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<b>TRANSMITTAL LETTER TO THE UNITED STATES DESIGNATED/ELECTED OFFICE (DO/EO/US) CONCERNING A SUBMISSION UNDER 35 U.S.C. 371</b>		Attorney Docket No. 4229.108WOUS01
		U.S. Application No. (if known, see 37 CFR 1.5)
International Application No. PCT/EP2013/066492	International Filing Date 06 August 2013	Priority Date Claimed 08 August 2012
Title of Invention METHOD FOR ENHANCING THE DETERMINATION OF A SEISMIC HORIZON		
First Named Inventor Guillaume ZINCK; Marc DONIAS; Jacques DANIEL; Olivier LAVIALLE; Sébastien GUILLON		
Applicant herewith submits to the United States Designated/Elected Office (DO/EO/US) the following items and other information.		
<p>1. <input type="checkbox"/> This is an express request to begin national examination procedures (35 U.S.C. 371(f)). NOTE: The express request under 35 U.S.C. 371(f) will not be effective unless the requirements under 35 U.S.C. 371(c)(1), (2), and (4) for payment of the basic national fee, copy of the International Application and English translation thereof (if required), and the oath or declaration of the inventor(s) have been received.</p> <p>2. <input type="checkbox"/> A copy of the International Application (35 U.S.C. 371(c)(2)) is attached hereto (not required if the International Application was previously communicated by the International Bureau or was filed in the United States Receiving Office (RO/US)).</p> <p>3. An English language translation of the International Application (35 U.S.C. 371(c)(2))</p> <p>a. <input type="checkbox"/> is attached hereto.</p> <p>b. <input type="checkbox"/> has been previously submitted under 35 U.S.C. 154(d)(4).</p> <p>4. An oath or declaration of the inventor(s) (35 U.S.C. 371(c)(4))</p> <p>a. <input type="checkbox"/> is attached.</p> <p>b. <input type="checkbox"/> was previously filed in the international phase under PCT Rule 4.17(iv).</p>		
Items 5 to 8 below concern amendments made in the international phase.		
<u>PCT Article 19 and 34 amendments</u>		
5. <input type="checkbox"/> Amendments to the claims under PCT Article 19 are attached (not required if communicated by the International Bureau) (35 U.S.C. 371(c)(3)).		
6. <input type="checkbox"/> English translation of the PCT Article 19 amendment is attached (35 U.S.C. 371(c)(3)).		
7. <input type="checkbox"/> English translation of annexes (Article 19 and/or 34 amendments only) of the International Preliminary Examination Report is attached (35 U.S.C. 371(c)(5)).		
<u>Cancellation of amendments made in the international phase</u>		
8a. <input type="checkbox"/> Do not enter the amendment made in the international phase under PCT Article 19.		
8b. <input type="checkbox"/> Do not enter the amendment made in the international phase under PCT Article 34.		
NOTE: A proper amendment made in English under Article 19 or 34 will be entered in the U.S. national phase application absent a clear instruction from applicant not to enter the amendment(s).		
The following items 9 to 17 concern a document(s) or information included.		
9. <input checked="" type="checkbox"/> An Information Disclosure Statement under 37 CFR 1.97 and 1.98.		
10. <input checked="" type="checkbox"/> A preliminary amendment.		
11. <input checked="" type="checkbox"/> An Application Data Sheet under 37 CFR 1.76		
12. <input checked="" type="checkbox"/> A substitute specification. NOTE: A substitute specification cannot include claims. See 37 CFR 1.125(b).		
13. <input type="checkbox"/> A power of attorney and/or change of address letter.		
14. <input type="checkbox"/> A computer-readable form of the sequence listing in accordance with PCT Rule 13ter.3 and 37 CFR 1.821-1.825.		
15. <input type="checkbox"/> Assignment papers (cover sheet and document(s)). Name of Assignee: _____		
16. <input type="checkbox"/> 37 CFR 3.73(c) Statement (when there is an Assignee).		

This collection of information is required by 37 CFR 1.414 and 1.491-1.492. The information is required to obtain or retain a benefit by the public, which is to file (and by the USPTO to process) an application. Confidentiality is governed by 35 U.S.C. 122 and 37 CFR 1.11 and 1.14. This collection is estimated to take 15 minutes to complete, including gathering, preparing, and submitting the completed application form to the USPTO. Time will vary depending upon the individual case. Any comments on the amount of time you require to complete this form and/or suggestions for reducing this burden should be sent to the Chief Information Officer, U.S. Patent and Trademark Office, U.S. Department of Commerce, P.O. Box 1450, Alexandria, VA 22313-1450. DO NOT SEND FEES OR COMPLETED FORMS TO THIS ADDRESS. SEND TO: Mail Stop PCT, Commissioner for Patents, P.O. Box 1450, Alexandria, VA 22313-1450.

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U.S. APPLN No. (if known - see 37 CFR 1.5)		INTERNATIONAL APPLICATION No PCT/EP2013/066492		ATTORNEY DOCKET No. 4229.108WOUS01			
17. <input checked="" type="checkbox"/> Other items or information: Front page of PCT Publication No. WO2014/1023737 A2; PCT International Search Report and PCT Written Opinion of the ISA for PCT/EP2013/066492; PCT/IB/301, PCT/IB/304, PCT/IB/308 (2), PCT/IB/311(2), PCT Request.							
The following fees have been submitted.				CALCULATIONS		PTO USE ONLY	
18. <input checked="" type="checkbox"/> Basic national fee (37 CFR 1.492(a))				\$ 280.00			
19. <input checked="" type="checkbox"/> Examination fee (37 CFR 1.492(c): If the written opinion prepared by ISA/US or the international preliminary examination report prepared by IPEA/US indicates all claims satisfy provisions of PCT Article 33(1)-(4) \$0 All other situations \$720				\$ 720.00			
20. <input checked="" type="checkbox"/> Search fee (37 CFR 1.492(b)) If the written opinion prepared by ISA/US or the international preliminary examination report prepared by IPEA/US indicates all claims satisfy provisions of PCT Article 33(1)-(4) \$0 Search fee (37 CFR 1.445(a)(2)) has been paid on the international application to the USPTO as an international Searching Authority \$120 International Search Report prepared by an ISA other than the US and provided to the Office or previously communicated to the US by the IB \$480 All other situations \$600				\$ 480.00			
TOTAL OF 18, 19, and 20 =				\$ 1,480.00			
<input type="checkbox"/> Additional fee for specification and drawings filed in paper over 100 sheets (excluding sequence listing in compliance with 37 CFR 1.821(c) or (e) in an electronic medium or computer program listing in an electronic medium) (37 CFR 1.492(j)). Fee for each additional 50 sheets of paper or fraction thereof \$400							
Total Sheets	Extra Sheets	Number of each addition 50 or fraction thereof (round up to a whole number)	RATE				
100	750	0	x \$400	\$			
Surcharge of \$140.00 for furnishing any of the search fee, examination fee, or the oath or declaration after the date of commencement of the national stage (37 CFR 1.492(h))				\$ 140.00			
CLAIMS	NUMBER FILED	NUMBER EXTRA	RATE				
Total claims	20	0	x \$80	\$ 0.00			
Independent claims	3	0	x \$420	\$ 0.00			
MULTIPLE DEPENDENT CLAIM(S) (if applicable)			+ \$780	\$			
Processing fee of \$140.00 for furnishing the English translation later than 30 months from the earliest claimed priority date (37 CFR 1.492(i))				\$			
TOTAL OF ABOVE CALCULATIONS =				\$ 1,620.00			
<input type="checkbox"/> Applicant asserts small entity status. See 37 CFR 1.27. Fees above are reduced by 1/3.							
<input type="checkbox"/> Applicant certifies micro entity status. See 37 CFR 1.25. Fees above are reduced by 3/4. Applicant must attach form PTO/SB/15A or B or equivalent.							
TOTAL NATIONAL FEE =				\$ 1,620.00			
Fee for recording the enclosed assignment (37 CFR 1.21(h)). The assignment must be accompanied by an appropriate cover sheet (37 CFR 3.28, 3.31) \$40.00 per property.				\$			
TOTAL FEES ENCLOSED =				\$ 1,620.00			
				Amount to be refunded:		\$	
				Amount to be charged:		\$	

Under the Paperwork Reduction Act of 1995, no persons are required to respond to a collection of information unless it displays a valid OMB control number.

- a.  A check in the amount of \$ \_\_\_\_\_ to cover the above fees is enclosed.
- b.  Please charge my Deposit Account No. \_\_\_\_\_ in the amount of \$ \_\_\_\_\_ to cover the above fees.
- c.  The Director is hereby authorized to charge additional fees which may be required, or credit any overpayment, to Deposit Account No. \_\_\_\_\_ as follows:
- any required fee.
  - any required fee except for excess claims fees required under 37 CFR 1.492(d) and (e) and multiple dependent claim fee required under 37 CFR 1.492(f).
- d.  Fees are to be charged to a credit card. **WARNING:** Information on this form may become public. Credit card information should not be included on this form. Provide credit card information and authorization on PTO-2038. The PTO-2038 should only be mailed or faxed to the USPTO. However, when paying the basic national fee, the PTO-2038 may NOT be faxed to the USPTO.
- ADVISORY:** If filing by EFS-Web, do NOT attach the PTO-2038 form as a PDF along with your EFS-Web submission. Please be advised that this is not recommended and by doing so your credit card information may be displayed via PAIR. To protect your information, it is recommended to pay fees online by using the electronic payment method.

