

Global research patterns on Ground Penetrating Radar (GPR)

Fabrizio Terenzio Gizzi, Giovanni Leucci

*Institute for Archaeological and Monumental Heritage - National Research Council-
C.da S.Loja, 85050 Tito Scalo (PZ), Italy; e-mail(s): f.gizzi@ibam.cnr.it, g.leucci@ibam.cnr.it*

Abstract – The paper deals with the analysis of worldwide research patterns concerning Ground Penetrating Radar (GPR) during 1995-2014. To reach the fixed aim the Thomson Reuters' Science Citation Index Expanded (SCI-EXPANDED) and the Social Sciences Citation Index (SSCI) accessed via the Web of Science Core Collection were the two bibliographic databases taken as a reference. The authors pay attention to the document typology, the publication trend and citations, the subject categories and journals, the most cited articles, the countries and the institutions involved, and the hot issues. As concerns the main research subfields involving the GPR use, they were five in the 20-years period investigated in this article. We refer to the physical-mathematical (PM), sedimentological-stratigraphical (SS), civil engineering/engineering geology/cultural heritage (CE/EG/CH), hydrological (HD), and glaciological (GL) subfields. The outcomes of this study can contribute both to get an insight into the changes made in GPR related research over the time and supply clues about the future research trends.

I. INTRODUCTION

Ground Penetrating Radar (GPR) is a relatively new geophysical technique that has seen major advances in the last decade due to the technological improvements. The history of GPR is intertwined with numerous applications of the technique. In point of fact, GPR has the most extensive set of applications of any geophysical technique. As a result, the spatial scales of applications and the diversity of instrument configurations are extensive. Both the value and the limitations of the method are better understood in the global user community.

The first large-scale application of radar was made during World War II when the British, and later the Americans, used crude but effective systems to detect reflections of radar pulses from airplanes in the sky. The word 'RADAR' was coined just prior to that time as the acronym of RADio Detection And Ranging [1].

Other applications and analysis were published after 1950. For example, we remember [2,3,4]. The first device commercially available appeared during the 1970s. It was

used on ice, different rocks and soil materials [5,6,7]. Little work was done with radar transmission in solid media until 1972 when a prototype GPR system was built by NASA and sent 17 to the moon on Apollo to study the electrical and geological properties of the crust [8]. At the end of 1970s and in the 1980s the applications of GPR increased due to the availability of technology. Experiments with GPR were reported by the Stanford Research Institute where measurements were made by [9] for archaeological applications. Other works were related to the applications on civil engineering [10] and geology fields [11]. Further, coal mine developments were reported by [12]. As regards the nuclear waste disposal problem, it was studied by [13]. Other applications of GPR, such as road investigations and utility mapping met with mixed success [14]. From these first works the number of applications and developments of GPR has increased remarkably. As a matter of fact, nowadays GPR is successfully involved in a large number of cases: road and pavement analysis, detection of voids and cavities, study of bridges and tunnels, assessment of structural health monitoring of civil buildings and cultural heritage, archaeological surveys, forensic investigations, water management analysis and so on.

Despite the importance of such geophysical technique, there are no earlier studies aimed at analyzing steadily from the statistical view point, the global scientific production concerning the georadar. Therefore, this article aims to fill this gap partly, dealing with the bibliometric analysis of the scientific production relating to the research about GPR, considering the time span of twenty years, from 1995 to 2014.

Bibliometric studies that rely on the analysis of citations, journals, keywords chosen by the authors or keyword plus, language of papers, collaboration between countries or institutions, is an approach that is being considered more and more in many discipline such as medicine, economy, chemistry, biology, engineering, geography, and earth sciences. The aim of such investigations is both to see how the research has changed over the time and get some clues about future research tendency [15,16,17,18,19].

With this in mind, the article analyses the research on georadar taking into account several aspects such as the

document typology, the publication trend and citations, the subject categories and journals, the most cited articles, the countries and institutions, the co-occurrence term network to detect the hot issues.

II. MATERIAL AND METHODS

In order to perform the bibliometric investigation, we have used the SCI-EXPANDED and SSCI citation indexes.

