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Global Research Patterns on Ground Penetrating Radar (GPR)

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Abstract   The article deals with the analysis of worldwide research patterns concerning ground penetrating radar (GPR) during 1995–2014. To do this, the Thomson Reuters' Science Citation Index Expanded (SCI-EXPANDED) and the Social Sciences Citation Index accessed via the Web of Science Core Collection were the two bibliographic databases taken as a reference. We pay attention to the document typology and language, the publication trend and citations, the subject categories and journals, the collaborations between authors, the productivity of the authors, the most cited articles, the countries and the institutions involved, and other hot issues. Concerning the main research subfields involving GPR use, there were five, physical–mathematical, sedimentological–stratigraphical, civil engineering/engineering geology/cultural heritage, hydrological (HD), and glaciological (GL), subfields.

Keywords   Ground penetrating radar · Bibliometry · Earth sciences · Civil engineering · Cultural heritage

1 Introduction

Ground penetrating radar (GPR) is a relatively new geophysical technique that has seen major advances in the last decade due to technological improvements. The history of GPR is intertwined with numerous applications of the technique, and it now has a more extensive set of applications than any other geophysical technique. The first use of electromagnetic signals to determine the presence of metal objects was attributed to Hulsmeyer

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(1904). Six years later, a first description of the electromagnetic wave used for the location of buried objects was made in a German patent by Leimbach and Löwy (1910a, b). They used buried dipole antennas in an array of vertical boreholes and compared the magnitude of signals received when successive pairs were used to transmit and receive. Using this array, they observed a crude image of any region in which the electromagnetic radiation was absorbed (through its higher conductivity than surrounding medium). Other applications describe the use of surface antennas to detect underground ores and water deposits. The method was improved in 1926 with the development of pulsed systems (Hulsenbeck 1926) based on the detection of reflection events due to buried targets. The first attempt at what would today be called ground penetrating radar was a survey conducted in Austria in 1929 to determine the depth of ice in a glacier (Stern 1929). This pioneering work got little attention at the time but demonstrated that electromagnetic energy could be transmitted in media other than air.

The first large-scale application of radar was during World War II when the British, and later the Americans, used crude but effective systems to detect reflections of radar pulses from aircraft in the sky and from ships in the sea. The word "RADAR" was coined just prior to that time and is the acronym for RAdio Detection And Ranging (Buderi 1996). Other applications and analyses were published after 1950, for example, Steenson(1951), El Said(1956), Waite and Schmidt (1961), and Evans(1963). The first device commercially available appeared during the 1970s. It was used in studies of ice, and different rocks and soil materials (Cook 1973; Cook, 1975; Balanis et al. 1976; Lytle et al. 1976; Cook 1977). Little work was done with radar transmission in solid media until 1972 when a prototype GPR system was built by NASA and sent on Apollo 17 to the Moon to study the electrical and geological properties of the crust (Conyers 2012) (Fig. 1).

At the end of 1970s and in the 1980s, the applications of GPR increased due to the availability of new technology. Experiments with GPR were reported by the Stanford Research Institute where measurements were made by Dolphin (1978) for archeological applications. Other works were related to applications for civil engineering (Morey 1976; Caldecott et al. 1988) and geology (Annan et al. 1988). Further, coal mine developments

Fig. 1 The surface electrical properties experiment carried out on Apollo 17 used a 3-component vector receiver mounted on the lunar rover and a dual axis multi-frequency dipolar antenna laid out on the surface to sound the subsurface (from Annan 2002)

were reported by Coon et al. (1981). As regards the nuclear waste disposal problem, this was studied by Olsson et al. (1987). Other applications for GPR, such as road investigations and utility mapping, met with mixed success (Ulriksen 1982). Nowadays, GPR is successfully involved in road and pavement analysis, detection of voids and cavities, study of bridges and tunnels, assessment of actual buildings and cultural heritage, archeological surveys, forensic, water management analysis and so on (Gizzi et al. 2010; Leucci et al. 2017).

Despite the importance of this geophysical technique, there are no previous studies aimed at analyzing, from the statistical viewpoint, the global scientific results concerning GPR. Therefore, this article fills this gap partly, dealing with a bibliometric analysis of the scientific results relating to ground penetrating radar research considering the time span of 20 years, from 1995 to 2014. Bibliometric studies that rely on the analysis of 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 the Earth sciences. The aim of such investigations is both to see how the research has changed over time and to obtain some clues about future research tendencies (Garcia-Ramon and Caballé 1998; Grant et al. 2000; Chiu and Ho 2007; Liu et al. 2012; Marx and Bornmann 2013; Niu et al. 2014; Gizzi 2015).

This paper represents an extended version of a previous paper that the authors published in the proceedings of the 3rd IMEKO International Conference on Metrology for Archaeology and Cultural Heritage (Gizzi and Leucci 2017). It analyses research on GPR taking into account several aspects such as the document typology and languages, the publication trend and citations, the subject categories and journals used, the collaboration between authors, the productivity of the authors, the most cited articles, the relevant countries and institutions, the author keywords and the co-occurrence term network to detect "hot" issues. The Thomson Reuters' Science Citation Index Expanded (SCI-EXPANDED) and the Social Sciences Citation Index (SSCI) accessed via the Web of Science Core Collection (WoSCC) have been the bibliographic databases used to carry out this study. According to the Journal Citation Report (JCR), the SCI-EXPANDED database indexes 8659 journals, while SSCI considers 3154 in 2014.

2 Materials and Methods

With the intention of pulling out suitable records from the 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 penetrating radar*"*, *"SPR radar*"*, *surface probing radar**, *"wall radar*"*, *"wall penetrating radar*"*, *"holographic* radar"*, *ice-penetrating radar**, and *radio-echo sounding**. In order to avoid possible fake results, the documents in the search output have been analyzed manually each time that a new search string has been added to the previous one. Once the records had been selected from the two databases, they were downloaded (on May 8, 2016) as plain text including the names of the authors, their addresses, the title of the paper, 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 analysis of the collaboration patterns has been determined through the authors' addresses and, therefore, the phrase "single country article" has been assigned if the scientists' addresses were from the same country, while the term "internationally collaborated article" has been associated with the articles co-authored by researchers from several countries. The traditional analysis of the data (such as the document typologies, the languages, the publication trends, the subject categories, the journals, the authors, the countries, the institutions, and the keywords) has been made using MS Excel software. As concerns the journal and author bibliographic coupling, and the author and country co-authorship, the co-occurrence term network was performed using VOSviewer software (version 1.6.5) that builds distance-based maps (www.vosvi ewer.com; Waltman et al. 2010).

3 Results and Discussion

3.1 Document Typology and Languages

The output of the search gives a total of 3968 publications. Articles, including items published as proceedings papers, were the most frequent document typology with 3802 records, amounting to about 96% of the entire collection. Reviews reflected 2.4%(95) of the collected works. The other documents concerned Editorial materials (27; 0.7%), Corrections (16), Book Reviews (11), Letters (4), New Items (3), Reviews-Book chapters (3), Meeting Abstracts (2), Reprints (2), Corrections (1), Discussions (1), and Notes (1). Considering that articles were predominant in the entire dataset, only this type of document has been used to perform the analysis discussed in the following sections. The twenty-year-long period considered in our analysis spans from 1995 to 2014. An overview of the publication languages shows that English was widely predominant (3740 records, 98.4%). Another nine languages were represented in a very few documents, such as Chinese (27), French (11), German (7), Polish (6), Portuguese (4), Spanish (3), Croatian (2), Malay (1), and Rumanian (1).