**NOTE:** Where an appropriate time limit under 37 CFR 1.495 has not been met, a petition to revive (37 CFR 1.137(a) or (b)) must be filed and granted to restore the International Application to pending status.

**Statement under 37 CFR 1.55 or 1.78 for AIA (First Inventor to File) Transition Applications**

This application (1) claims priority to or the benefit of an application filed before March 16, 2013, and (2) also contains, or contained at any time, a claim to a claimed invention that has an effective filing date on or after March 16, 2013.

**NOTE 1:** By providing this statement under 37 CFR 1.55 or 1.78, this application, with a filing date on or after March 16, 2013, will be examined under the first inventor to file provisions of the AIA.

**NOTE 2:** A U.S. national stage application may not claim priority to the international application of which it is the national phase. The filing date of a U.S. national stage application is the international filing date. See 35 U.S.C. 363.

**Correspondence Address**

The address associated with Customer Number: \_\_\_\_\_ OR  Correspondence address below

Name					
Address					
City		State		Zip Code	
Country				Telephone	
Email					

Signature	<i>Thomas G. Dickson</i>	Date	February 6, 2015
Name (Print/Type)	Thomas G. Dickson	Registration No. (Attorney/Agent)	51616

## Privacy Act Statement

The Privacy Act of 1974 (P.L. 93-579) requires that you be given certain information in connection with your submission of the attached form related to a patent application or patent. Accordingly, pursuant to the requirements of the Act, please be advised that: (1) the general authority for the collection of this information is 35 U.S.C. 2(b)(2); (2) furnishing of the information solicited is voluntary; and (3) the principal purpose for which the information is used by the U.S. Patent and Trademark Office is to process and/or examine your submission related to a patent application or patent. If you do not furnish the requested information, the U.S. Patent and Trademark Office may not be able to process and/or examine your submission, which may result in termination of proceedings or abandonment of the application or expiration of the patent.

The information provided by you in this form will be subject to the following routine uses:

1. The information on this form will be treated confidentially to the extent allowed under the Freedom of Information Act (5 U.S.C. 552) and the Privacy Act (5 U.S.C. 552a). Records from this system of records may be disclosed to the Department of Justice to determine whether disclosure of these records is required by the Freedom of Information Act.
2. A record from this system of records may be disclosed, as a routine use, in the course of presenting evidence to a court, magistrate, or administrative tribunal, including disclosures to opposing counsel in the course of settlement negotiations.
3. A record in this system of records may be disclosed, as a routine use, to a Member of Congress submitting a request involving an individual, to whom the record pertains, when the individual has requested assistance from the Member with respect to the subject matter of the record.
4. A record in this system of records may be disclosed, as a routine use, to a contractor of the Agency having need for the information in order to perform a contract. Recipients of information shall be required to comply with the requirements of the Privacy Act of 1974, as amended, pursuant to 5 U.S.C. 552a(m).
5. A record related to an International Application filed under the Patent Cooperation Treaty in this system of records may be disclosed, as a routine use, to the International Bureau of the World Intellectual Property Organization, pursuant to the Patent Cooperation Treaty.
6. A record in this system of records may be disclosed, as a routine use, to another federal agency for purposes of National Security review (35 U.S.C. 181) and for review pursuant to the Atomic Energy Act (42 U.S.C. 218(c)).
7. A record from this system of records may be disclosed, as a routine use, to the Administrator, General Services, or his/her designee, during an inspection of records conducted by GSA as part of that agency's responsibility to recommend improvements in records management practices and programs, under authority of 44 U.S.C. 2904 and 2906. Such disclosure shall be made in accordance with the GSA regulations governing inspection of records for this purpose, and any other relevant (*i.e.*, GSA or Commerce) directive. Such disclosure shall not be used to make determinations about individuals.
8. A record from this system of records may be disclosed, as a routine use, to the public after either publication of the application pursuant to 35 U.S.C. 122(b) or issuance of a patent pursuant to 35 U.S.C. 151. Further, a record may be disclosed, subject to the limitations of 37 CFR 1.14, as a routine use, to the public if the record was filed in an application which became abandoned or in which the proceedings were terminated and which application is referenced by either a published application, an application open to public inspection or an issued patent.
9. A record from this system of records may be disclosed, as a routine use, to a Federal, State, or local law enforcement agency, if the USPTO becomes aware of a violation or potential violation of law or regulation.

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<b>Application Data Sheet 37 CFR 1.76</b>		Attorney Docket Number	4229.108WOUS01
		Application Number	
Title of Invention	METHOD FOR ENHANCING THE DETERMINATION OF A SEISMIC HORIZON		
<p>The application data sheet is part of the provisional or nonprovisional application for which it is being submitted. The following form contains the bibliographic data arranged in a format specified by the United States Patent and Trademark Office as outlined in 37 CFR 1.76. This document may be completed electronically and submitted to the Office in electronic format using the Electronic Filing System (EFS) or the document may be printed and included in a paper filed application.</p>			

**Secrecy Order 37 CFR 5.2**

<input type="checkbox"/>	Portions or all of the application associated with this Application Data Sheet may fall under a Secrecy Order pursuant to 37 CFR 5.2 (Paper filers only. Applications that fall under Secrecy Order may not be filed electronically.)
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**Inventor Information:**

<b>Inventor 1</b>					<input type="button" value="Remove"/>
<b>Legal Name</b>					
<b>Prefix</b>	<b>Given Name</b>	<b>Middle Name</b>	<b>Family Name</b>	<b>Suffix</b>	
	Guillaume		ZINCK		
<b>Residence Information (Select One)</b> <input type="radio"/> US Residency <input checked="" type="radio"/> Non US Residency <input type="radio"/> Active US Military Service					
<b>City</b>	Talence	<b>Country of Residence<sup>i</sup></b>	FR		

**Mailing Address of Inventor:**

<b>Address 1</b>	351 Cours de la Libération				
<b>Address 2</b>					
<b>City</b>	Talence	<b>State/Province</b>			
<b>Postal Code</b>	F-33405	<b>Country<sup>i</sup></b>	FR		

<b>Inventor 2</b>					<input type="button" value="Remove"/>
<b>Legal Name</b>					
<b>Prefix</b>	<b>Given Name</b>	<b>Middle Name</b>	<b>Family Name</b>	<b>Suffix</b>	
	Marc		DONIAS		
<b>Residence Information (Select One)</b> <input type="radio"/> US Residency <input checked="" type="radio"/> Non US Residency <input type="radio"/> Active US Military Service					
<b>City</b>	Talence	<b>Country of Residence<sup>i</sup></b>	FR		

**Mailing Address of Inventor:**

<b>Address 1</b>	351 Cours de la Libération				
<b>Address 2</b>					
<b>City</b>	Talence	<b>State/Province</b>			
<b>Postal Code</b>	F-33405	<b>Country<sup>i</sup></b>	FR		

<b>Inventor 3</b>					<input type="button" value="Remove"/>
<b>Legal Name</b>					

<b>Application Data Sheet 37 CFR 1.76</b>		Attorney Docket Number	4229.108WOUS01
		Application Number	
Title of Invention	METHOD FOR ENHANCING THE DETERMINATION OF A SEISMIC HORIZON		

Prefix	Given Name	Middle Name	Family Name	Suffix
	Jacques		DANIEL	
Residence Information (Select One) <input type="radio"/> US Residency <input checked="" type="radio"/> Non US Residency <input type="radio"/> Active US Military Service				
City	Talence	Country of Residence <sup>i</sup>		FR

<b>Mailing Address of Inventor:</b>				
Address 1	351 Cours de la Libération			
Address 2				
City	Talence	State/Province		
Postal Code	F-33405	Country <sup>i</sup>	FR	
Inventor <b>4</b>				<input type="button" value="Remove"/>

<b>Legal Name</b>				
Prefix	Given Name	Middle Name	Family Name	Suffix
	Olivier		LAVIALLE	
Residence Information (Select One) <input type="radio"/> US Residency <input checked="" type="radio"/> Non US Residency <input type="radio"/> Active US Military Service				
City	Talence	Country of Residence <sup>i</sup>		FR

<b>Mailing Address of Inventor:</b>				
Address 1	351 Cours de la Libération			
Address 2				
City	Talence	State/Province		
Postal Code	F-33405	Country <sup>i</sup>	FR	
Inventor <b>5</b>				<input type="button" value="Remove"/>

<b>Legal Name</b>				
Prefix	Given Name	Middle Name	Family Name	Suffix
	Sébastien		GUILLON	
Residence Information (Select One) <input type="radio"/> US Residency <input checked="" type="radio"/> Non US Residency <input type="radio"/> Active US Military Service				
City	Pau	Country of Residence <sup>i</sup>		FR

<b>Mailing Address of Inventor:</b>				
Address 1	c/o TOTAL SA, CSTJF-EB 279, Avenue Larribau			
Address 2				
City	Pau	State/Province		
Postal Code	F-64000	Country <sup>i</sup>	FR	

<b>Application Data Sheet 37 CFR 1.76</b>	Attorney Docket Number	4229.108WOUS01
	Application Number	
Title of Invention	METHOD FOR ENHANCING THE DETERMINATION OF A SEISMIC HORIZON	

All Inventors Must Be Listed - Additional Inventor Information blocks may be generated within this form by selecting the **Add** button.

