Brief history of international consortium project "Seismic waves in complex 3–D structures" (SW3D)

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1. Introduction

Study of wave propagation in complex structures, especially of the ray theory and its extensions, has had a tradition at the Department of Geophysics of the Faculty of Mathematics and Physics of the Charles University since early sixties. It included organization of international meetings and development of software broadly used by the seismological community (e.g., SEIS). This lead to the suggestions of several foreign colleagues to start a consortium project focused on wave propagation.

The research project "Seismic waves in complex 3–D structures" (SW3D) of the Department of Geophysics, Faculty of Mathematics and Physics, Charles University started on October 1, 1993. The project was supported by a consortium, whose members were industrial companies, research institutions and universities. The financial support of the SW3D project terminated on April 30, 2022. Project SW3D has currently no industrial member, and continues as a voluntary research project.

2. Consortium SW3D

Foundation of a consortium used to be a very popular method of supporting universities by industrial companies. Assume that a team of researchers at a university had a research program which might be of an interest for some industrial companies. Then the team sent its research program to relevant companies and they might become the members of the consortium supporting it. The team at the university prepared a research report and organized a consortium meeting each year. For this activity, it was financially supported by the members of the consortium by a fixed yearly fee.

The consortium "Seismic waves in complex 3–D structures" (SW3D) was founded on October 1, 1993. It was probably the first consortium of this type at Czech universities. Professor Vlastislav Červený created a small research team theoretically and numerically studying wave propagation. The team built the appropriate environment and computer facilities. This resulted in the increase of both extent and efficiency of the theoretical research, and allowed us to develop the software for numerical solution of forward and inverse problems of wave propagation.

The SW3D research project focused primarily on the fundamental issues of high–frequency wave propagation in complex 3–D isotropic and anisotropic structures, which went beyond the traditional approaches. This theoretical orientation distinguished our research project from the majority of other consortia which were often focused on data processing.

In the beginning of the SW3D project, we had to build our computer facilities from scratch. The beginning of the SW3D project on October 1, 1993, roughly coincided with the beginning of the two–year European Commission project JOU2-CT92-0099 "Integrated structural imaging" which started on January 1, 1994, and whose part "Structural imaging of seismic wave fields by dynamic ray tracing" (0.1 million EUR = 3 million CZK) was awarded to Vlastislav Červený. This grant probably represented

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the largest one of the first European Commission grants in the Czech Republic. Due to this fortunate coincidence, the SW3D team was able to speed up building necessary research background.

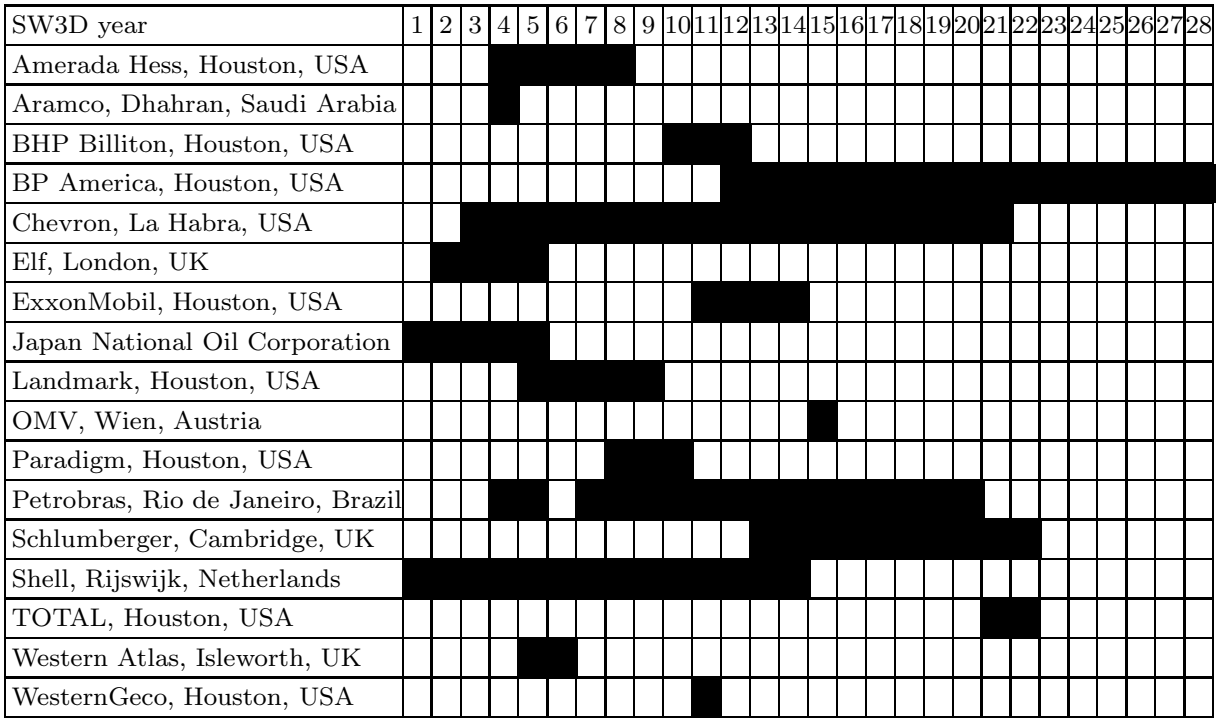
In the first three years of the SW3D project (1993–1996), we invested 3 million CZK into computer facilities. Since then, we have continuously maintained and upgraded the computer facilities. For example, we can now perform elastic 3–D ray–based Kirchhoff migrations in heterogeneous anisotropic media using our software and our computers.