3.2 Publication Trend, Citations, and Other Trends in Research Production

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, reaching 117 items against 76 in the previous year. The period 2000–2004 showed a yearly average of about 142 articles; it was 215 and 347 during the periods 2005–2009 and 2010–2014, respectively (Table 1 and Fig. 2). Concerning the annual total number of citations (from Web of Science Core Collection), an uneven trend can be observed in Fig. 2: 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 decreased quite regularly, reaching 871 in 2014. This is explained by the fact that the most recent articles have had less time to be cited.

Beyond these aspects, some other features related to the georadar-related articles have been summarized by the statistical data in Table 1. From it one can argue, for example, that the number of individual authors (each author is counted only once, even if he/she

Table 1 Yearly outputs regarding georadar research during the 1995–2014 period

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

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
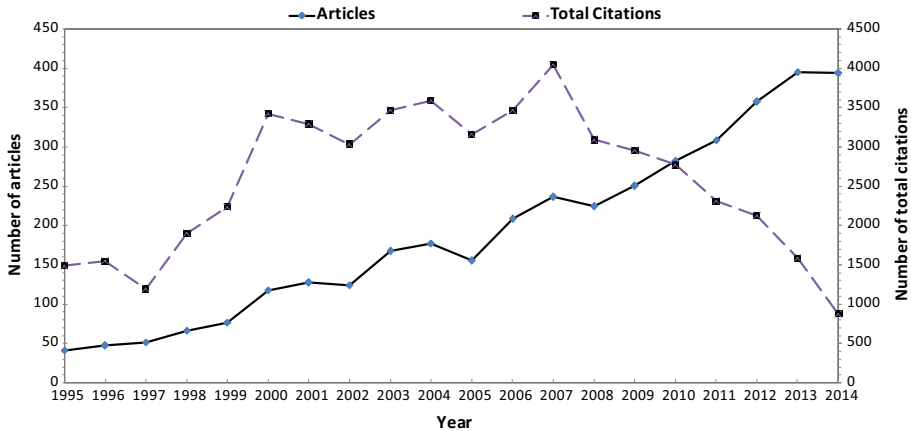

Fig. 2 Time-dependent trends of the number of articles and citations related to GPR research (data in Table 1)

published multiple articles) as well as the total number of authors involved yearly in the articles increases systematically over the entire period, reaching the values of 1429 and 1736, respectively. The same remark can be made for the average number of authors per article which grew from 2.8 at the beginning of the twenty-year period to 4.4 at the end of it. Furthermore, it can be observed that there is a quite constant increase of the number of references per article, whose mean was about 20 in 1995, and doubling in 2014. Taken on the whole, all these data indicate that research on GPR has constantly gained importance, has become more and more complex, and has involved more and more cooperation between scientists.

4 Subject Categories and Journals

The number of categories involved in georadar research varied over the entire period, fluctuating from 20 in 1995 to the highest value of 65 in 2014. Considering the entire period, 104 were the ISI categories interested, about 42% of the total groups scheduled by Web of Sciences. The significant number of categories involved depends also on the circumstance that journals where the articles are published can be assigned to multiple WoS categories. Among these, multidisciplinary geosciences was the most important (1347 records, 18.2% of the total), followed by geochemistry and geophysics (905, 12.2%), engineering electrical and electronic (639; 8.6%), physical geography (384, 5.2%), and water resources (342, 4.6%). Taken on the whole, these five groups cover about 50% of the georadar-related research articles.

Analyzing the growth trend of the five most important categories, one can see that, even if the trends indicate a general increase in the number of articles published, the scientific interest for each category has changed over time (Fig. 3). The first three groups stay predominant in almost all the period under investigation; on the other hand, physical geography and the water resources have exchanged their relative ranks several times over the
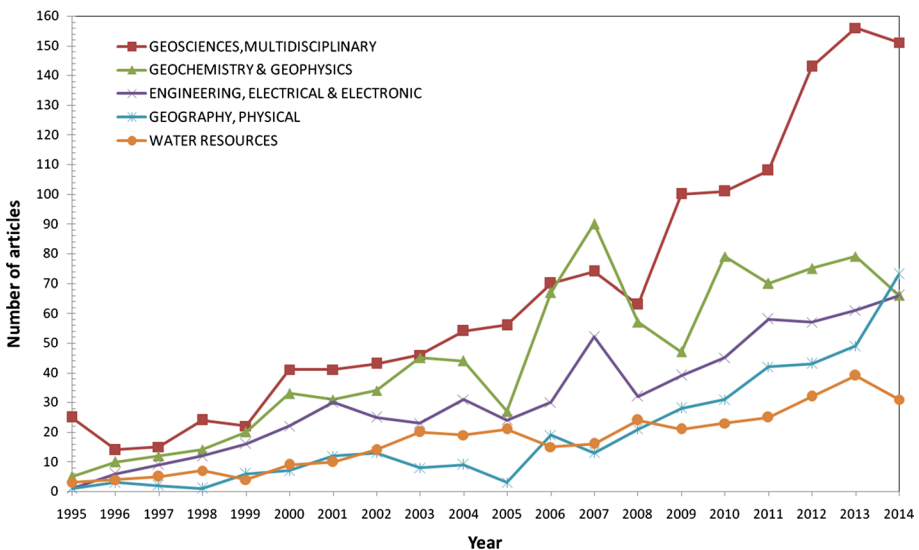

Fig. 3 Yearly significance of the first five subject categories in GPR-related research during 1995–2014

years. Furthermore, some abrupt changes in number of articles have occurred, such as the peaks recorded in engineering electrical-electronic and geochemistry and geophysics categories in 2007, and the sudden increase in the number of articles published in the multidisciplinary geosciences from 2008 onwards.

In 1995–2014, articles on GPR were published in 589 journals. The number of journals active yearly grew from 22 in 1994 to the highest number of 167 in 2014. 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 providing evidence for the importance of these journals for GPR-related research (Table 2). Among the 20 journals, there were four where about 22.3% of the total articles were published: *Journal of Applied Geophysics* published most articles (313; 8.2%), followed by *IEEE Transaction on Geosciences and Remote Sensing* (214; 5.6%), *Geophysics* with 169 items (4.4%) and *Near Surface Geophysics*- active since 2003-(152, 4%). Figure 4, that reports the annual number of publications for each of these four journals, shows that each of them recorded yearly fluctuations in the number of papers published, with several peaks that tend to converge in the same periods, such as that from 2000 to 2001 and from 2006 to 2007.