With the intention of pull out the suitable records from the two databases, we have considered some terms to be used to search for titles, abstracts, or keywords of the indexed papers. The search terms used have been *georadar**, *"geo radar*"*, *GPR microwave**, *GPR microwave**, *GPR radar**, *ground penetrating radar**, *ground penetration radar**, *ground probing radar**, *"surface penetrat* radar"*, *"SPR radar*"*, *surface probing radar**, *"wall radar*"*, *"wall penetrating radar*"*, *"holographic* radar"*, *ice-penetrating radar**, *radio-echo sounding**. Once the records have been selected from the two databases, they have been downloaded (May 8, 2016) as plain text including the name of the authors, the address, the title, the publication year, the author keywords and keyword plus, the abstract, the journal name, the Web of Science categories of the paper, the citations, and the references.

The articles from England, Northern Ireland, Scotland and Wales have been reclassified as derived from the United Kingdom (UK). The traditional analysis of the data such as the document typologies, the publication trend, the subject categories, the journals, the countries, the institutions has been made through the MS Excel software. As concerns the building of the term co-occurrence network, it was performed through the VOSviewer software (version 1.6.5) that builds distance-based maps (www.vosviewer.com, [20]).

III. RESULTS AND DISCUSSION

A. Document typology

The output of the search gives 3,968 total publications. Articles, including items published as proceeding papers, were the most frequent document typology with 3,802 records, amounting to about 96% of the entire collection. Considering that the articles were predominant in the entire dataset, only this type of document has been used to perform the analysis discussed in the following sections.

B. Publication trend and citations

The yearly number of articles shows a quite significant increase, from 41 in 1995 to 394 in 2014.

During the period 1995-1999 the annual number of articles was less than 100 with a yearly average of about 56. In 2000 the annual number of articles increased quite

significantly, counting 117 items against 76 of the previous year. The period 2000-2004 showed a yearly average of about 142 articles that was 215 and 347 respectively during the periods 2005-2009 and 2010-2014 (Tab.1).

Year	TP	TP(%)	IA	TA	TA/TP	SR	TR	TR/TP	TC	TC/TP
1995	41	1.1	105	113	2.8	708	803	19.6	1485	36.2
1996	47	1.2	113	124	2.6	1175	1343	28.6	1544	32.9
1997	51	1.3	138	148	2.9	1184	1288	25.3	1193	23.4
1998	66	1.7	182	205	3.1	1310	1513	22.9	1897	28.7
1999	76	2.0	250	272	3.6	1499	1734	22.8	2230	29.3
2000	117	3.1	338	384	3.3	2375	2894	24.7	3418	29.2
2001	127	3.3	375	430	3.4	2534	2977	23.4	3290	25.9
2002	124	3.3	367	422	3.4	2685	3252	26.2	3029	24.4
2003	167	4.4	492	574	3.4	3869	4588	27.5	3464	20.7
2004	177	4.7	545	616	3.5	4157	5037	28.5	3583	20.2
2005	155	4.1	478	540	3.5	3472	4021	25.9	3156	20.4
2006	208	5.5	630	729	3.5	4752	5927	28.5	3464	16.7
2007	236	6.2	721	854	3.6	5812	7291	30.9	4040	17.1
2008	224	5.9	720	847	3.8	5811	7001	31.3	3086	13.8
2009	250	6.6	832	977	3.9	6430	7861	31.4	2953	11.8
2010	282	7.4	938	1106	3.9	8008	9936	35.2	2769	9.8
2011	308	8.1	1002	1214	3.9	9057	11154	36.2	2310	7.5
2012	357	9.4	1221	1465	4.1	11561	14510	40.6	2122	5.9
2013	395	10.4	1429	1703	4.3	11576	14493	36.7	1582	4.0
2014	394	10.4	1426	1736	4.4	12955	15936	40.4	871	2.2

Table 1 Yearly outputs regarding the georadar research during the 1995-2014 period. TP= Total Publications (articles); IA=number of Individual Authors (each author is counted only once, even if they published multiple articles), TA=number of Total Authors, TA/TP=average authors per article; IR=number of Individual References; TR= number of Total References; TR/TP=average references per article; TC=Total citations at the time the data were downloaded (May 8, 2016, from WoSCC); TC/TP=average citation per article.

As regards the annual total citations (from Web of Science Core Collection), an uneven trend can be observed: the three highest values can be observed in 2007, 2004 and 2003 with 4040, 3583, and 3464 citations respectively. However, since 2008 the yearly number of citations decrease quite regularly until 871 in 2014. This fact is linked to the circumstance, as expected, that the most recent articles have had less time to be cited.