During the SW3D project, we created a library focused on the theory of wave propagation containing more than 500 books.

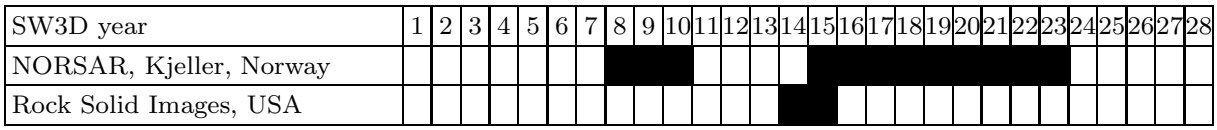
3. SW3D Members

The SW3D consortium was supported by the following organizations:

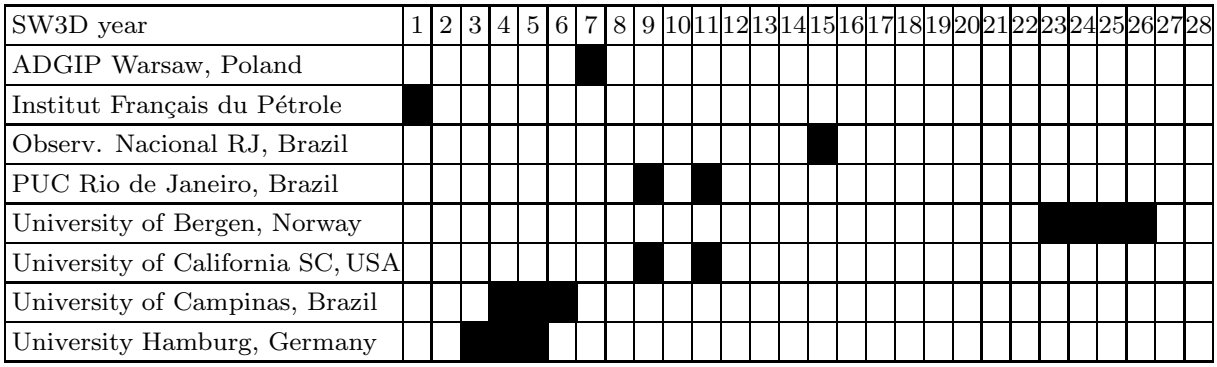
Large companies:



Medium companies:



Universities and research institutions:



The standard SW3D research year started on October 1, and terminated on September 30 next calendar year. However, some SW3D research years were slightly delayed for several SW3D members. SW3D research year 28 thus effectively terminated on April 30, 2022 rather than on September 30, 2021.