The first three most productive journals also led the percentage of total citations; on the contrary, the journals with the highest number of average citations per article were

Table 2 The twenty most significant journals that published articles in GPR research during the 1995–2014 period

Journal	TP	TP(%)	TC	TC(%)	TC/TP	IF (2014)
Journal of Applied Geophysics	313	8.2	5078	9.9	16.2	1.5
IEEE Transactions on Geoscience and Remote Sensing	214	5.6	5095	9.9	23.8	3.514
Geophysics	169	4.4	3825	7.4	22.6	1.612
Near Surface Geophysics	152	4.0	1048	2.0	6.9	1.179
Archeological Prospection	79	2.1	527	1.0	6.7	1.917
Water Resources Research	78	2.1	2852	5.5	36.6	3.549
NDT & E International	68	1.8	869	1.7	12.8	2.225
IEEE Transactions on Antennas and Propagation	67	1.8	1132	2.2	16.9	2.181
Journal of Glaciology	59	1.6	990	1.9	16.8	3.24
Vadose Zone Journal	57	1.5	942	1.8	16.5	1.778
Geomorphology	56	1.5	1006	2.0	18.0	2.785
Journal of Geophysics and Engineering	56	1.5	263	0.5	4.7	0.778
Geophysical Research Letters	50	1.3	885	1.7	17.7	4.196
Journal of Hydrology	48	1.3	1680	3.3	35.0	3.053
Journal of Environmental and Engineering Geophysics	46	1.2	284	0.6	6.2	0.629
Journal of Coastal Research	45	1.2	313	0.6	7.0	0.98
Microwave and Optical Technology Letters	44	1.2	168	0.3	3.8	0.568
Sedimentology	42	1.1	1288	2.5	30.7	2.948
IEEE Geoscience and Remote Sensing Letters	41	1.1	283	0.5	6.9	2.095
Environmental Earth Sciences[a]	40	1.0	331	0.6	8.3	1.765

TP total publications (articles), *TC* total citations at the time the data were downloaded (May 8, 2016, from WoSCC), *TC/TP* average citation per article, *IF* 2014 ISI impact factor

[a]Considering that this Journal was published as Environmental Geology before Volume 59, issue 1, the data related to two journals were summed and reported in the table
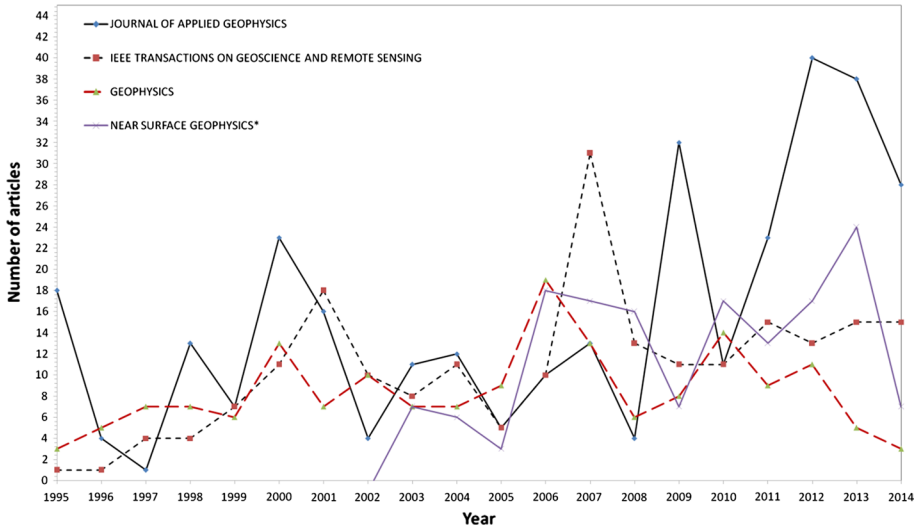
Fig. 4 Number of articles published yearly by the four top journals active in publish GPR-related research during 1995–2014

not ranked among the first three most productive or cited documents: *Water Resources Research* held the highest number (36.6) followed by *Journal of Hydrology* (35.0) and *Sedimentology* (30.7). However, among the first three most productive journals, articles published in *IEEE Transaction on Geosciences and Remote Sensing* and *Geophysics* have received, on average, 23.2 citations per article, indicating that GPR research papers published in these journals have had a high influence on this field.

For the most 20 productive journals, we have performed the bibliographic coupling by VOSviewer software to perform GPR research computer-aided subfield analysis. Bibliographic coupling was first introduced by Kessler (1963) to describe the topical similarity between two papers. Two papers are coupled bibliographically if there is a third paper that is cited by both publications: this means that bibliographic coupling looks at the overlap in the references sections of papers. The larger the number of common references between two papers, the more intellectually related are the articles. Even though bibliographic coupling was initially planned to find articles having similar research perspectives, the approach can also be extended and referred to, for example, journals as well as authors. As a matter of fact, using the references cited by the articles published by two journals, it is possible to gain information about their similarity (Small and Koenig 1977). For example, journal bibliographic coupling was used to know the educational research performance of Taiwan and to evaluate the subfield characteristics (Tseng et al. 2013).

Figure 5 shows the bibliographic coupling between the most 20 influential journals. Each source is identified by a circle size that is directly proportional to the number of articles a specific source published. In general, the distance between each circle shows how strong the relationship with the other journal is—the shorter the distance, the stronger the connection. Furthermore, the scientific sources are grouped into four color-identified clusters, each of them identifying a set of sources that is relatively strongly connected to each other, so providing evidence that journals belonging to the same cluster deal with comparable topics. The clusters have sizes ranging from 3 to 9 journals. The widest red
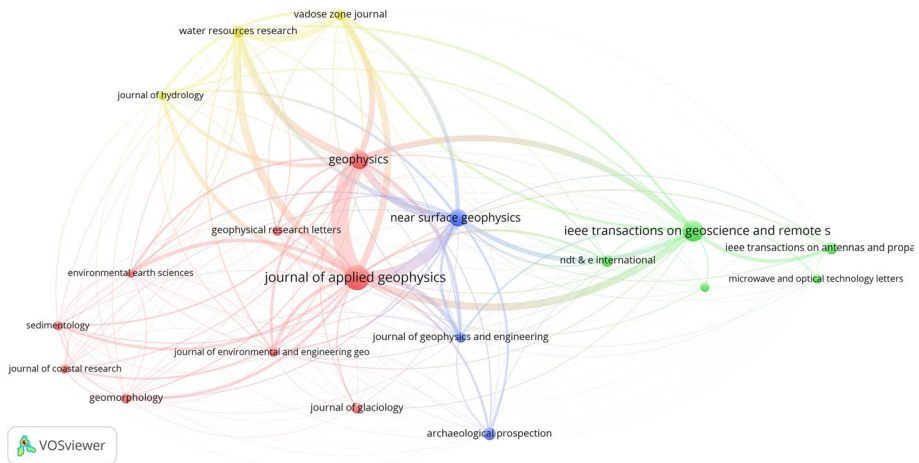
Fig. 5 Bibliographic coupling of the top 20 journals

cluster includes journals that published mainly articles on sedimentology, geomorphology, hydrology, glaciology, and engineering (geology and civil). The green cluster on the right of the network refers to journals that published articles on glaciology and engineering. The two three-journal-based yellow clusters reflect hydrology studies, engineering geology, and civil researches as well as applications of GPR in archeological research.

5 Productivity of Authors

The number of individual authors involved in GPR-related research was 7862 and the average of the collaboration index, that is the number of authors for article, was 3.8 in the overall time span considered. The number of individual authors and total authors increased from 105 and 113, in 1995, up to 1426 and 1736, in 2014, respectively. However, this analysis could be influenced by problems affecting the authorship; two or more authors may have the same name or may use more than one name to sign their own articles (Tang and Walsh 2010).