Taken on the whole, all these data indicate that the research about GPR has constantly gained importance, has become more and more complex and has involved more and more cooperation between scientists.

C. Subject categories and journals

The number of categories involved in the georadar research was not equal over the entire period, fluctuating from 20 in 1995 to the highest value of 65 in 2014. Considering the entire period, from 1995 to 2014, 104 were the ISI categories interested, about 42% of the total

groups scheduled by Web of Sciences.

In 1995-2014 articles on GPR were published in 589 journals.

Journal	TP	TP(%)
JOURNAL OF APPLIED GEOPHYSICS	313	8.2
IEEE TRANSACTIONS ON GEOSCIENCE AND REMOTE SENSING	214	5.6
GEOPHYSICS	169	4.4
NEAR SURFACE GEOPHYSICS	152	4.0
ARCHAEOLOGICAL PROSPECTION	79	2.1
WATER RESOURCES RESEARCH	78	2.1
NDT & E INTERNATIONAL	68	1.8
IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION	67	1.8
JOURNAL OF GLACIOLOGY	59	1.6
VADOSE ZONE JOURNAL	57	1.5
GEOMORPHOLOGY	56	1.5
JOURNAL OF GEOPHYSICS AND ENGINEERING	56	1.5
GEOPHYSICAL RESEARCH LETTERS	50	1.3
JOURNAL OF HYDROLOGY	48	1.3
JOURNAL OF ENVIRONMENTAL AND ENGINEERING GEOPHYSICS	46	1.2
JOURNAL OF COASTAL RESEARCH	45	1.2
MICROWAVE AND OPTICAL TECHNOLOGY LETTERS	44	1.2
SEDIMENTOLOGY	42	1.1
IEEE GEOSCIENCE AND REMOTE SENSING LETTERS	41	1.1
ENVIRONMENTAL EARTH SCIENCES ¹	40	1.0

Table 2 Twenty most significant journals that published articles in GPR research. TP=Total Publications (articles)

Analyzing the entire 20-year period, the 20 (3.4%) most productive journals published a number of articles covering about 45% of the total, so putting in evidence the importance of these journals for GPR-related research (Tab. 2). Among the 20 journals, four were those where were published about 22.3% of the total articles: *Journal of Applied Geophysics* published most of the articles (313;8.2%) followed by *IEEE Transaction on Geosciences and Remote Sensing* (214; 5.6%, 2rd), *Geophysics* with 169 items (4.4%, 3rd) and *Near Surface Geophysics*- active since 2003- (152, 4%, 4th).

D. Most cited articles

The total citation count was obtained from the Web of Sciences Core Collection, up to the time of the data analysis (May 8, 2016).

Thirty-one articles had a number of citations greater than or equal 100. The first (197) most cited article was *Vadose zone flow model parameterisation using cross-borehole radar and resistivity imaging* by [21] published in *Journal of Hydrology* (IF 2014, 3.053). The second most cited article (196) was *Shrinking thermokarst ponds and groundwater dynamics in discontinuous permafrost near Council, Alaska* by [22] published in *Permafrost and Periglacial Processes* (IF 2.119). The third most cited article was *Velocity variations and water content estimated from multi-offset, ground-penetrating radar* by [23] in *Geophysics* (IF 1.612) and was cited 189 times. The fourth (170) article was *Modeling of ground-penetrating radar for accurate characterization of subsurface electric properties* authored by [24] and published in *IEEE Transactions on Geoscience and*

Remote Sensing, the journal with the highest impact factor (IF 3.514, 2014) among the four journals that published the most cited articles. Only one of the four journals (*Permafrost and Periglacial Processes*) was not ranked among the 20 most productive journals (Tab. 2).

E. Where the publications were born: country and institution analysis

Among 3,802 articles, 28 (~1%) have no author address information and, therefore, these data have been excluded both from the analysis of the publication country and the institutional distribution of research outputs.

Eighty-six countries all around the world were involved in the GPR research in the 1995-2014 time span. Considering the most productive top 20 countries, four continents were active in the GPR-related research. Europe topped the rank with 11 countries, Asia counted 4 countries, America 3 and Oceania 2, while Africa was not ranked.

The country that held the leadership was the United States, with 1,212 records (32.1%). Among the European countries, Italy occupied the second place but significantly distant from the first, signing 384 articles (10.2%).