Add

## Correspondence Information:

Enter either Customer Number or complete the Correspondence Information section below. For further information see 37 CFR 1.33(a).

An Address is being provided for the correspondence information of this application.

Customer Number 24113

Email Address dickson@ptslaw.com

Add Email

Remove Email

## Application Information:

Title of the Invention	METHOD FOR ENHANCING THE DETERMINATION OF A SEISMIC HORIZON		
Attorney Docket Number	4229.108WOUS01	Small Entity Status Claimed	<input type="checkbox"/>
Application Type	Nonprovisional		
Subject Matter	Utility		
Total Number of Drawing Sheets (if any)	8	Suggested Figure for Publication (if any)	

## Filing By Reference :

Only complete this section when filing an application by reference under 35 U.S.C. 111(c) and 37 CFR 1.57(a). Do not complete this section if application papers including a specification and any drawings are being filed. Any domestic benefit or foreign priority information must be provided in the appropriate section(s) below (i.e., "Domestic Benefit/National Stage Information" and "Foreign Priority Information").

For the purposes of a filing date under 37 CFR 1.53(b), the description and any drawings of the present application are replaced by this reference to the previously filed application, subject to conditions and requirements of 37 CFR 1.57(a).

Application number of the previously filed application	Filing date (YYYY-MM-DD)	Intellectual Property Authority or Country

## Publication Information:

Request Early Publication (Fee required at time of Request 37 CFR 1.219)

**Request Not to Publish.** I hereby request that the attached application not be published under 35 U.S.C. 122(b) and certify that the invention disclosed in the attached application **has not and will not** be the subject of an application filed in another country, or under a multilateral international agreement, that requires publication at eighteen months after filing.

## Representative Information:

Representative information should be provided for all practitioners having a power of attorney in the application. Providing this information in the Application Data Sheet does not constitute a power of attorney in the application (see 37 CFR 1.32). Either enter Customer Number or complete the Representative Name section below. If both sections are completed the customer Number will be used for the Representative Information during processing.

<b>Application Data Sheet 37 CFR 1.76</b>		Attorney Docket Number	4229.108WOUS01	
		Application Number		
Title of Invention	METHOD FOR ENHANCING THE DETERMINATION OF A SEISMIC HORIZON			
Please Select One:	<input checked="" type="radio"/> Customer Number	<input type="radio"/> US Patent Practitioner	<input type="radio"/> Limited Recognition (37 CFR 11.9)	
Customer Number	24113			

### Domestic Benefit/National Stage Information:

This section allows for the applicant to either claim benefit under 35 U.S.C. 119(e), 120, 121, or 365(c) or indicate National Stage entry from a PCT application. Providing this information in the application data sheet constitutes the specific reference required by 35 U.S.C. 119(e) or 120, and 37 CFR 1.78.

When referring to the current application, please leave the application number blank.

Prior Application Status	Pending	<a href="#">Remove</a>	
Application Number	Continuity Type	Prior Application Number	Filing Date (YYYY-MM-DD)
	a 371 of international	PCT/EP2013/066492	2013-08-06
Prior Application Status	Expired	<a href="#">Remove</a>	
Application Number	Continuity Type	Prior Application Number	Filing Date (YYYY-MM-DD)
PCT/EP2013/066492	Claims benefit of provisional	61/681005	2012-08-08
Additional Domestic Benefit/National Stage Data may be generated within this form by selecting the <b>Add</b> button.			<a href="#">Add</a>

### Foreign Priority Information:

This section allows for the applicant to claim priority to a foreign application. Providing this information in the application data sheet constitutes the claim for priority as required by 35 U.S.C. 119(b) and 37 CFR 1.55(d). When priority is claimed to a foreign application that is eligible for retrieval under the priority document exchange program (PDX) the information will be used by the Office to automatically attempt retrieval pursuant to 37 CFR 1.55(h)(1) and (2). Under the PDX program, applicant bears the ultimate responsibility for ensuring that a copy of the foreign application is received by the Office from the participating foreign intellectual property office, or a certified copy of the foreign priority application is filed, within the time period specified in 37 CFR 1.55(g)(1).

<a href="#">Remove</a>			
Application Number	Country <sup>i</sup>	Filing Date (YYYY-MM-DD)	Access Code <sup>i</sup> (if applicable)
Additional Foreign Priority Data may be generated within this form by selecting the <b>Add</b> button.			<a href="#">Add</a>

<b>Application Data Sheet 37 CFR 1.76</b>	Attorney Docket Number	4229.108WOUS01
	Application Number	
Title of Invention	METHOD FOR ENHANCING THE DETERMINATION OF A SEISMIC HORIZON	

## Statement under 37 CFR 1.55 or 1.78 for AIA (First Inventor to File) Transition Applications

<p>This application (1) claims priority to or the benefit of an application filed before March 16, 2013 and (2) also contains, or contained at any time, a claim to a claimed invention that has an effective filing date on or after March 16, 2013.</p> <p><input type="checkbox"/> NOTE: By providing this statement under 37 CFR 1.55 or 1.78, this application, with a filing date on or after March 16, 2013, will be examined under the first inventor to file provisions of the AIA.</p>
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## Authorization to Permit Access:

<input checked="" type="checkbox"/> Authorization to Permit Access to the Instant Application by the Participating Offices
<p>If checked, the undersigned hereby grants the USPTO authority to provide the European Patent Office (EPO), the Japan Patent Office (JPO), the Korean Intellectual Property Office (KIPO), the World Intellectual Property Office (WIPO), and any other intellectual property offices in which a foreign application claiming priority to the instant patent application is filed access to the instant patent application. See 37 CFR 1.14(c) and (h). This box should not be checked if the applicant does not wish the EPO, JPO, KIPO, WIPO, or other intellectual property office in which a foreign application claiming priority to the instant patent application is filed to have access to the instant patent application.</p> <p>In accordance with 37 CFR 1.14(h)(3), access will be provided to a copy of the instant patent application with respect to: 1) the instant patent application-as-filed; 2) any foreign application to which the instant patent application claims priority under 35 U.S.C. 119(a)-(d) if a copy of the foreign application that satisfies the certified copy requirement of 37 CFR 1.55 has been filed in the instant patent application; and 3) any U.S. application-as-filed from which benefit is sought in the instant patent application.</p> <p>In accordance with 37 CFR 1.14(c), access may be provided to information concerning the date of filing this Authorization.</p>

## Applicant Information:

<p>Providing assignment information in this section does not substitute for compliance with any requirement of part 3 of Title 37 of CFR to have an assignment recorded by the Office.</p>
--

<b>Application Data Sheet 37 CFR 1.76</b>	Attorney Docket Number	4229.108WOUS01
	Application Number	
Title of Invention	METHOD FOR ENHANCING THE DETERMINATION OF A SEISMIC HORIZON	

<b>Applicant 1</b>	<input type="button" value="Remove"/>
--------------------	---------------------------------------

If the applicant is the inventor (or the remaining joint inventor or inventors under 37 CFR 1.45), this section should not be completed. The information to be provided in this section is the name and address of the legal representative who is the applicant under 37 CFR 1.43; or the name and address of the assignee, person to whom the inventor is under an obligation to assign the invention, or person who otherwise shows sufficient proprietary interest in the matter who is the applicant under 37 CFR 1.46. If the applicant is an applicant under 37 CFR 1.46 (assignee, person to whom the inventor is obligated to assign, or person who otherwise shows sufficient proprietary interest) together with one or more joint inventors, then the joint inventor or inventors who are also the applicant should be identified in this section.

<input checked="" type="radio"/> Assignee	<input type="radio"/> Legal Representative under 35 U.S.C. 117	<input type="radio"/> Joint Inventor
<input type="radio"/> Person to whom the inventor is obligated to assign.	<input type="radio"/> Person who shows sufficient proprietary interest	

If applicant is the legal representative, indicate the authority to file the patent application, the inventor is:

Name of the Deceased or Legally Incapacitated Inventor :

If the Applicant is an Organization check here.

Organization Name

**Mailing Address Information For Applicant:**

Address 1	2 place Jean Millier		
Address 2	La Défense 6		
City	Courbevoie	State/Province	
Country	FR	Postal Code	F-92400
Phone Number		Fax Number	
Email Address			

Additional Applicant Data may be generated within this form by selecting the Add button.

<b>Applicant 2</b>	<input type="button" value="Remove"/>
--------------------	---------------------------------------

If the applicant is the inventor (or the remaining joint inventor or inventors under 37 CFR 1.45), this section should not be completed. The information to be provided in this section is the name and address of the legal representative who is the applicant under 37 CFR 1.43; or the name and address of the assignee, person to whom the inventor is under an obligation to assign the invention, or person who otherwise shows sufficient proprietary interest in the matter who is the applicant under 37 CFR 1.46. If the applicant is an applicant under 37 CFR 1.46 (assignee, person to whom the inventor is obligated to assign, or person who otherwise shows sufficient proprietary interest) together with one or more joint inventors, then the joint inventor or inventors who are also the applicant should be identified in this section.