The most productive authors were *Soldovieri F* of the Italian National Research Council with 61 articles, followed by *Lambot S* of the Université Catholique de Louvain, Belgium, with 50 and a group of three authors (*Green AG*, ETH Zurich, Switzerland, *Van der Kruck J*, Forschungszentrum Jülich, Germany and *Vereecken H,* Forschungszentrum Jülich, Germany) with 39 articles (Table 3). Other authors followed with a number of articles that gradually tends to 23, the twentieth position. Most of these researchers collaborated with two or more authors, and so very few were articles with only one author (17). *Soldovieri F* involved the highest number of individual and total authors, with a mean number of authors per article equal to 4.6, as well as the highest number of journals (25) and countries (16) in co-authorship. *Green AG*, *Lambot S*, *Holliger K* (University of Lausanne, Switzerland), and *Vereecken H* were ranked among the authors that included the highest number of references in their own articles, which probably indicates the complexity of their research.

For this group of top 20 scientists, we performed the author bibliographic coupling. The author bibliographic coupling, introduced by Zhao and Strotmann (2008), arises from

Table 3 Top 20 most productive authors in GPR research during the 1995–2014 period

Author	TP	TP(%)	SA	IA	TA	TA/TP	SR	TR	TR/TP	Journals (no)	Country (no)	First article year	Last article year
Soldovieri F	61	1.6	0	107	283	4.6	897	1479	24.2	25	16	2003	2014
Lambot S	50	1.3	0	64	236	4.7	1052	2113	42.3	16	8	2004	2014
Green AG	39	1.0	0	66	179	4.6	1031	1463	37.5	13	10	1999	2014
Van der Kruk J	39	1.0	2	70	175	4.5	1020	1586	40.7	14	10	1998	2014
Vereecken H	39	1.0	0	71	219	5.6	1245	2071	53.1	11	12	2006	2014
Holliger K	37	1.0	0	36	127	3.4	698	1374	37.1	12	5	1996	2013
Persico R	33	0.9	2	49	134	4.1	494	812	24.6	16	3	2002	2014
Al-Qadi IL	30	0.8	0	33	102	3.4	314	476	15.9	15	4	1997	2014
Leucci G	30	0.8	5	33	98	3.3	639	901	30.0	12	1	2002	2014
McMechan GA	29	0.8	0	39	110	3.8	802	1157	39.9	8	4	1995	2014
Lorenzo H	28	0.7	0	36	128	4.6	572	740	26.4	23	3	2001	2014
Sato M	27	0.7	0	47	93	3.4	562	675	25.0	14	7	1997	2014
Tronicke J	27	0.7	1	41	89	3.3	766	1119	41.4	10	5	1999	2014
Pettinelli E	25	0.7	0	67	162	6.5	546	712	28.5	13	4	1995	2014
Solla M	24	0.6	0	32	108	4.5	469	657	27.4	15	3	2010	2014
Binley A	23	0.6	0	64	125	5.4	728	1048	45.6	11	9	2001	2014
Endres AL	23	0.6	0	50	93	4.0	568	787	34.2	16	6	2000	2013
Bradford JH	22	0.6	3	30	95	4.3	499	743	33.8	10	4	2005	2013
Cassidy NJ	22	0.6	4	48	85	3.9	776	980	44.5	14	5	2007	2013
Eisen O	23	0.6	0	47	108	4.7	555	824	35.8	12	9	2002	2014

TP total publications (articles), *SA* single-authored 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 per article, *TR* number of total references, *TR/TP* average references per article

the bibliographic coupling concept and shows that two authors with more common references have more comparable research interests. Figure 6 shows the bibliographic coupling between the top 20 most productive authors. The node size is directly proportional to the number of the articles of an author, the color represents the membership cluster, and the distance between each circle shows how strong the relationship with the other scientist is—in general the shorter the distance, the higher the connection based on bibliographic coupling. In other words, scientists that are located close to each other tend to cite the same publications; on the contrary, authors that are located far away from their pair tend to cite different papers. Figure 6 also reports the lines between nodes: the stronger the bibliographic coupling between two authors is, the thicker is the line. The network shows that the researchers are grouped into three clusters (the VOSviewer's default clustering resolution equal to 1.00 was adopted) where the researchers are relatively strongly related to each other and treated quite similar subjects. Each cluster has a number of authors that ranges from 4 to 9; the widest red cluster includes authors that published articles in physical–mathematical aspects of GPR data processing, archeological prospection, engineering geology, and civil engineering fields, the last involving GPR applications on buildings and civil structures as well as on cultural heritage. The second green cluster, made up of 7 authors, includes authors that were active in sedimentology, hydrological, glaciological, and active tectonic fields. The blue, smallest, cluster, made up of 4 authors involves scientists active mainly on hydrological researches and physical–mathematical aspects of GPR data processing.

Figure 7 shows the co-authorship of authors related to the top 20 most productive researchers. Not all these scientists collaborated with each other, so that the collaboration network is made up of only 16 authors. Four are clusters having a size ranging from 3 to 5. The figure shows well the difference between the bibliographic coupling and the co-authorship network. The authors included in a specific co-authorship cluster can be part of
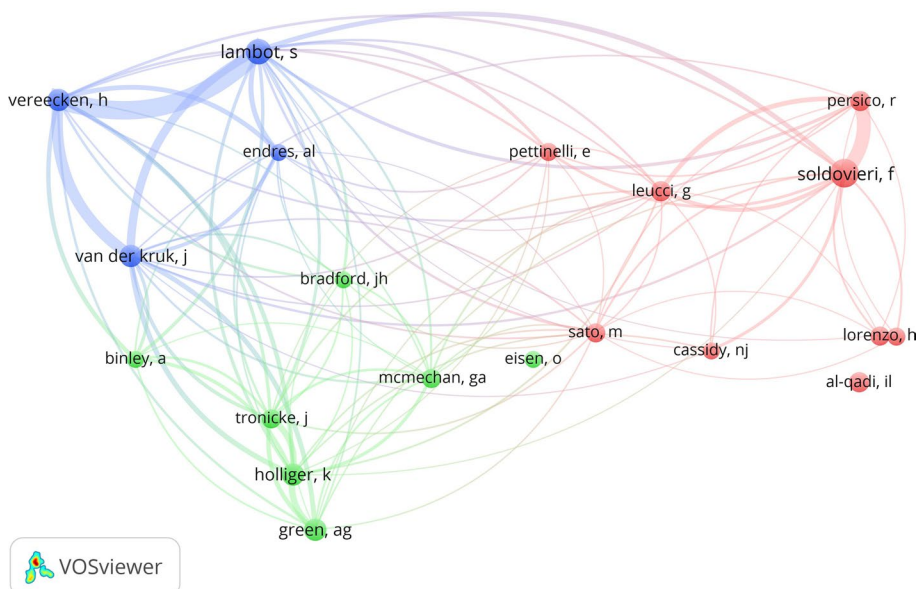