Organization	TP
CONSIGLIO NAZIONALE DELLE RICERCHE CNR, Italy	123
SWISS FEDERAL INSTITUTE OF TECHNOLOGY ZURICH ETH, Switzerland	122
CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE CNRS, France	111
UNIVERSITY OF CALIFORNIA SYSTEM, USA	74
FLORIDA STATE UNIVERSITY SYSTEM, USA	73
DELFT UNIVERSITY OF TECHNOLOGY, Netherlands	71
UNITED STATES DEPARTMENT OF DEFENSE, USA	64
JULICH RESEARCH CENTER, Germany	58
UNITED STATES DEPARTMENT OF ENERGY DOE, USA	56
UNITED STATES ARMY, USA	56
UNIVERSITY OF LEEDS, UK	54
BOISE STATE UNIVERSITY, USA	54
CHINESE ACADEMY OF SCIENCES, China	53
UNIVERSITY OF ILLINOIS SYSTEM, USA	51
UNIVERSITY OF CALGARY, Canada	51
OHIO STATE UNIVERSITY, USA	47
NERC NATURAL ENVIRONMENT RESEARCH COUNCIL, UK	47
UNITED STATES GEOLOGICAL SURVEY, USA	46
KU LEUVEN, Belgium	46
DUKE UNIVERSITY, USA	46

Table 3 Top 20 most productive institutions in GPR research during the 1995-2014 period. TP=Total Publications (articles).

The analysis of the institution contribution has been performed considering the affiliation of at least one author of the articles. The top 20 institutions active in the past 20 years are listed in Table 3. The table shows that as good as 10 (50%) of the top institutions active in the GPR research field were those having the seat in the USA and about 43% of the total articles were co-authored by the USA institutions. Among the leading USA institutions, the University of California (UC) System was the most prolific, with 74 articles.

As concerns the other not USA ten institutions, they were from nine countries with a clear dominance of European organizations. CNR was the most prolific

institution with 123 articles, closely followed by ETH (122) and CNRS (111).

F. Co-occurrence term network

In order to obtain information about the subfield in which the georadar was involved, we performed the analysis of the articles' title and abstract so as to build the co-occurrence word network by using the VOSviewer software.

Generally speaking, co-occurrence networks are used to give a graphic image of possible relationships between words. Word co-occurrence network are among the most common linguistic networks studied in the past due to their topological features [25]. It was proposed in the seventies to detect semantic similarity between terms [26]. In order to build a term map the VOSviewer software uses the text mining technique to identify the noun phrases from titles and/or abstracts. After that, the noun phrases are classified on the basis of a relevance score: high relevance score is assigned when terms co-occurs mainly with a limited set of other noun phrases so showing a more specific meaning in the domain under investigation. In this way, noun phrases with low relevance score are those tend to be too general and meaningless for the domain of interest and therefore, excluded by the analysis. Therefore, VOSViewer groups the high relevance noun phrases (referred as terms) together into clusters to identify possible subfield or research topics.

So as to examine our article database, we built five co-occurrence term maps: the first regards the whole time-span covered by this study (1995-2014), the other four maps concern the analysis over four 5-years time windows: 1995-1999; 2000-2004; 2005-2009 and 2010-2014. On the one hand, the first map gives a "frozen" overview of GPR structures and contents of subfields with their interdependence; on the other hand, the other maps provide information about the temporal evolution of GPR subfields, identifying their modifications over the time.

As concerns the 20-years co-occurrence map, out of the 1363 noun phrases that occur in at least 10 articles in the titles and abstracts, 818 (60%) relevant terms have been selected to be inserted in the co-occurrence map (Fig. 1). In the visualization the diameter of a circle reflects the number of publications that have the corresponding term in their title or abstract. The terms that co-occur many times (that is the number of articles in which both words occur together is high) tend to be placed close to each other in the map, so that five well shaped clusters of important size, ranging from 250 to 102 items, can be identified. Each of these clusters is marked by leading terms.

The widest red group is related to the physical-mathematical (PM) aspects of GPR data acquisition and processing and it consists mainly of single-word terms.

Prominent item are: *algorithm* (470 occurrences, ranked 1st both in the cluster/whole map), *signal* (422, 2nd/3rd), *parameter* (407, 3rd/4th), *target* (334, 4th/5th), and *function* (320, 5th/6th).