<input checked="" type="radio"/> Assignee	<input type="radio"/> Legal Representative under 35 U.S.C. 117	<input type="radio"/> Joint Inventor
<input type="radio"/> Person to whom the inventor is obligated to assign.	<input type="radio"/> Person who shows sufficient proprietary interest	

If applicant is the legal representative, indicate the authority to file the patent application, the inventor is:

Name of the Deceased or Legally Incapacitated Inventor :

<b>Application Data Sheet 37 CFR 1.76</b>	Attorney Docket Number	4229.108WOUS01
	Application Number	
Title of Invention	METHOD FOR ENHANCING THE DETERMINATION OF A SEISMIC HORIZON	

If the Applicant is an Organization check here. <input checked="" type="checkbox"/>			
Organization Name	Centre National De La Recherche Scientifique - CNRS		
<b>Mailing Address Information For Applicant:</b>			
Address 1	3, rue Michel Ange		
Address 2			
City	Paris Cedex 16	State/Province	
Country <sup>i</sup>	FR	Postal Code	75794
Phone Number		Fax Number	
Email Address			

Additional Applicant Data may be generated within this form by selecting the Add button.

<b>Applicant 3</b>	<input type="button" value="Remove"/>
<p>If the applicant is the inventor (or the remaining joint inventor or inventors under 37 CFR 1.45), this section should not be completed. The information to be provided in this section is the name and address of the legal representative who is the applicant under 37 CFR 1.43; or the name and address of the assignee, person to whom the inventor is under an obligation to assign the invention, or person who otherwise shows sufficient proprietary interest in the matter who is the applicant under 37 CFR 1.46. If the applicant is an applicant under 37 CFR 1.46 (assignee, person to whom the inventor is obligated to assign, or person who otherwise shows sufficient proprietary interest) together with one or more joint inventors, then the joint inventor or inventors who are also the applicant should be identified in this section.</p>	
<input type="button" value="Clear"/>	

<input checked="" type="radio"/> Assignee	<input type="radio"/> Legal Representative under 35 U.S.C. 117	<input type="radio"/> Joint Inventor
<input type="radio"/> Person to whom the inventor is obligated to assign.	<input type="radio"/> Person who shows sufficient proprietary interest	

If applicant is the legal representative, indicate the authority to file the patent application, the inventor is:

Name of the Deceased or Legally Incapacitated Inventor :	
--	--

If the Applicant is an Organization check here. <input checked="" type="checkbox"/>	
Organization Name	Universite De Bordeaux

<b>Mailing Address Information For Applicant:</b>			
Address 1	35 Place Pey Berland		
Address 2			
City	Bordeaux	State/Province	
Country <sup>i</sup>	FR	Postal Code	33000
Phone Number		Fax Number	
Email Address			

Additional Applicant Data may be generated within this form by selecting the Add button.

<b>Application Data Sheet 37 CFR 1.76</b>	Attorney Docket Number	4229.108WOUS01
	Application Number	
Title of Invention	METHOD FOR ENHANCING THE DETERMINATION OF A SEISMIC HORIZON	

<b>Applicant 4</b>				<input type="button" value="Remove"/>
<p>If the applicant is the inventor (or the remaining joint inventor or inventors under 37 CFR 1.45), this section should not be completed. The information to be provided in this section is the name and address of the legal representative who is the applicant under 37 CFR 1.43; or the name and address of the assignee, person to whom the inventor is under an obligation to assign the invention, or person who otherwise shows sufficient proprietary interest in the matter who is the applicant under 37 CFR 1.46. If the applicant is an applicant under 37 CFR 1.46 (assignee, person to whom the inventor is obligated to assign, or person who otherwise shows sufficient proprietary interest) together with one or more joint inventors, then the joint inventor or inventors who are also the applicant should be identified in this section.</p>				
<input type="button" value="Clear"/>				
<input checked="" type="radio"/> Assignee		<input type="radio"/> Legal Representative under 35 U.S.C. 117		<input type="radio"/> Joint Inventor
<input type="radio"/> Person to whom the inventor is obligated to assign.			<input type="radio"/> Person who shows sufficient proprietary interest	
If applicant is the legal representative, indicate the authority to file the patent application, the inventor is:				
Name of the Deceased or Legally Incapacitated Inventor : <input type="text"/>				
If the Applicant is an Organization check here. <input checked="" type="checkbox"/>				
Organization Name		École Nationale Supérieure Des Sciences Agronomiques De Bordeaux-Aquitaine		
<b>Mailing Address Information For Applicant:</b>				
Address 1		1 Cours du Général de Gaulle		
Address 2				
City		Gradignan	State/Province	
Country	FR	Postal Code	F-33170	
Phone Number		Fax Number		
Email Address				

Additional Applicant Data may be generated within this form by selecting the Add button.

<b>Applicant 5</b>				<input type="button" value="Remove"/>
<p>If the applicant is the inventor (or the remaining joint inventor or inventors under 37 CFR 1.45), this section should not be completed. The information to be provided in this section is the name and address of the legal representative who is the applicant under 37 CFR 1.43; or the name and address of the assignee, person to whom the inventor is under an obligation to assign the invention, or person who otherwise shows sufficient proprietary interest in the matter who is the applicant under 37 CFR 1.46. If the applicant is an applicant under 37 CFR 1.46 (assignee, person to whom the inventor is obligated to assign, or person who otherwise shows sufficient proprietary interest) together with one or more joint inventors, then the joint inventor or inventors who are also the applicant should be identified in this section.</p>				
<input type="button" value="Clear"/>				
<input checked="" type="radio"/> Assignee		<input type="radio"/> Legal Representative under 35 U.S.C. 117		<input type="radio"/> Joint Inventor
<input type="radio"/> Person to whom the inventor is obligated to assign.			<input type="radio"/> Person who shows sufficient proprietary interest	
If applicant is the legal representative, indicate the authority to file the patent application, the inventor is:				
Name of the Deceased or Legally Incapacitated Inventor : <input type="text"/>				

<b>Application Data Sheet 37 CFR 1.76</b>	Attorney Docket Number	4229.108WOUS01
	Application Number	
Title of Invention	METHOD FOR ENHANCING THE DETERMINATION OF A SEISMIC HORIZON	

If the Applicant is an Organization check here. <input checked="" type="checkbox"/>			
Organization Name	Institut Polytechnique De Bordeaux		
<b>Mailing Address Information For Applicant:</b>			
Address 1	1 avenue du Docteur Albert Schweitzer		
Address 2			
City	Talence	State/Province	
Country i	FR	Postal Code	F-33400
Phone Number		Fax Number	
Email Address			
Additional Applicant Data may be generated within this form by selecting the Add button.			<input type="button" value="Add"/>

## Assignee Information including Non-Applicant Assignee Information:

Providing assignment information in this section does not substitute for compliance with any requirement of part 3 of Title 37 of CFR to have an assignment recorded by the Office.				
<b>Assignee 1</b>				
Complete this section if assignee information, including non-applicant assignee information, is desired to be included on the patent application publication. An assignee-applicant identified in the "Applicant Information" section will appear on the patent application publication as an applicant. For an assignee-applicant, complete this section only if identification as an assignee is also desired on the patent application publication.				
				<input type="button" value="Remove"/>
If the Assignee or Non-Applicant Assignee is an Organization check here. <input type="checkbox"/>				
Prefix	Given Name	Middle Name	Family Name	Suffix
<b>Mailing Address Information For Assignee including Non-Applicant Assignee:</b>				
Address 1				
Address 2				
City		State/Province		
Country i		Postal Code		
Phone Number		Fax Number		
Email Address				
Additional Assignee or Non-Applicant Assignee Data may be generated within this form by selecting the Add button.				<input type="button" value="Add"/>

Under the Paperwork Reduction Act of 1995, no persons are required to respond to a collection of information unless it contains a valid OMB control number.

<b>Application Data Sheet 37 CFR 1.76</b>	Attorney Docket Number	4229.108WOUS01
	Application Number	
Title of Invention	METHOD FOR ENHANCING THE DETERMINATION OF A SEISMIC HORIZON	

**Signature:**

NOTE: This form must be signed in accordance with 37 CFR 1.33. See 37 CFR 1.4 for signature requirements and certifications.

<b>Signature</b>	/Thomas G. Dickson/			Date (YYYY-MM-DD)	2015-02-06
First Name	Thomas G.	Last Name	Dickson	Registration Number	51616

Additional Signature may be generated within this form by selecting the Add button.

This collection of information is required by 37 CFR 1.76. The information is required to obtain or retain a benefit by the public which is to file (and by the USPTO to process) an application. Confidentiality is governed by 35 U.S.C. 122 and 37 CFR 1.14. This collection is estimated to take 23 minutes to complete, including gathering, preparing, and submitting the completed application data sheet form to the USPTO. Time will vary depending upon the individual case. Any comments on the amount of time you require to complete this form and/or suggestions for reducing this burden, should be sent to the Chief Information Officer, U.S. Patent and Trademark Office, U.S. Department of Commerce, P.O. Box 1450, Alexandria, VA 22313-1450. DO NOT SEND FEES OR COMPLETED FORMS TO THIS ADDRESS. **SEND TO: Commissioner for Patents, P.O. Box 1450, Alexandria, VA 22313-1450.**

# Privacy Act Statement

The Privacy Act of 1974 (P.L. 93-579) requires that you be given certain information in connection with your submission of the attached form related to a patent application or patent. Accordingly, pursuant to the requirements of the Act, please be advised that: (1) the general authority for the collection of this information is 35 U.S.C. 2(b)(2); (2) furnishing of the information solicited is voluntary; and (3) the principal purpose for which the information is used by the U.S. Patent and Trademark Office is to process and/or examine your submission related to a patent application or patent. If you do not furnish the requested information, the U.S. Patent and Trademark Office may not be able to process and/or examine your submission, which may result in termination of proceedings or abandonment of the application or expiration of the patent.