Fig. 6 Bibliographic coupling between the top 20 most productive authors
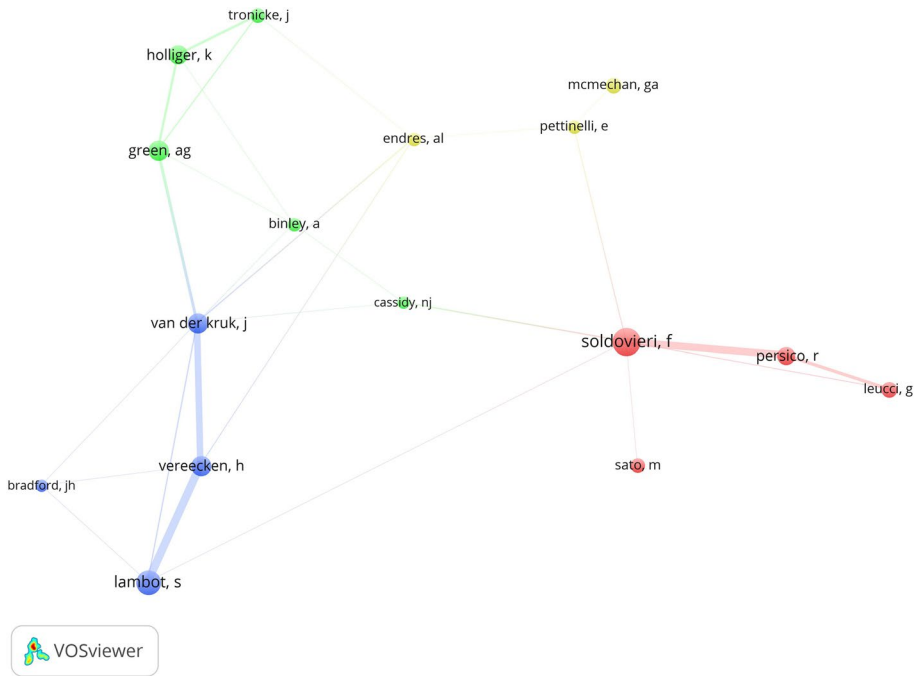
Fig. 7 Co-authorship between the top 20 most productive authors. Sixteen were the scientists that collaborated to each other in co-signing the articles

a wider cluster of bibliographic coupling that, therefore, can include scientists who are part of other co-authorship clusters. For example *Green AG* and *Soldovieri F* are part of two co-authorship clusters made up of 4 authors each. Conversely, the same authors are part of two wider author bibliographic coupling clusters, made up of 7 and 9 scientists, respectively.

6 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). The first most cited (197) article was *Vadose zone flow model parameterisation using cross-borehole radar and resistivity imaging* by Binley et al. (2002), published in Journal of Hydrology (Impact Factor, IF 2014, 3.053). The second most cited article (196) was *Shrinking thermokarst ponds and groundwater dynamics in discontinuous permafrost near Council, Alaska* by Yoshikawa and Hinzman (2003) 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 Greaves et al. (1996) in Geophysics (IF 1.612) which was cited 189 times. The fourth (170) article was *Modeling of ground-penetrating radar for accurate characterization of subsurface electric properties* authored by Lambot et al. (2004) and published in IEEE Transactions on Geoscience and Remote Sensing, the journal with the highest impact factor (IF 3.514) 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 twenty most productive journals (Table 2).

7 Where the Publications were Born: Country and Institution Analysis

Among 3802 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. Taking into consideration the most productive top 20 countries (Table 4), one can see that four continents were active in 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 USA, with 1212 records (32.1%). Italy occupied the second place but was significantly distant from the first, with 384 articles (10.2%). Paying attention to the other countries that authored 200 articles at least, we find the UK (353, 9.4%), Germany (331,8.8%), China (276,7.3%), Canada (269, 7.1%), and France (249,6.6%). Belgium held the highest percentage (78.6%) of international collaborative articles. Also New Zealand had a high percentage of collaborative papers (73.2%). Conversely, the countries with the lowest rate were Turkey and India, with 22.2% and 11.3% of articles co-authored with scientists from other countries.

Table 4 Top 20 most productive countries in GPR research during the 1995–2014 period

Country	TP	TP(%)	SCA	SCA(%)	ICA	ICA(%)
USA	1212	32.1	799	65.9	413	34.1
Italy	384	10.2	262	68.2	122	31.8
UK	353	9.4	167	47.3	186	52.7
Germany	331	8.8	145	43.8	186	56.2
Peoples R China	276	7.3	162	58.7	114	41.3
Canada	269	7.1	138	51.3	131	48.7
France	249	6.6	117	47.0	132	53.0
Switzerland	199	5.3	75	37.7	124	62.3
Spain	152	4.0	96	63.2	56	36.8
Japan	122	3.2	66	54.1	56	45.9
Norway	111	2.9	45	40.5	66	59.5
Netherlands	108	2.9	36	33.3	72	66.7
Belgium	98	2.6	21	21.4	77	78.6
Australia	89	2.4	33	37.1	56	62.9
Denmark	76	2.0	38	50.0	38	50.0
Turkey	72	1.9	56	77.8	16	22.2
Brazil	71	1.9	38	53.5	33	46.5
Sweden	65	1.7	30	46.2	35	53.8
India	62	1.6	55	88.7	7	11.3
New Zealand	56	1.5	15	26.8	41	73.2

TP total publication (articles), *SCA* single country article, *ICA* internationally collaborated article

The international complex collaboration network of the top 20 most productive countries is shown in Fig. 8, where the nodes identify the countries, their size the total number of articles from each country, and the line thickness the cooperation link strength between the two countries. The USA collaborated with all top-producing countries. Furthermore, the USA was the main collaborator of most of countries, such as the People's Republic of China (63), the UK (60), and Canada (51). Italy, which collaborated with other 17 countries of the network, had more cooperation with the USA (26) and the UK (24). Germany, that similarly to Italy co-authored articles with 17 top-producing nations, had Switzerland (39) as its main collaborator followed by Belgium (38) and the USA (36). All these data imply that GPR research strongly calls for teamwork between countries, with a specific reference to the USA.

The analysis of the institution contribution has been performed considering the affiliation of at least one author of the articles. In order to identify the institutions, we take advantage of the Web of Science "Organizations-Enhanced Field" search tool through which the count of articles attributed to a certain institution benefits from the filtered sum of articles considering the names variants of the organization itself. However, as declared by WoS itself, not all the organizations have been included in the list. On the whole, 2373 institutions contributed in GPR-related research.