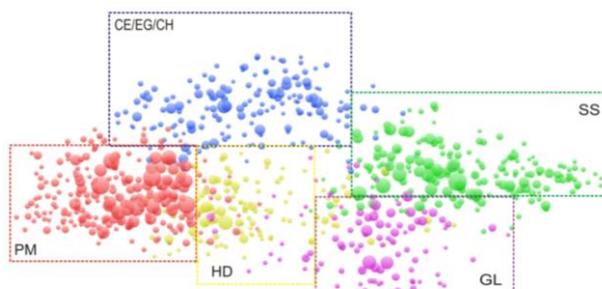


Fig. 1 Co-occurrence term network in 1995-2014 for GPR-related research. The colors show the five clusters identifying the main research subfields in which the georadar was involved. Terms are not shown due to the small size of the figure

The second green cluster shows words that mainly refer to sedimentological/stratigraphical (SS) application of GPR, such as *sediment* (467, 1st/2nd), *sand* (281, 2nd/7th), *rate* (258, 3rd/10th) and *formation* (238, 4th/13th). The third blue cluster (165) looks at the civil engineering (CE), engineering geology (EG)/cultural heritage (CH) applications of GPR such as *wall* (223, 1st/14th), *excavation* (146, 2nd/38th), *building* (118, 3rd/55th), *non destructive technique* (112, 4th/59th), *cavity* (109, 5th/63rd), and *void* (100, 6th/76th). The fourth yellow cluster, that is well linked to the red cluster so showing a close interconnection between the two subfields, has behind the hydrological (HD) research with terms such as *water content* (268, 1st/8th), *conductivity* (145, 2nd/39th), *soil moisture* (117, 3rd/57th), and *porosity* (103, 4th/68th), while the fifth purple cluster calls for glaciological (GL) studies as indicated by *ice* (216, 1st/17th), *glacier* (194, 2nd/19th), and *dynamic* (137, 3rd/43rd).

Once analyzed the term map for the whole period under investigation in this article, in order to get clues about the change of subfields over the time we built four term maps based on time windows of five-years wide.

As concerns the 1995-1999 time span, the term map shows two well separated clusters. The widest group refers mainly to the application of GPR in SS research (as the terms *sediment*, *sequence*, *sand*, *dune*, *barrier*, *internal structure*, *dip*) but it also involves HD (as the terms *groundwater*, *water level*, *water table*, *porosity*) and GL (as *antarctica*, *ice*, *glacier*, *ice thickness*) studies that saw the support of GPR. According to what will be discussed later, these research domains will receive more attention by the scientific community in the following years so as to build independent clusters. Looking at the second cluster, that involves PM aspects of GPR data

acquisition and processing, the term bunch is quite well structured and defined so highlighting that research about *model, frequency, medium, parameter, and algorithm* were the leading topics considered by the scientific community in this time-span. Therefore, the period saw research activities based on the development of models and algorithms to analyze better the electromagnetic signals [27,28]. Finite-difference time-domain numerical analysis technique and the method of moments were quite widely used for modeling computational electrodynamics and to setup algorithms for electromagnetic wave propagation in dispersive and attenuating media such as buried plastic mine target [29,30]. It is important to emphasize that in this period the evolution of the technology in the computer hardware and software allowed a significant advances both in GPR data acquisition and processing. Therefore acquisition of data on grids to make maps and grids and 3D visualization became a routine [31].

Looking at the 2000-2004 map we can see that the terms are organized in three clusters, the first of which clearly predominates on the others which have roughly equal size. A glance at the general structure of the map suggest a closer interaction between the subfields. The widest group of SS/GL studies is followed by the cluster of words representing the PM dimension. The third and emerging cluster refers to the HD studies that assume more relevance once compared with the previous five-years period so as to allow the building of an independent and quite well identified topic. Comparing the map with that of 1995-1999 it emerges that the PM set has a quite stable core terms where, however, some new items come into sight such as *synthetic aperture radar (SAR), uxo, uwb, polarization, forward model, and pml*. These items put into evidence the increase in complexity of the GPR research. As regards the HD cluster, we can note the entry of terms such as *contaminant* that indicates that GPR supported the hydrogeological studies aimed at understanding the controlling processes of contaminant distribution in the subsurface environment [32].

In 2005-2009 we find another increase in the number of clusters that become four so showing a boost in complexity of studies involving the use of GPR. The additional cluster clearly identifies a new domain made up of the civil engineering (CE), engineering geology (EG)/cultural heritage (CH) applications of GPR [33].

