraulic properties in the hyporheic and saturated zones, including water-table to capillary-fringe relationships, and the freshwater-brackish water interface delineation in coastal and inland areas (Paz *et al.*, 2017). Unfortunately, the range of the attenuation expressions validity in SGR to define properly these processes is biased because no information for variable-loss heterogeneous media and wider antenna frequency intervals could be compiled from the consulted scientific literature. Only one case (ID 70 in Table 1) was addressed in a variable-loss evaporitic environment with expected high pore-water salinity, although the attenuation expression was not used. The general lack of attenuation information in SGR (only 19 experimental attenuation data could be compiled) limits further discussions on the performance of attenuation expressions under different geological environments and hydrogeological contexts.

CONCLUSIONS

This work examines the status of the GPR attenuation formulation in the applied SGR literature. This is an open research matter because: (1) most of them rely on approximations specifically formulated for specific low-loss geological media and resolution needed; and (2) the existing ones were rarely applied to characterize the experimental GPR-signal attenuation in variable-loss heterogeneous media determining key hydrogeological processes, such as high-salinity interfaces delineating available freshwater, clay-rich aquitards controlling local groundwater flow paths, organic-matter-rich deposits modifying GPR-signal attenuation, and oxide-rich interlaying altering the magnetic and electrical behaviour, among others. This work underlines the need of systematizing the attenuation data monitoring to interpret a wider (desirably complete) spectrum of hydrogeological and technical field conditions in SGR. This gap must be the subject of future experimental research. These findings together with the attenuation database generated seek to improve the design of GPR surveys in SGR.

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Acknowledgments

Research funded by the Portuguese Foundation of Science and Technology (FCT) Research Projects PTDC/CLI/72585/2006 and PTDC/AAC-AMB/104639/2008, and the Chilean FONDECYT Research Project 1161105. The first author would like to acknowledge the financial support of FCT through project UIDB/50019/2020 - IDL, and through the PhD grant SFRH/BD/75327/2010. Dr. Remke L. Van Dam from Michigan State University, Dr. Jorge Carvalho from University of Porto, and Dr. Pedro Martínez-Pagán from Technical University of Cartagena are also acknowledged for revising and improving the manuscript.