The top 20 institutions active in the past 20 years are listed in Table 5, whose data rises from further analyses of the institutions' name variants performed by the authors of this article. The table shows that as many as 10 (50%) of the top institutions active in the GPR research field were those from the US and about 43% of the total articles were co-authored by US institutions. Among the leading American institutions, the University of California (UC) System was the most prolific, with 74 articles. Of the other ten non-US institutions, they were from nine countries, with a clear dominance of European institutions; CNR was the most prolific institution, with 123 articles, closely followed by ETH (122) and CNRS (111).
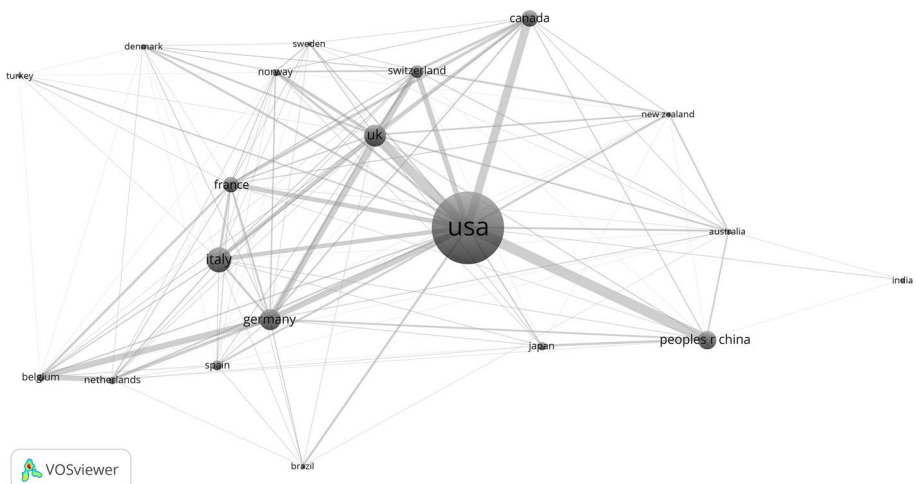

Fig. 8 Co-authorship between the top 20 most productive countries

Table 5 Top 20 most productive institutions in GPR research during the 1995–2014 period

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

TP total publications (articles)

8 Author Keywords and Co-occurrence Term Map

According to previous experiences, author keywords can help to find trends regarding a specific research field (Chiu and Ho 2007; Wang et al. 2014). Therefore, we performed an analysis of the author keywords to try to show up the most significant issues dealt with in the articles over the twenty years covered by this study. Of 3802 total articles, 2506 (65.9%) included one or more keywords; the remaining 1296 articles did not have any keywords. Most articles (735; 29.3%) had five keywords (Fig. 9).

We have identified 6550 unique author keywords, with a total of 12491 occurrences. The words that occurred only once were 5136 (78.4%), showing a lack of standardization of the terms chosen by the authors (Chuang et al. 2007). Only 101 (1.5%) keywords appeared in ten or more articles. In order to get a closer view, we selected the 30 (0.5%) most frequent keywords. These terms refer to some major "hot" issues such as physical–mathematical aspects of GPR, shown by *Finite Difference Time Domain [FDTD]* or *numerical modeling* words, or civil engineering aspects referred by, for example, *landmine detection*, *Concrete[s]*, or hydrological research highlighted by *hydrogeophysics*, *soil moisture, water content,* and archeological investigations shown by *Arch[a]eology* (Table 6).

We have also performed an 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 an image of possible relationships between words. Word co-occurrence networks, among the most common linguistic networks studied in the past due to their topological features (Choudhury et al. 2010), are used to detect
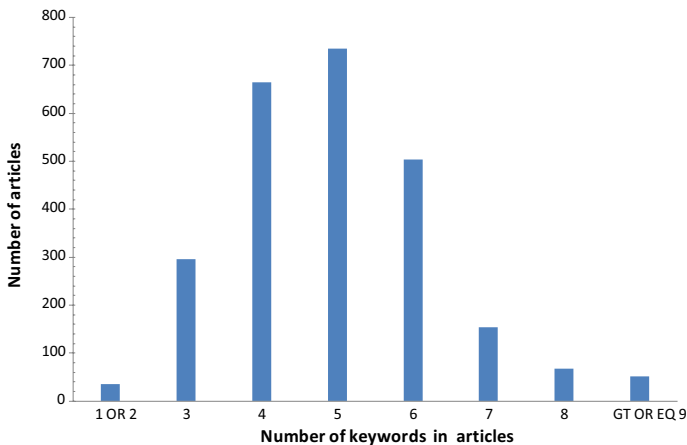
Fig. 9 Statistical distribution of the number of keywords in the articles on GPR research

semantic similarity between terms (Van Rijsbergen 1977). 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-occur 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 that tend to be too general and meaningless for the domain of interest and, therefore, are excluded from the analysis. Therefore, VOSviewer grouped the high relevance noun phrases (referred as terms) together into clusters to identify possible subfield or research topics. The default option of the software is to select the 60% most relevant terms among the noun phrase that occurred 10 times at least (Van Eck and Waltman 2011, 2014).

With the intention of building the co-occurrence term map of GPR-related research, we used the titles and abstracts to extract noun phrases as well as all the other default options proposed by VOSviewer. Furthermore, the option to insert a thesaurus text file was considered. This option is helpful in order to merge different spellings of the same term (e.g., *land mine* and *landmine*, *FDTD* and *Finite Difference Time Domain*). In addition, the option was considered also for merging different terms referring to the same concept (e.g., *archeological prospection* and *archeological prospecting*) or deleting irrelevant words (e.g., *April, introduction, paper, review*).

The software produces three typologies of maps: network visualization, overlay visualization, and density visualization. The network visualization shows the items by their label and also by a circle. For each term, the size of the term's label and the size of the term's circle depend on the weight of the term. Furthermore, the color of an item is determined by the cluster to which the item belongs. The overlay visualization is the same as the network visualization except that items are colored in a different way depending on the user choice (e.g., colors can indicate the impact factors of the journal or the age at which terms are related). The density visualization highlights the density of an item at a certain point. Density can be displayed separately for each cluster at which items belong (cluster density view) or without considering this distinction (item density view). We performed the analysis of the co-occurrence map examining comparatively the network and the density visualizations. However, for the sake of brevity and visualization we report the network

Table 6 The 30 most frequent keywords in GPR-related research

Author keywords	TP
Ground[-]penetrating radar [(GPR)]	1480
Radar	76
Geophysics	71
Electrical resistivity tomography/ERT	57
Arch[a]eology	50
Non[-]destructive testing/NDT	44
Land[]mine[s] detection	40
FDTD/finite[-]difference time[-]domain[(FDTD)]	38
Permafrost	37
Remote sensing	36
Radar imaging	33
Tomography	32
Holocene	30
Inverse scattering	30
Concrete[s]	29
Mars	29
Water content	29
Dielectric constant[s]	28
Resistivity	28
Microwave tomography	26
Hydrogeophysics	25
Buried[-]object detection	24
Stratigraphy	24
Inversion	22
Soil moisture	22
Magnetometry	20
Numerical model[l]ing	20
Fracture[s]	18
Karst	18
Migration	18

visualizations. We emphasize that due to the need for making the maps as readable as possible, each of them was adjusted considering the visualization scale and the label size in a different way. Therefore, even if circle and label size reproduce strictly the item frequency within a map, the comparison between different maps is not allowed.

In order to examine our article database, we built five co-occurrence maps: the first regards the whole time span covered by this study (1995–2014), the other four maps concern the analysis over four 5-year 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 the contents of subfields with their interdependence; on the other hand, the other maps also provide information about the temporal evolution of GPR subfields, identifying their modifications over the time. According to previous experiences (Gobster 2014), in order to assure the building of maps and clusters having a number of terms suitable to represent the article content, the VOSviewer parameters such as the minimum number of term occurrences to be included in the map and the cluster resolution were adjusted considering

that the elaborations for earlier periods rely on a database made up of a fewer number of articles (Table 7). It will be emphasized that all the different terms referring to ground-penetrating radar were grouped together under the term "GPR." Therefore, due to the low relevance score, VOSviewer excluded "GPR" from the term maps.