Finally, the 2010-2014 period also shows four clusters, each of them well-defined: PM becomes the widest group followed by the cluster of SS research, and the GL subfield that gains the role of an independent cluster. Conversely what happened for GL cluster, HD subfield diminished of importance as respect to the 2005-2009 period so as to lost its rank of independent cluster.

IV. CONCLUSION

The article has presented a synthetic overview of the

global research on ground penetrating radar during the 1995-2014 period based on SCI-EXPANDED and SSCI citation indexes.

The study has highlighted that 3,082 articles were published. Multidisciplinary geoscience was the most important subject category. As regards the journals, *Journal of Applied Geophysics* published most of the articles followed by *IEEE Transaction on Geosciences and Remote Sensing and Geophysics*. The most-cited article was *Vadose zone flow model parameterisation using cross-borehole radar and resistivity imaging* by Binley et al. (2002) published in *Journal of Hydrology*. Eighty-six countries/territories all around the world were involved in the GPR research in the 1995-2014. The most prolific institution was the Consiglio Nazionale delle Ricerche (CNR, Italy).

The main research subfields involving the GPR use were five in the 20-years period investigated in this article. We refer to the physical-mathematical (with the three most prominent terms to be *signal, parameter and target*) sedimentological-stratigraphical (*sediment, sand, and rate*) and civil engineering-engineering geology-cultural heritage (*wall, excavation, and building*), hydrological (*water content, conductivity, and soil moisture*), and glaciological (*ice, glacier, and dynamic*) subfields. The stability of the first two domains over the four 5-years time-windows suggests that the research in these fields will also engage the scientific community in the coming years. Another domain that might be a leading topic in the after years is represented by the applications of GPR in engineering geology, civil engineering, and cultural heritage fields that have had a growing importance in the last decade.

Considering the skills and the research targets that the analysis of the institutions, countries, journals and hot issues have put into evidence, the scientists can find this study cooperative in order to put together a network of co-workers to join in research activities involving the GPR use and give high visibility to their own research results. In addition, the article can also supply a support to scientists that are approaching in the GPR research area.

REFERENCES

- [1] Buder, R. 1996. *The Invention That Changed the World*. Simon & Schuster, New York.
- [2] Steenson, B.O., 1951. Radar methods for exploration of glaciers. *Pas. Cal. Inst. of Tech.*
- [3] El Said, M., 1956. Geophysical prospection of underground water in the desert by means of electromagnetic interference fringes: *Pro. I.R.E.*,44, pp. 24-30 and 940.
- [4] Waite, A.H. and Schmidt, S.J., 1961. Gross errors in height indication from pulsed radar altimeters operating over thick ice or snow, *IRE International Convention Record, Part 5* pp 38-54.