The fee for any company was specified every research year by the research agreement, signed by the company and by the dean of the faculty. The member fees of the large companies were 12 000 USD in SW3D years 1–7, 15 000 USD in SW3D years 8–10, 20 000 USD in SW3D years 11–15, and 16 000 EUR in SW3D years 16–28. The member fees of the medium companies were reduced with respect to large companies since the 14th SW3D year. The member fees of the universities or research institutions were reduced even more since the 3rd SW3D year.

The total member fees in individual research years were:

SW3D year	Members	Total member fees	Total member fees in CZK
1 (1993–1994)	3	36 000 USD	1.04 million CZK
2 (1994–1995)	3	36 000 USD	0.95 million CZK
3 (1995–1996)	5	53 000 USD	1.44 million CZK
4 (1996–1997)	9	94 000 USD	2.78 million CZK
5 (1997–1998)	10	106 000 USD	3.53 million CZK
6 (1998–1999)	6	62 500 USD	2.08 million CZK
7 (1999–2000)	6	65 000 USD	2.42 million CZK
8 (2000–2001)	7	105 000 USD	3.92 million CZK
9 (2001–2002)	8	100 000 USD	3.48 million CZK
10 (2002–2003)	6	90 000 USD	2.56 million CZK
11 (2003–2004)	8	120 000 USD	3.14 million CZK
12 (2004–2005)	6	120 000 USD	2.73 million CZK
13 (2005–2006)	6	120 000 USD	2.69 million CZK
14 (2006–2007)	7	130 000 USD	2.70 million CZK
15 (2007–2008)	8	122 500 USD	1.97 million CZK
16 (2008–2009)	5	72 000 EUR	1.93 million CZK
17 (2009–2010)	5	72 000 EUR	1.83 million CZK
18 (2010–2011)	5	72 000 EUR	1.74 million CZK
19 (2011–2012)	5	72 000 EUR	1.77 million CZK
20 (2012–2013)	5	72 000 EUR	1.81 million CZK
21 (2013–2014)	5	72 000 EUR	1.56 million CZK
22 (2014–2015)	4	56 000 EUR	1.51 million CZK
23 (2015–2016)	3	26 000 EUR	0.69 million CZK
24 (2016–2017)	2	18 000 EUR	0.46 million CZK
25 (2017–2018)	2	18 000 EUR	0.45 million CZK
26 (2018–2019)	2	18 000 EUR	0.44 million CZK
27 (2019–2020)	1	16 000 EUR	0.43 million CZK
28 (2020–2021)	1	16 000 EUR	0.41 million CZK
Total	143	1 360 000 USD + 600 000 EUR	52.48 million CZK

Of the total income of 52.5 million CZK, we paid the overheads of 9.4 million CZK to the Faculty of Mathematics and Physics of the Charles University.

4. Related projects

In the beginning of the SW3D project, our team was awarded not only the above mentioned European Commission project, but also the grant of the Elf Enterprise Caledonia, Aberdeen, UK (16700 GBP = 1 million CZK). During the SW3D project, the team was granted additional 23 projects by the European Union and the Czech government in the total amount of 36 million CZK. Since the amount of 39 million CZK received from the European Union and the Czech government roughly corresponded to the taxes which the SW3D project paid to the Czech government, the research within the SW3D project was carried out with a minimum net support from the state budget.

5. Investigators

The permanent staff of the SW3D project consisted of five researchers: Václav Bucha (responsible for system administration and numerical calculations), Petr Bulant (responsible for our software and numerical calculations), Vlastislav Červený (founder of the project and its leader in the first 19 research years, project coleader until his death on May 21, 2022, research in seismic ray theory), Luděk Klimeš (leader since the twentieth research year of the project, research in ray theory) and Ivan Pšenčík (coleader of the project, research in seismic ray theory).

The following researchers also worked within the SW3D project during its 28 years: Johana Brokešová, Leo Eisner, Jaromír Janský, Jiří Jech, Petr Jílek, Michal Kvasnička, Ctirad Matyska, Mehrdad Pakzad, Bohuslav Růžek, Jan Šílený, Václav Vavryčuk, Jiří Zahradník.