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 (Table 7 and Fig. 10). The diameter of a circle and the size of labels reflect the number of publications that have the corresponding term in their title or abstract. The terms that co-occur many times (i.e., 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 first both in the cluster/whole map)*, signal* (422)*, parameter* (407) *target* (334), and *function* (320). The second green cluster shows words that mainly refer to sedimentological/stratigraphical (SS) applications of GPR, such as *sediment* (467), *sand* (281), *rate* (258) and *formation* (238). The third blue cluster (165) looks at the civil engineering (CE), engineering geology (EG)/cultural heritage (CH) applications of GPR such as *wall* (223), *excavation* (146), *building* (118), *non-destructive technique* (112), *cavity* (109), and *void* (100). The fourth yellow cluster, that is well linked to the red cluster so showing a close interconnection between the two subfields, lies behind the hydrological (HD) research with terms such as *water content* (268), *conductivity* (145), *soil moisture* (117), and *porosity* (103), while the fifth purple cluster calls for glaciological (GL) studies as indicated by *ice* (216), *glacier* (194), and *dynamic* (137).

As concerns the 1995–1999 time span, the term map both in network visualization and in density visualization shows two well-separated clusters (Fig. 11). The lack of terms at the boundary between the two clusters seems to demonstrate that the connection between the two research fields was not high. Furthermore, the green cluster shows a rather scattered pattern with a weak connection between some concepts of the cluster, so that one might argue that the subfield was not yet well developed. The widest green group refers mainly to the application of GPR in SS research (terms located at the right part of the map such as *sediment*, *sequence*, *sand, dune, barrier, internal structure, stratigraphy, dip*), but it also involves HD (concepts at the center-left portion of the green cluster with *groundwater*, *water level, water table, porosity*) and GL (lower portion of the cluster with *Antarctica*, *ice*, *glacier*, *ice thickness*, and *Svalbard* terms) studies that saw the support of GPR.

The co-occurrence of SS terms shows that the coastal barrier systems were studied by a combined use of stratigraphic analysis, sedimentological investigation of borings, analysis of trenches, with the support of the georadar mapping. The barriers located in the *USA* were the main subject of these studies. This circumstance is probably due to the Coastal Barrier Resources Act (CBRA) that aims to protect coastal areas that serve as barriers against wind and tidal forces caused by coastal storms (https://www.fema.gov/media-library/assets/documents/17075, accessed April 4, 2017). However, the map also shows that stratigraphic and sedimentological studies supported by GPR applications were performed from a paleoseismological perspective, as the terms *fault* and *trench* suggest. Furthermore, the location of hydrogeological items close to the sedimentological group of terms shows that the use of GPR was also performed in order to characterize the sediments from the hydrogeological point of view (Huggenberger and Aigner 1999; Klingbeil et al. 1999). As regards the GL studies, these refer mainly to the use of GPR to measure the ice thickness

Table 7 VOSviewer parameters used to build the co-occurrence maps

Periods	N of articles	Min N term occurrence	N total terms	N terms meet threshold	N most relevant terms (60%)	Cluster resolution	N of clusters	N terms (colors) for each cluster
1995–1999	281	5	7382	210	126	0.8	2	**73**(G)/**53**(R)
2000–2004	712	7	17203	384	230	0.9	3	**92**(G)/**73**(R)/**65**(Y)
2005–2009	1073	8	25674	496	298	1.0	4	**102**(G)/**81**(R)/**64**(Y)/**49**(B)
2010–2014	1736	10	40164	637	382	1.0	4	**135**(R)/**102**(G)/**93**(B)/**52**(P)
1995–2014	3802	10	74552	1363	818	1.0	5	**250**(R)/**186**(G)/**165**(B)/**115**(Y)/**102**(P)

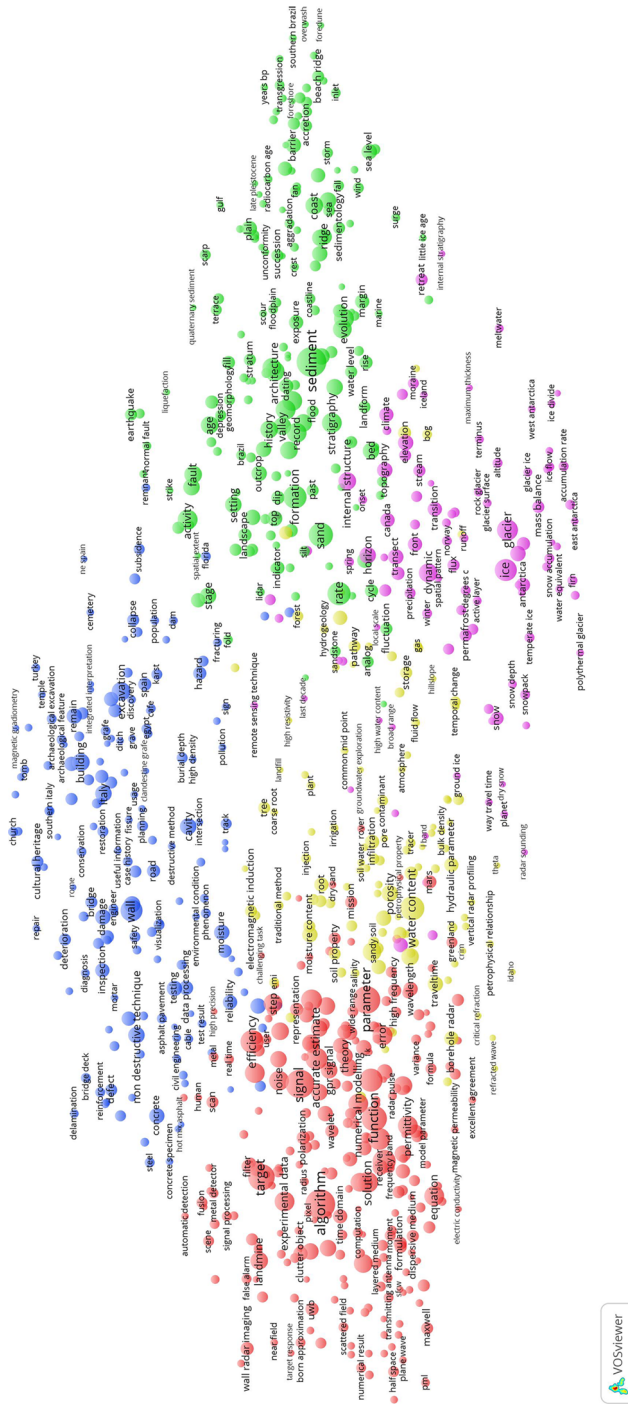*B* blue, *G* green, *R* red, *Y* yellow, *P* purple

Fig. 10 Co-occurrence term network in 1995–2014 for GPR-related research. The colors identify the five main research subfields involving the georadar use

Fig. 11 Co-occurrence term network in 1995–1999 for GPR-related research

and infer the ice bedrock topography in Antarctica and Svalbard (Arctic) (Macheret and Moskalevsky 1999; Tabacco et al. 1999). In the term map, we can also see *Mars* approximately at the same distance between the group of terms related to the GL studies and SS ones. This illustrates that the use of GPR to explore the Martian subsurface from the point of view of both determining the quantity of water believed to reside beneath the surface as ground ice and the architectures and geometries of layers of the subsurface was also considered (Barbin et al. 1995; Ori and Ogliani 1996). Looking at the red cluster, that involves PM aspects of GPR data acquisition and processing, we can note that the term bunch is quite well structured and defined so highlighting that researches 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 (Cai and McMechan 1995; Bergmann et al. 1996; Carcione 1996; Casper and Kung 1996; Roberts and Daniels 1997; Bergman et al. 1999). Finite-difference time-domain numerical analysis techniques and the method of moments were quite widely used for modeling computational electrodynamics and to set up algorithms for electromagnetic wave propagation in dispersive and attenuating media such as buried plastic mine targets (Bergmann et al. 1998; Geng and Carin 1999). It is important to emphasize that in this period, the evolution of computer hardware and software technology allowed 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 (Grasmueck 1996, Annan et al. 1997).