The information provided by you in this form will be subject to the following routine uses:

1. The information on this form will be treated confidentially to the extent allowed under the Freedom of Information Act (5 U.S.C. 552) and the Privacy Act (5 U.S.C. 552a). Records from this system of records may be disclosed to the Department of Justice to determine whether the Freedom of Information Act requires disclosure of these records.
2. A record from this system of records may be disclosed, as a routine use, in the course of presenting evidence to a court, magistrate, or administrative tribunal, including disclosures to opposing counsel in the course of settlement negotiations.
3. A record in this system of records may be disclosed, as a routine use, to a Member of Congress submitting a request involving an individual, to whom the record pertains, when the individual has requested assistance from the Member with respect to the subject matter of the record.
4. A record in this system of records may be disclosed, as a routine use, to a contractor of the Agency having need for the information in order to perform a contract. Recipients of information shall be required to comply with the requirements of the Privacy Act of 1974, as amended, pursuant to 5 U.S.C. 552a(m).
5. A record related to an International Application filed under the Patent Cooperation Treaty in this system of records may be disclosed, as a routine use, to the International Bureau of the World Intellectual Property Organization, pursuant to the Patent Cooperation Treaty.
6. A record in this system of records may be disclosed, as a routine use, to another federal agency for purposes of National Security review (35 U.S.C. 181) and for review pursuant to the Atomic Energy Act (42 U.S.C. 218(c)).
7. A record from this system of records may be disclosed, as a routine use, to the Administrator, General Services, or his/her designee, during an inspection of records conducted by GSA as part of that agency's responsibility to recommend improvements in records management practices and programs, under authority of 44 U.S.C. 2904 and 2906. Such disclosure shall be made in accordance with the GSA regulations governing inspection of records for this purpose, and any other relevant (i.e., GSA or Commerce) directive. Such disclosure shall not be used to make determinations about individuals.
8. A record from this system of records may be disclosed, as a routine use, to the public after either publication of the application pursuant to 35 U.S.C. 122(b) or issuance of a patent pursuant to 35 U.S.C. 151. Further, a record may be disclosed, subject to the limitations of 37 CFR 1.14, as a routine use, to the public if the record was filed in an application which became abandoned or in which the proceedings were terminated and which application is referenced by either a published application, an application open to public inspections or an issued patent.
9. A record from this system of records may be disclosed, as a routine use, to a Federal, State, or local law enforcement agency, if the USPTO becomes aware of a violation or potential violation of law or regulation.



- (51) International Patent Classification:  
G01V 1/34 (2006.01)
- (21) International Application Number:  
PCT/EP2013/066492
- (22) International Filing Date:  
6 August 2013 (06.08.2013)
- (25) Filing Language:  
English
- (26) Publication Language:  
English
- (30) Priority Data:  
61/681 005 8 August 2012 (08.08.2012) US
- (71) Applicants: TOTAL SA [FR/FR]; 2 place Jean Millier La Défense 6, F-92400 Courbevoie (FR). CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE - CNRS - [FR/—]; 3, rue Michel Ange, Paris Cedex 16, 75794 (FR). UNIVERSITE DE BORDEAUX I [FR/—]; 351, cours de la Libération, Talence, 33400 (FR). ÉCOLE NATIONALE SUPÉRIEURE DES SCIENCES AGRO-NOMIQUES DE BORDEAUX-AQUITAINE [FR/FR];

1 Cours du Général de Gaulle, F-33170 Gradignan (FR). INSTITUT POLYTECHNIQUE DE BORDEAUX [FR/FR]; 1 avenue du Docteur Albert Schweitzer, F-33400 Talence (FR).

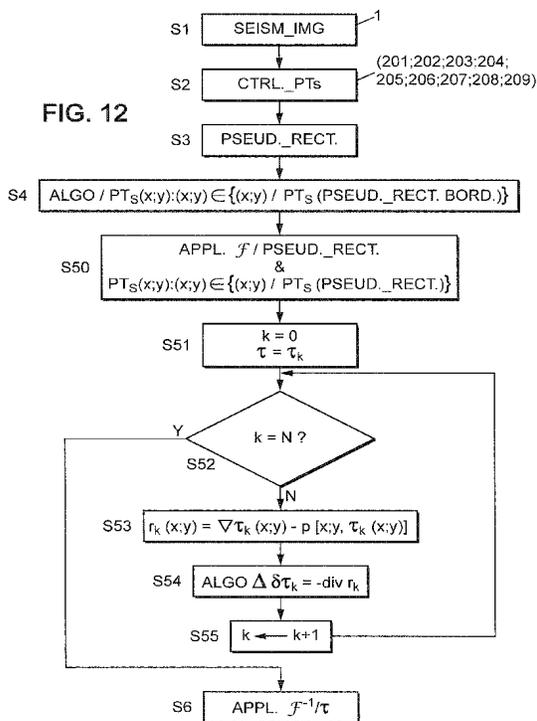
(72) Inventors: ZINCK, Guillaume; 351 Cours de la Libération, F-33405 Talence (FR). DONIAS, Marc; 351 Cours de la Libération, F-33405 Talence (FR). DANIEL, Jacques; 351 Cours de la Libération, F-33405 Talence (FR). LAVIALLE, Olivier; 351 Cours de la Libération, F-33405 Talence (FR). GUILLON, Sébastien; C/O TOTAL SA CSTJF-EB 279 Avenue Larribau, F-64000 Pau (FR).

(74) Agents: AMELINE, Jean-Paul et al.; Cabinet PLASSERAUD, 52 rue de la Victoire, F-75440 Paris Cedex 09 (FR).

(81) Designated States (unless otherwise indicated, for every kind of national protection available): AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT,

[Continued on next page]

(54) Title: METHOD FOR ENHANCING THE DETERMINATION OF A SEISMIC HORIZON



(57) Abstract: The invention pertains to a method for enhancing the determination, from a seismic image, of at least a portion of a seismic horizon in a three-dimensional domain, wherein said method comprises: - receiving the seismic image; - receiving a plurality of related control points; - defining pseudo-rectangles; - for each pseudo-rectangle: - applying a diffeomorphic transformation F : - defining a new domain; - transforming points of the seismic image; - transforming said pseudo-rectangle into a corresponding rectangle; - applying a horizon reconstruction algorithm to the transformed points, to determine a part of a transformed horizon, the reconstruction comprising solving a Poisson equation; - computing a part of the horizon, said computing comprising applying an inverse diffeomorphic transformation F<sup>-1</sup> to the determined part of a transformed horizon.



HN, HR, HU, ID, IL, IN, IS, JP, KE, KG, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

**(84) Designated States** (*unless otherwise indicated, for every kind of regional protection available*): ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, SZ, TZ,

**Published:**

— *without international search report and to be republished upon receipt of that report (Rule 48.2(g))*

From the INTERNATIONAL BUREAU

**PCT**NOTIFICATION OF RECEIPT OF  
RECORD COPY

(PCT Rule 24.2(a))

To:

AMELINE, Jean-Paul  
Cabinet PLASSERAUD  
52 rue de la Victoire  
F-75440 Paris Cedex 09  
FRANCE

Date of mailing ( <i>day/month/year</i> ) 26 August 2013 (26.08.2013)	<b>IMPORTANT NOTIFICATION</b>
Applicant's or agent's file reference BCT130177OD	International application No. PCT/EP2013/066492

The applicant is hereby **notified** that the International Bureau has received the record copy of the international application as detailed below.

Name(s) of the applicant(s) and State(s) for which they are applicants:

**TOTAL SA et al (all designated States)**

International filing date: 06 August 2013 (06.08.2013)

Priority date(s) claimed: 08 August 2012 (08.08.2012)

Date of receipt of the record copy by the International Bureau: 12 August 2013 (12.08.2013)

List of designated Offices:

**AP:** BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, SZ, TZ, UG, ZM, ZW

**EA:** AM, AZ, BY, KG, KZ, RU, TJ, TM

**EP:** AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR

**OA:** BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG

**National:** AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IS, JP, KE, KG, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW

**ATTENTION:** The applicant should carefully check the data appearing in this Notification. In case of any discrepancy between these data and the indications in the international application, the applicant should immediately inform the International Bureau. **In addition, the applicant's attention is drawn to:**

- time limits for entry into the national phase (see [www.wipo.int/pct/en/texts/time\\_limits.html](http://www.wipo.int/pct/en/texts/time_limits.html) and *PCT Applicant's Guide*, National Phase, especially Chapters 3 and 4)
- requirements regarding priority documents (if applicable) (see *PCT Applicant's Guide*, International Phase, paragraph 5.070)

A copy of this notification is being sent to the receiving Office and to the International Searching Authority.