- [5] Cook, J.C., 1973. Radar exploration through rock in advance of mining: Trans. Society Mining Engineers, AIME, v. 254, pp 140-146.
- [6] Balanis, C.A., Rice, W.S., Smith N.S., 1976. Microwave measurements of coal. Radio Science 11(4), 413-418.
- [7] Cook, J.C. 1977. Borehole radar exploration in a coal seam. Geophysics 42, 1254-1257.
- [8] Conyers, L.B., 2012. Interpreting Ground-penetrating Radar for Archaeology. Left Coast Press: Walnut Creek, CA.
- [9] Dolphin, L.T., 1978. Radar Probing of Victorio Peak, New Mexico: Geophysics 43(7),1441-1448.
- [10] Morey, R.M.,1976. Detection of subsurface cavities by ground penetrating radar. Highway Geological Symposium 27: 28-30.
- [11] Annan, A.P., Davis J.L., Gendzwill D. 1988. Radar Sounding in Potash Mines: Saskatchewan, Canada. Geophysics 53, 1556-1564.
- [12] Coon, J.B., Fowler, J.C., Schafers, C.J.,1981. Experimental uses of short pulse radar in coal seams: Geophysics, 46(8), 1163-1168.
- [13] Olsson, O., Falk, L., Forslund, O. and Sandberg, E., 1987. Crosshole Investigations-Results from Borehole Radar Investigations. Stripa Project TR 87-11. SKB, Stockholm, Sweden.
- [14] Ulriksen, C.P.F., 1982. Application of impulse radar to civil engineering: Unpublished Ph.D. Thesis, Dept. of Engr. Geol., U. of Technology, Lund, Sweden, p. 175.
- [15] Chiu, W.T., Ho, Y.S., 2007. Bibliometric analysis of tsunami research. Scientometrics 73, 3-17.
- [16] Liu, X., Zhan, F.B., Hong, S., Niu, B., and Liu, Y. (2012) A bibliometric study of earthquake research: 1900-2010. Scientometrics, 92(3), 747-765. doi:10.1007/s11192-011-0599-z
- [17] Marx, Wand Bornmann L., 2013. The emergence of plate tectonics and the Kuhnian model of a paradigm shift: a bibliometric case study based on the Anna Karenina principle. Scientometrics 94 (2), 595-614. doi: 10.1007/s11192-012-0741-6.
- [18] Niu, B., Hong, S., Yuan, J., Peng, S., Wang, Z., & Zhang X., 2014. Global trends in sediment-related research in earth science during 1992-2011: A bibliometric analysis. Scientometrics 98(1). 511-529.
- [19] Gizzi, F.T., 2015. Worldwide trends in research on the San Andreas Fault System. Arabian Journal of Geosciences 8(12), 10893-10909. doi: 10.1007/s12517-015-1878-4.
- [20] Waltman, L., Van Eck, N.J., Noyons, E., 2010. A unified approach to mapping and clustering of bibliometric networks. Journal of Infometrics 4(4), 629-635.
- [21] Binley, A., Winship, P., West, L. J., Pokar, M. and Middleton, R. 2002. Seasonal variation of moisture content in unsaturated sandstone inferred from borehole radar and resistivity profiles, Journal of Hydrology, 267(3-4), 160-172
- [22] Yoshikawa, K., and Hinzman, L. D., 2003. Shrinking thermokarst ponds and groundwater dynamics in discontinuous permafrost near Council, Alaska, Permafrost Periglacial Processes, 14, 151-160.
- [23] Greaves, R. J., Lesmes, D. P., Lee, J. M. and Toksoz, M. N., 1996. Velocity variations and water content estimated from multi-offset, ground-penetrating radar, Geophysics, 61(3), 683-695.
- [24] Lambot, S., Slob, E. C., van den Bosch, I., Stockbroeckx, B., and Vanclooster, M., 2004. Modeling of ground-penetrating radar for accurate characterization of subsurface electric properties, IEEE Trans. Geosci. Remote Sens., 42, 2555-2568.
- [25] Choudhury, M., Chatterjee, D., Mukherjee, A., 2010. Global topology of word co-occurrence networks: Beyond the two-regime power-law, Proceedings of International Conference on Computational Linguistics, pp. 162-170.
- [26] Van Rijnsbergen, C.J., 1977. A theoretical basis for the use of co-occurrence data in information retrieval. Journal of Documentation 33, 106-119.
- [27] Bergmann, T., Robertsson, J.O.A., and Holliger, K., 1996. Numerical properties of staggered finite-difference solutions of Maxwell's equations for ground-penetrating radar modeling, Geophys. Res. Lett., 23, 45-48.
- [28] Roberts, RL, Daniels, JJ., 1997. Modeling near-field GPR in three dimensions using the FDTD method Geophysics, 62(4), 1114-1126.
- [29] Bergmann, T., Robertsson, J. O. A. and Holliger, K., 1998. Finite-difference modeling of electromagnetic wave propagation in dispersive and attenuating media, Geophysics, 63(3), 856-867.
- [30] Geng N., Carin L., 1999. Wide-Band Electromagnetic Scattering from a Dielectric BOR Buried in a Layered Lossy Dispersive Medium", IEEE Transactions on Antennas & Propagation, 47(4), 610-619.
- [31] Annan, A.P., Redman, J.D., Pilon, J.A., Gilson, E.W., and Johnston, G.B., 1997. Crosshole GPR for Engineering and Environmental Applications. Proceedings of the High Resolution Geophysics Workshop, University of Arizona, Tuscon, AZ, January 6-9, 1997.
- [32] Binley, A., Winship, P., West, L. J., Pokar, M. and Middleton, R. 2002. Seasonal variation of moisture content in unsaturated sandstone inferred from borehole radar and resistivity profiles, Journal of Hydrology, 267(3-4), 160-172.
- [33] Leucci, G., Negri, S., 2006. Use of ground penetrating radar to map subsurface archaeological features in an urban area. Journal of Archaeological Science, 33, 502-512