Looking at the 2000–2004 map, we can see that the terms are organized in three clusters, the first of which clearly predominates over the others which have roughly equal size (Fig. 12). There is a closer interaction between the subfields, the yellow and the green clusters especially. The widest green group of SS/GL studies is followed by the red cluster of words representing the PM dimension. The third and emerging yellow cluster refers to the HD studies that assume more relevance once compared with the previous five-year period so as to allow the building of an independent and quite well-identified topic. Comparing the map with that of 1995–1999, one can see that the PM set shows 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 provide evidence of the increasing complexity of GPR research. The new words refer to the use of ultrawide-band (uwb) SAR for detection of buried landmines, unexploded ordnances (uxo), and clutter objects (Sullivan et al. 2000). Furthermore, the need to have efficient forward model algorithms for GPR data simulations led to the use of perfect matched layer (pml), the artificial absorbing layer for wave equations (Teixeira and Chew 2000; Fan and Liu 2000). During this period, the activity related to the other theoretical studies continued and consolidated. They are related to inverse scattering theory and a new tool for GPR data processing (Pierri et al. 2001; Persico and Soldovieri 2004). Full 3D problems and related numerical modeling became more extensive (Gurel and Oguz 2000; Lampe and Holliger 2000) as testified by the position of the term in the core of the cluster. This ability to manage the large volumes of information in digital form and manipulate them became routine. A new technology, the Stepped Frequency GPR, was also developed in this period (Alberti et al., 2001). Furthermore, the application of GPR increases due to the development of compact ultra-wideband ground penetrating radars (Kim et al., 2004).

As concerns the green SS/GL cluster, a substantial coherence with the previous period can be noticed even if some terms such as *seismic reflection* and *electrical resistivity* seem to suggest that the SS research involved more the synergistic use of different geophysical techniques. Other words such as *climate* and *sea level* located in the lower

Fig. 12 Co-occurrence term network in 2000–2004 for GPR-related research

part of the green group referring to the GL domain seem to indicate that research involving GPR paid attention to the study of glaciers having their relationship with climate and rising sea level in mind. As regards the HD yellow 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 (Binley et al., 2002). The upper portion of the cluster (*ferron sandstone*, *east central Utah*) calls for research performed with the aim to delineate the reservoir model of the Cretaceous Ferron Sandstone reservoir, including its hydraulic properties (Novakovic et al. 2002).

In the 2005–2009 time window, we find another increase in the number of clusters that becomes four, so showing a boost in the complexity of studies involving the use of GPR (Fig. 13). Analyzing the map on the whole, one can perceive that the four clusters are quite well linked to each other, except the connection between the GL and PM domains whose relationship appears to be weaker than between the other subfields. One might conclude that the applications of PM studies orientated in developing innovative applications in GL research did not see much attention from scientists in this period. Once again the green cluster was the widest. However, it does not reveal new significant words. The second (red) group shows the same core terms but some emerging words become visible such as *wall radar imaging*, at the left side of the cluster. The third (yellow) field includes terms well referred as HD studies, in line with the trend observed for the previous 5-year time span. The last blue cluster clearly identifies a new domain made up of civil engineering (CE), engineering geology (EG) (lower-left portion of the cluster)/cultural heritage (CH) applications of GPR (Leucci and Negri 2006; Leucci et al. 2007). From a general structure point of view, on the one hand it emerges that the connection between HD and PM clusters appears to be stronger than the connection between PM and EG. On the other hand, the network map as well as the density map shows well as SS is the cluster more isolated by each other. Consequently, one might argue that the PM studies were more oriented to find technical solutions to improve the use of GPR in HD and EN fields than in the SS domain.

Finally, the 2010–2014 period also shows four clusters, each of them well defined: PM (red) becomes the widest group followed by the cluster of SS (green) research, and the GL subfield that gains the role of an independent cluster (Fig. 14). The PM group shows a stable core of terms, and no new significant terms seem to catch the eye. However, in this period developments were related to sensor, algorithm and models (Huang et al. 2010; Jadoon et al. 2010). The third (blue) group of terms expanded their importance, in CE and EG fields, especially. As a matter of fact, new terms such as *defect*, *corrosion*, *inspection*, *asphalt pavement* (in the left fringe of the cluster), *sinkhole*, *collapse*, *karst*, and *cave* (in the right fringe of the cluster), seem to indicate an increase in interest in GPR applications in these fields. Interest in CH applications was quite stable, involving both the investigation for building conservation purposes and the surveys to detect archeological remains. Purpose-built equipment for each of these applications is being developed, and the user now has a better choice of equipment and techniques (Leucci 2012; Liu and Arcone 2014; Nunez-Nieto et al. 2014; Moghadasi and Dehmollaian 2014). The group of GL studies (purple) has grown in importance so as to build a well-defined and independent cluster of numerous terms, even if the core terms have not changed much. Entering words were *precipitation*, *snow water equivalent, direct measurement*, *firn,* and *digital elevation model* (below the word "climate" in the upper-right portion of the cluster). The item *seismic refraction* was not a new term, but its shifting from the SS to the GL cluster suggests that in these years the glaciological studies saw a more integrated use of survey geophysical techniques. Conversely to what happened for the GL cluster, the HD subfield diminished in

Fig. 13 Co-occurrence term network in 2005–2009 for GPR-related research

Fig. 14 Co-occurrence term network in 2010–2014 for GPR-related research

importance with respect to the 2005–2009 period, so as to lose its rank of an independent cluster.

9 Conclusions

The article has presented an overview of the global research on ground penetrating radar during the 1995–2014.

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 followed by *Shrinking thermokarst ponds and groundwater dynamics in discontinuous permafrost near Council, Alaska* by Yoshikawa and Hinzman (2003) published in Permafrost and Periglacial Processes. Eighty-six countries/territories all around the world were involved in the GPR research. The most prolific institution was the Consiglio Nazionale delle Ricerche (CNR, Italy*),* followed closely by the Swiss Federal Institute of Technology (ETH, Switzerland).

There were five main research subfields involving GPR use. 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-year 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 future years is represented by the applications of GPR in engineering geology, civil engineering, and cultural heritage fields.

All the results and discussions must be considered to result from the analysis of the two ISI databases which do not index some journals so that some GPR articles published in those other journals are excluded from the investigations performed here.

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