In addition to the above researchers (several of them worked within the SW3D project formerly as students), the following students also worked within the SW3D project during its 28 years: Peter Cigánik, Ellen Gomes, Leonard Martins, Stanislav Med, Ivo Opršal, Vladimír Plicka, Libor Šachl, Miłosz Wcisło, Han Xiao, Karel Žáček and Xuyao Zheng.

The SW3D team also cooperated with many researches from foreign universities, research institutions and companies. These researchers are coauthors of many papers in serial *Seismic Waves in Complex 3–D Structures*.

The SW3D team yearly organized consortium meetings attended by the representatives of the consortium members. We summarized our recent research during these meetings.

The SW3D project had more than 130 foreign visitors during its 28 years, see "http://sw3d.cz/consort/visitors.htm". Many of them visited us several times.

6. Publications

During the SW3D project, the SW3D team published more than 300 original research papers in yearly regular issues of serial *Seismic Waves in Complex 3–D Structures* (ISSN 2336–3827) established within the SW3D project. With few exceptions, the research papers are available online at "http://sw3d.cz". Note that these research papers of the serial *Seismic Waves in Complex 3–D Structures* have many citations in international journals and books.

The revised and extended versions of approximately half of these research papers have later been published in reviewed journals with impact factors.

In 2001, Vlastislav Červený published his widely cited book "Seismic Ray Theory". Three preliminary versions of this book were published in three irregular issues of serial *Seismic Waves in Complex 3–D Structures*.

We do not count our papers published in conference proceedings, which usually summarized the research described in the serial *Seismic Waves in Complex 3–D Structures*. These papers are also mostly available at "http://sw3d.cz".

The presentations at recent international meetings (since 2010) are also mostly available at "http://sw3d.cz".

7. Software

As a byproduct of our research, we continuously developed the software for calculating wave fields, which is available at "http://sw3d.cz". The SW3D software has often been referred to as the benchmark programs in the literature.

Between years 1990 and 1993, the Hypertext Markup Language (HTML) and the Hypertext Transfer Protocol (HTTP) have been designed in CERN in order to facilitate the exchange of data and computer codes. This represented an outstanding example of the importance of basic research for a real life. In 1997, we created a manual of our software in HTML. About a decade later, this approach was applied by a majority of software companies.

8. Awards

During the project, its founder Vlastislav Červený was awarded
in 1997 by the Beno Gutenberg Medal from the European Geophysical Society (EGS),
in 1999 by the Conrad Schlumberger Award from the European Association of Geoscientists & Engineers (EAGE),
in 2001 by the Ernst Mach Award from the Academy of Sciences of the Czech Republic, "for the contribution to physical sciences",
in 2002 by the Gold Commemorative Medal of the Charles University Prague, "for the outstanding work in the field of geophysics and theoretical seismology",
in 2002, simultaneously with Ivan Pšenčík, by the Commemorative Medals of the Slovak Academy of Sciences on the occasion of 100 years of seismology in Slovakia,
in 2004 by the Maurice Ewing Medal from the Society of Exploration Geophysicists (SEG).

Two of our students received the following awards for their work within the SW3D project:
Petr Bulant
in 1999 was one of the winners of the Young Physicists Poster Prize Competition at the General Conference of the European Physical Society in London, and
in 2000 received The 1999 Van Weelden Award from the European Association of Geoscientists & Engineers (EAGE) "for the contribution to the calculation of 3D travel times".
Karel Žáček
in 2001 received the Award of the Minister of Education, awarded annually to the best 5 university students in the Czech Republic, and
in 2002 the Award of Merit from the Society of Exploration Geophysicists (SEG) for the Best Student Paper presented at 2001 SEG annual meeting (title "Optimization of the shape of Gaussian beams").

9. Conclusions

Project SW3D was devoted to the development of ray theory for elastic and viscoelastic waves in heterogeneous anisotropic media, together with its extensions and modifications. Such methods play an important role in seismology, mainly in seismic prospecting for oil. The research resulted in the book "Seismic Ray Theory" and in more than 300 original research papers. The research was carried out with a minimum support from the state budget.

The developed theory is also well applicable to electromagnetic and gravitational waves. For long propagation distances in the universe, ray theory has no alternative.

Despite the end of the financial support, the team continues in its efforts to extend the applicability of theory and software developed in previous years.