The International Bureau of WIPO 34, chemin des Colombettes 1211 Geneva 20, Switzerland	Authorized officer <b>Brahmi Khemais</b> e-mail <a href="mailto:pt06.pct@wipo.int">pt06.pct@wipo.int</a> Telephone No. +41 22 338 74 06
Facsimile No. +41 22 338 89 70	

From the INTERNATIONAL BUREAU

**PCT**NOTIFICATION CONCERNING SUBMISSION,  
OBTENTION OR TRANSMITTAL  
OF PRIORITY DOCUMENT

(PCT Administrative Instructions, Section 411)

To:

AMELINE, Jean-Paul  
Cabinet PLASSERAUD  
52 rue de la Victoire  
F-75440 Paris Cedex 09  
FRANCE

Date of mailing ( <i>day/month/year</i> ) 27 September 2013 (27.09.2013)	
Applicant's or agent's file reference BCT130177OD	IMPORTANT NOTIFICATION
International application No. PCT/EP2013/066492	International filing date ( <i>day/month/year</i> ) 06 August 2013 (06.08.2013)
International publication date ( <i>day/month/year</i> ) Not yet published	Priority date ( <i>day/month/year</i> ) 08 August 2012 (08.08.2012)
Applicant TOTAL SA et al	

The applicant is hereby notified of the date of receipt (or of obtaining by the International Bureau) of the priority document(s) relating to all earlier application(s) whose priority is claimed. Unless otherwise indicated by the letters "NR", in the right-hand column or by an asterisk appearing next to the date of receipt, **the priority document concerned was submitted or transmitted to or obtained by the International Bureau in compliance with Rule 17.1(a), (b) or (b-bis)**. This Form replaces any previously issued notification concerning submission, transmittal or obtaining of priority documents.

<u>Priority date</u>	<u>Priority application No.</u>	<u>Country or regional Office or PCT receiving Office</u>	<u>Date of receipt of priority document</u>
08 August 2012 (08.08.2012)	61/681 005	US	24 September 2013 (24.09.2013)

The letters "NR" denote a priority document which, on the date of mailing of this Form, had not yet been received or obtained by the International Bureau in compliance with Rule 17.1(a), (b) or (b-bis). Where the applicant has failed to either submit, request to prepare and transmit, or to request the International Bureau to obtain the priority document within the applicable time limit under that Rule, the attention of the applicant is directed to Rule 17.1(c) which provides that no designated Office may disregard the priority claim concerned before giving the applicant an opportunity, upon entry into the national phase, to furnish the priority document within a time limit which is reasonable under the circumstances.

An asterisk "\*" next to a date of receipt, denotes a priority document submitted or transmitted to or obtained by the International Bureau but not in compliance with Rule 17.1(a), (b) or (b-bis) (the priority document was received after the time limit prescribed in Rule 17.1(a); the request to prepare and transmit the priority document was submitted to the receiving Office after the applicable time limit under Rule 17.1(b) or the request to the International Bureau to obtain the priority document was made after the applicable time limit under Rule 17.1(b-bis)). Even though the priority document was not furnished in compliance with Rule 17.1(a), (b) or (b-bis), the International Bureau will nevertheless transmit a copy of the document to the designated Offices, for their consideration. In case such a copy is not accepted by the designated Office as the priority document, Rule 17.1(c) provides that no designated Office may disregard the priority claim concerned before giving the applicant an opportunity, upon entry into the national phase, to furnish the priority document within a time limit which is reasonable under the circumstances.

The International Bureau of WIPO 34, chemin des Colombettes 1211 Geneva 20, Switzerland	Authorized officer  Agnès Wittmann-Regis e-mail <a href="mailto:pi06.pct@wipo.int">pi06.pct@wipo.int</a> Telephone No. +41 22 338 74 06
Facsimile No. +41 22 338 89 70	

From the INTERNATIONAL BUREAU

# PCT

## NOTIFICATION OF THE RECORDING OF A CHANGE

(PCT Rule 92bis.1 and  
Administrative Instructions, Section 422)

To:

AMELINE, Jean-Paul  
Cabinet PLASSERAUD  
52 rue de la Victoire  
F-75440 Paris Cedex 09  
FRANCE

Date of mailing (day/month/year) 28 January 2015 (28.01.2015)	<b>IMPORTANT NOTIFICATION</b>
Applicant's or agent's file reference BCT130177OD	
International application No. PCT/EP2013/066492	International filing date (day/month/year) 06 August 2013 (06.08.2013)

1. The following indications appeared on record concerning:

the applicant       the inventor       the agent       the common representative

Name and Address UNIVERSITE DE BORDEAUX I 351, cours de la Libération Talence, 33400 France	State of Nationality FR	State of Residence
	Telephone No.	
	Facsimile No.	
	E-mail address	

2. The International Bureau hereby notifies the applicant that the following change has been recorded concerning:

the person       the name       the address       the nationality       the residence

Name and Address UNIVERSITE DE BORDEAUX 35 Place Pey Berland 33000 Bordeaux France	State of Nationality FR	State of Residence FR
	Telephone No.	
	Facsimile No.	
	E-mail address <input type="checkbox"/> Notifications by e-mail authorized	

3. Further observations, if necessary:

4. A copy of this notification has been sent to:

<input checked="" type="checkbox"/> the receiving Office	<input type="checkbox"/> the International Preliminary Examining Authority
<input type="checkbox"/> the International Searching Authority	<input checked="" type="checkbox"/> the designated Offices concerned
<input type="checkbox"/> the Authority(ies) specified for supplementary search	<input type="checkbox"/> the elected Offices concerned
	<input type="checkbox"/> other:

The International Bureau of WIPO 34, chemin des Colombettes 1211 Geneva 20, Switzerland	Authorized officer  Hoeltker Christoph e-mail pt06.pct@wipo.int Telephone No. +41 22 338 74 06
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From the INTERNATIONAL BUREAU

# PCT

FIRST NOTICE INFORMING THE APPLICANT OF THE COMMUNICATION OF THE INTERNATIONAL APPLICATION (TO DESIGNATED OFFICES WHICH DO NOT APPLY THE 30 MONTH TIME LIMIT UNDER ARTICLE 22(1))

(PCT Rule 47.1(c))

To:

AMELINE, Jean-Paul  
Cabinet PLASSERAUD  
52 rue de la Victoire  
F-75440 Paris Cedex 09  
FRANCE

Date of mailing ( <i>day/month/year</i> ) 13 March 2014 (13.03.2014)		<b>IMPORTANT NOTICE</b>	
Applicant's or agent's file reference BCT130177OD			
International application No. PCT/EP2013/066492	International filing date ( <i>day/month/year</i> ) 06 August 2013 (06.08.2013)	Priority date ( <i>day/month/year</i> ) 08 August 2012 (08.08.2012)	
Applicant TOTAL SA et al			

1. **ATTENTION:** For any designated Office(s), for which the time limit under Article 22(1), as in force from 1 April 2002 (30 months from the priority date), **does apply**, please see Form PCT/IB/308(Second and Supplementary Notice) (to be issued promptly after the expiration of 28 months from the priority date).

2. Notice is hereby given that the following designated Office(s), for which the time limit under Article 22(1), as in force from 1 April 2002, **does not apply**, has/have requested that the communication of the international application, as provided for in Article 20, be effected under Rule 93bis.1. The International Bureau has effected that communication on the date indicated below:  
13 February 2014 (13.02.2014)

**None**

In accordance with Rule 47.1(c-bis)(i), those Offices will accept the present notice as conclusive evidence that the communication of the international application has duly taken place on the date of mailing indicated above and no copy of the international application is required to be furnished by the applicant to the designated Office(s).

3. The following designated Offices, for which the time limit under Article 22(1), as in force from 1 April 2002, **does not apply**, have not requested, as at the time of mailing of the present notice, that the communication of the international application be effected under Rule 93bis.1 :

**LU, TZ, UG**

In accordance with Rule 47.1(c-bis)(ii), those Offices accept the present notice as conclusive evidence that the Contracting State for which that Office acts as a designated Office does not require the furnishing, under Article 22, by the applicant of a copy of the international application.

**4. TIME LIMITS for entry into the national phase**

For the designated Office(s) listed above, and unless a demand for international preliminary examination has been filed before the expiration of **19 months** from the priority date (see Article 39(1)), the applicable time limit for entering the national phase will, **subject to what is said in the following paragraph**, be **20 MONTHS** from the priority date.

In practice, **time limits other than the 20-month time limit** will continue to apply, for various periods of time, in respect of certain of the designated Offices listed above. For **regular updates on the applicable time limits** (20 or 21 months, or other time limit), Office by Office, refer to the *PCT Gazette*, the *PCT Newsletter* and the *PCT Applicant's Guide*, Volume II, National Chapters, all available from WIPO's Internet site, at <http://www.wipo.int/pct/en/index.html>.

It is the applicant's **sole responsibility** to monitor all these time limits.

The International Bureau of WIPO 34, chemin des Colombettes 1211 Geneva 20, Switzerland	Authorized officer  <b>Agnès Wittmann-Regis</b>
Facsimile No. +41 22 338 82 70	e-mail: <a href="mailto:pt06.pct@wipo.int">pt06.pct@wipo.int</a>



From the INTERNATIONAL BUREAU

# PCT

SECOND AND SUPPLEMENTARY NOTICE  
INFORMING THE APPLICANT OF THE  
COMMUNICATION OF THE INTERNATIONAL  
APPLICATION (TO DESIGNATED OFFICES  
WHICH APPLY THE 30 MONTH TIME  
LIMIT UNDER ARTICLE 22(1))

(PCT Rule 47.1(c))

To:

AMELINE, Jean-Paul  
Cabinet PLASSERAUD  
52 rue de la Victoire  
F-75440 Paris Cedex 09  
FRANCE

Date of mailing ( <i>day/month/year</i> ) 11 December 2014 (11.12.2014)		<b>IMPORTANT NOTICE</b>	
Applicant's or agent's file reference BCT130177OD			
International application No. PCT/EP2013/066492	International filing date ( <i>day/month/year</i> ) 06 August 2013 (06.08.2013)	Priority date ( <i>day/month/year</i> ) 08 August 2012 (08.08.2012)	
Applicant TOTAL SA et al			

1. **ATTENTION:** For any designated Office(s), for which the time limit under Article 22(1), as in force from 1 April 2002 (30 months from the priority date), **does not apply**, please see Form PCT/IB/308(First Notice) issued previously.

2. Notice is hereby given that the following designated Office(s), for which the time limit under Article 22(1), as in force from 1 April 2002, **does apply**, has/have requested that the communication of the international application, as provided for in Article 20, be effected under Rule 93bis.1. The International Bureau has effected that communication on the date indicated below:  
13 February 2014 (13.02.2014)

AZ, BY, CN, EP, HU, KG, KP, KR, MD, MK, MZ, NA, NG, PG, RU, SY, TM

In accordance with Rule 47.1(c-bis)(i), those Offices will accept the present notice as conclusive evidence that the communication of the international application has duly taken place on the date of mailing indicated above and no copy of the international application is required to be furnished by the applicant to the designated Office(s).

3. The following designated Offices, for which the time limit under Article 22(1), as in force from 1 April 2002, **does apply**, have not requested, as at the time of mailing of the present notice, that the communication of the international application be effected under Rule 93bis.1 :

AE, AG, AL, AM, AO, AP, AT, AU, BA, BB, BG, BH, BN, BR, BW, BZ, CA, CH, CL, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EA, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, ID, IL, IN, IS, JP, KE, KN, KZ, LA, LC, LK, LR, LS, LT, LY, MA, ME, MG, MN, MW, MX, MY, NI, NO, NZ, OA, OM, PA, PE, PH, PL, PT, QA, RO, RS, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, TH, TJ, TN, TR, TT, UA, US, UZ, VC, VN, ZA, ZM, ZW

In accordance with Rule 47.1(c-bis)(ii), those Offices accept the present notice as conclusive evidence that the Contracting State for which that Office acts as a designated Office does not require the furnishing, under Article 22, by the applicant of a copy of the international application.

4. **TIME LIMITS for entry into the national phase**

For the designated or elected Office(s) listed above, the applicable time limit for entering the national phase will, **subject to what is said in the following paragraph**, be **30 MONTHS** from the priority date.

In practice, **time limits other than the 30-month time limit** will continue to apply, for various periods of time, in respect of certain of the designated or elected Office(s) listed above. For **regular updates on the applicable time limits** (30 or 31 months, or other time limit), Office by Office, refer to the *PCT Gazette*, the *PCT Newsletter* and the *PCT Applicant's Guide*, Volume II, National Chapters, all available from WIPO's Internet site, at <http://www.wipo.int/pct/en/index.html>.

It is the applicant's **sole responsibility** to monitor all these time limits.

The International Bureau of WIPO 34, chemin des Colombettes 1211 Geneva 20, Switzerland	Authorized officer  <b>Agnès Wittmann-Regis</b>
Facsimile No. +41 22 338 82 70	e-mail: <a href="mailto:pt06.pct@wipo.int">pt06.pct@wipo.int</a>



From the INTERNATIONAL BUREAU

**PCT**NOTIFICATION CONCERNING  
AVAILABILITY OF THE PUBLICATION  
OF THE INTERNATIONAL APPLICATION

To:

AMELINE, Jean-Paul  
Cabinet PLASSERAUD  
52 rue de la Victoire  
F-75440 Paris Cedex 09  
FRANCE

Date of mailing ( <i>day/month/year</i> ) 13 February 2014 (13.02.2014)		<b>IMPORTANT NOTICE</b>	
Applicant's or agent's file reference BCT130177OD			
International application No. PCT/EP2013/066492	International filing date ( <i>day/month/year</i> ) 06 August 2013 (06.08.2013)	Priority date ( <i>day/month/year</i> ) 08 August 2012 (08.08.2012)	
Applicant TOTAL SA et al			

The applicant is hereby **notified** that the International Bureau:

has **published** the above-indicated international application on 13 February 2014 (13.02.2014) under No. WO 2014/023737

has **republished** the above-indicated international application on under No. WO

For an explanation as to the reason for this republication of the international application, reference is made to INID codes (15), (48) or (88) (*as the case may be*) on the front page of the published international application.

A copy of the international application is available for viewing and downloading on WIPO's website at the following address: [www.wipo.int/pctdb](http://www.wipo.int/pctdb) (in the appropriate field of the structured search, enter the PCT or WO number).

The applicant may also obtain a paper copy of the published international application from the International Bureau by sending an e-mail to [patentscope@wipo.int](mailto:patentscope@wipo.int) or by submitting a written request to the contact details provided below.

The International Bureau of WIPO 34, chemin des Colombettes 1211 Geneva 20, Switzerland	Authorized officer  Agnès Wittmann-Regis
Facsimile No. +41 22 338 82 70	e-mail: <a href="mailto:pt06.pct@wipo.int">pt06.pct@wipo.int</a>



From the INTERNATIONAL BUREAU

**PCT**NOTIFICATION CONCERNING  
AVAILABILITY OF THE PUBLICATION  
OF THE INTERNATIONAL APPLICATION

To:

AMELINE, Jean-Paul  
Cabinet PLASSERAUD  
52 rue de la Victoire  
F-75440 Paris Cedex 09  
FRANCE

Date of mailing ( <i>day/month/year</i> ) 01 May 2014 (01.05.2014)		
Applicant's or agent's file reference BCT130177OD		<b>IMPORTANT NOTICE</b>
International application No. PCT/EP2013/066492	International filing date ( <i>day/month/year</i> ) 06 August 2013 (06.08.2013)	Priority date ( <i>day/month/year</i> ) 08 August 2012 (08.08.2012)
Applicant TOTAL SA et al		

The applicant is hereby **notified** that the International Bureau:

- has **published** the above-indicated international application on under No. WO
- has **republished** the above-indicated international application on 01 May 2014 (01.05.2014) under No. WO 2014/023737  
For an explanation as to the reason for this republication of the international application, reference is made to INID codes (15), (48) or (88) (*as the case may be*) on the front page of the published international application.

A copy of the international application is available for viewing and downloading on WIPO's website at the following address: [www.wipo.int/pctdb](http://www.wipo.int/pctdb) (in the appropriate field of the structured search, enter the PCT or WO number).The applicant may also obtain a paper copy of the published international application from the International Bureau by sending an e-mail to [patentscope@wipo.int](mailto:patentscope@wipo.int) or by submitting a written request to the contact details provided below.

The International Bureau of WIPO 34, chemin des Colombettes 1211 Geneva 20, Switzerland	Authorized officer  Agnès Wittmann-Regis
Facsimile No. +41 22 338 82 70	e-mail: <a href="mailto:pt06.pct@wipo.int">pt06.pct@wipo.int</a>

**PCT REQUEST**

Print Out (Original in Electronic Form)

<b>0</b>	<b>For receiving Office use only</b>	
<b>0-1</b>	International Application No.	<b>PCT/EP2013/066492</b>
<b>0-2</b>	International Filing Date	<b>06 AUG 2013 (06.08.2013)</b>
<b>0-3</b>	Name of receiving Office and "PCT International Application"	<b>RO/EP</b>
<b>0-4</b>	<b>Form PCT/RO/101 PCT Request</b>	
0-4-1	Prepared Using	<b>PCT Online Filing Version 3.5.000.235 MT/FOP 20020701/0.20.5.20</b>
<b>0-5</b>	<b>Petition</b> The undersigned requests that the present international application be processed according to the Patent Cooperation Treaty	
<b>0-6</b>	<b>Receiving Office (specified by the applicant)</b>	<b>European Patent Office (EPO) (RO/EP)</b>
<b>0-7</b>	<b>Applicant's or agent's file reference</b>	<b>BCT130177OD</b>
<b>I</b>	<b>Title of Invention</b>	<b>METHOD FOR ENHANCING THE DETERMINATION OF A SEISMIC HORIZON</b>
<b>II</b>	<b>Applicant</b>	
II-1	This person is	<b>Applicant only</b>
II-2	Applicant for	<b>All designated States</b>
II-4	Name	<b>TOTAL SA</b>
II-5	Address	<b>2 place Jean Millier La Défense 6 92400 COURBEVOIE France</b>
II-6	State of nationality	<b>FR</b>
II-7	State of residence	<b>FR</b>
<b>III-1</b>	<b>Applicant and/or inventor</b>	
III-1-1	This person is	<b>Applicant only</b>
III-1-2	Applicant for	<b>All designated States</b>
III-1-4	Name	<b>CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE - CNRS -</b>
III-1-5	Address	<b>3, rue Michel Ange 75794 PARIS CEDEX 16</b>
III-1-6	State of nationality	<b>FR</b>
III-1-7	State of residence	

**PCT REQUEST**

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<b>III-2</b>	<b>Applicant and/or inventor</b>	
III-2-1	This person is	<b>Applicant only</b>
III-2-2	Applicant for	<b>All designated States</b>
III-2-4	Name	<b>UNIVERSITE de BORDEAUX I</b>
III-2-5	Address	<b>351, cours de la Libération 33400 TALENCE</b>
III-2-6	State of nationality	<b>FR</b>
III-2-7	State of residence	<b>FR</b>
<b>III-3</b>	<b>Applicant and/or inventor</b>	
III-3-1	This person is	<b>Applicant only</b>
III-3-2	Applicant for	<b>All designated States</b>
III-3-4	Name	<b>École Nationale Supérieure des Sciences Agronomiques de Bordeaux-Aquitaine</b>
III-3-5	Address	<b>1 Cours du Général de Gaulle 33170 GRADIGNAN France</b>
III-3-6	State of nationality	<b>FR</b>
III-3-7	State of residence	<b>FR</b>
<b>III-4</b>	<b>Applicant and/or inventor</b>	
III-4-1	This person is	<b>Applicant only</b>
III-4-2	Applicant for	<b>All designated States</b>
III-4-4	Name	<b>INSTITUT POLYTECHNIQUE DE BORDEAUX</b>
III-4-5	Address	<b>1 avenue du Docteur Albert Schweitzer 33400 TALENCE France</b>
III-4-6	State of nationality	<b>FR</b>
III-4-7	State of residence	<b>FR</b>
<b>III-5</b>	<b>Applicant and/or inventor</b>	
III-5-1	This person is	<b>Inventor only</b>
III-5-3	Inventor for	
III-5-4	Name (LAST, First)	<b>ZINCK, Guillaume</b>
III-5-5	Address	<b>351 Cours de la Libération 33405 TALENCE France</b>
<b>III-6</b>	<b>Applicant and/or inventor</b>	
III-6-1	This person is	<b>Inventor only</b>
III-6-3	Inventor for	
III-6-4	Name (LAST, First)	<b>DONIAS, Marc</b>
III-6-5	Address	<b>351 Cours de la Libération 33405 TALENCE France</b>

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<b>III-7</b>	<b>Applicant and/or inventor</b>	
III-7-1	This person is	<b>Inventor only</b>
III-7-3	Inventor for	
III-7-4	Name (LAST, First)	<b>DANIEL, Jacques</b>
III-7-5	Address	<b>351 Cours de la Libération 33405 TALENCE France</b>
<b>III-8</b>	<b>Applicant and/or inventor</b>	
III-8-1	This person is	<b>Inventor only</b>
III-8-3	Inventor for	
III-8-4	Name (LAST, First)	<b>LAVIALLE, Olivier</b>
III-8-5	Address	<b>351 Cours de la Libération 33405 TALENCE France</b>
<b>III-9</b>	<b>Applicant and/or inventor</b>	
III-9-1	This person is	<b>Inventor only</b>
III-9-3	Inventor for	
III-9-4	Name (LAST, First)	<b>GUILLOIN, Sébastien</b>
III-9-5	Address	<b>C/O TOTAL SA CSTJF-EB 279 Avenue Larribau 64000 PAU France</b>
<b>IV-1</b>	<b>Agent or common representative; or address for correspondence</b>	
	The person identified below is hereby/ has been appointed to act on behalf of the applicant(s) before the competent International Authorities as:	<b>Agent</b>
IV-1-1	Name (LAST, First)	<b>AMELINE, Jean-Paul</b>
IV-1-2	Address	<b>Cabinet PLASSERAUD 52 rue de la Victoire 75440 PARIS CEDEX 09 France</b>
IV-1-3	Telephone No.	<b>00 33 1 40 16 70 00</b>
IV-1-4	Facsimile No.	<b>00 33 1 42 80 01 59</b>
IV-1-5	e-mail	<b>info@plass.com</b>
<b>IV-2</b>	<b>Additional agent(s)</b>	<b>additional agent(s) with same address as first named agent</b>
IV-2-1	Name(s)	<b>BEROGIN, Francis; KOENIG, Christine; BOIRE, Philippe; BURBAUD, Eric; CHATEAU, Marielle; COUSIN, Geoffroy; HASSINE, Albert; LE FALHER, Guy; LOISEL, Bertrand; LOUBAT, Patrice; PRIEUR, Patrick; VERDURE, Stéphane; WLODARCZYK, Lukasz; LOUVEL, Philippe; MOORE, Nicholas</b>

**PCT REQUEST**

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<b>V</b>	<b>DESIGNATIONS</b>		
<b>V-1</b>	<b>The filing of this request constitutes under Rule 4.9(a), the designation of all Contracting States bound by the PCT on the international filing date, for the grant of every kind of protection available and, where applicable, for the grant of both regional and national patents.</b>		
<b>VI-1</b>	<b>Priority claim of earlier national application</b>		
VI-1-1	Filing date	<b>08 August 2012 (08.08.2012)</b>	
VI-1-2	Number	<b>61/681 005</b>	
VI-1-3	Country	<b>US</b>	
<b>VI-2</b>	<b>Incorporation by reference :</b> where an element of the international application referred to in Article 11(1)(iii)(d) or (e) or a part of the description, claims or drawings referred to in Rule 20.5(a) is not otherwise contained in this international application but is completely contained in an earlier application whose priority is claimed on the date on which one or more elements referred to in Article 11(1)(iii) were first received by the receiving Office, that element or part is, subject to confirmation under Rule 20.6, incorporated by reference in this international application for the purposes of Rule 20.6.		
<b>VII-1</b>	<b>International Searching Authority Chosen</b>	<b>European Patent Office (EPO) (ISA/EP)</b>	
<b>VIII</b>	<b>Declarations</b>	Number of declarations	
VIII-1	Declaration as to the identity of the inventor	—	
VIII-2	Declaration as to the applicant's entitlement, as at the international filing date, to apply for and be granted a patent	—	
VIII-3	Declaration as to the applicant's entitlement, as at the international filing date, to claim the priority of the earlier application	—	
VIII-4	Declaration of inventorship (only for the purposes of the designation of the United States of America)	—	
VIII-5	Declaration as to non-prejudicial disclosures or exceptions to lack of novelty	—	
<b>IX</b>	<b>Check list</b>	Number of sheets	Electronic file(s) attached
IX-1	Request (including declaration sheets)	<b>5</b>	✓
IX-2	Description	<b>32</b>	✓
IX-3	Claims	<b>8</b>	✓
IX-4	Abstract	<b>1</b>	✓
IX-5	Drawings	<b>8</b>	✓
IX-7	TOTAL	<b>54</b>	

**PCT REQUEST**

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	<b>Accompanying Items</b>	Paper document(s) attached	Electronic file(s) attached
IX-8	Fee calculation sheet	—	✓
IX-18	PCT-SAFE physical media	—	—
<b>IX-20</b>	<b>Figure of the drawings which should accompany the abstract</b>	<b>12</b>	
<b>IX-21</b>	<b>Language of filing of the international application</b>	<b>English</b>	
<b>X-1</b>	<b>Signature of applicant, agent or common representative</b>	<b>(PKCS7 Digital Signature)</b>	
<b>X-1-1</b>	Name (LAST, First)	<b>AMELINE, Jean-Paul</b>	
<b>X-1-2</b>	Name of signatory	<b>, Jean-Paul Ameline 33528</b>	
<b>X-1-3</b>	Capacity (if such capacity is not obvious from reading the request)	<b>(Representative)</b>	

**FOR RECEIVING OFFICE USE ONLY**

<b>10-1</b>	<b>Date of actual receipt of the purported international application</b>	<b>06 AUG 2013 (06.08.2013)</b>
<b>10-2</b>	<b>Drawings:</b>	<b>X</b>
10-2-1	Received	
10-2-2	Not received	
<b>10-3</b>	<b>Corrected date of actual receipt due to later but timely received papers or drawings completing the purported international application</b>	
<b>10-4</b>	<b>Date of timely receipt of the required corrections under PCT Article 11(2)</b>	
<b>10-5</b>	<b>International Searching Authority</b>	<b>ISA/EP</b>
<b>10-6</b>	<b>Transmittal of search copy delayed until search fee is paid</b>	

**FOR INTERNATIONAL BUREAU USE ONLY**

<b>11-1</b>	<b>Date of receipt of the record copy by the International Bureau</b>	
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PATENT APPLICATION

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

In re the application of:

Attorney Docket No.: 4229.108WOUS01

Guillaume ZINCK et al.

Confirmation No.:

Application No.:

Examiner:

Filed: Concurrent herewith

Group Art Unit:

For: METHOD FOR ENHANCING THE DETERMINATION OF A SEISMIC HORIZON

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PRELIMINARY AMENDMENT

Mail Stop Amendment  
Commissioner for Patents  
P.O. Box 1450  
Alexandria, VA 22313-1450

Commissioner:

INTRODUCTORY COMMENTS

Prior to examination, please amend the above-identified application as follows:

The present amendment comprises the following sections:

- A. Amendments to the Specification
- B. Amendments to the Claims
- C. Remarks

*Please grant any extension of time necessary for entry; charge any fee due to Deposit Account No. 16-0631.*

AMENDMENTS TO THE SPECIFICATION

In the Specification

Please substitute the attached Substitute Specification, marked "Clean Copy" for the Specification currently on file. A "Marked-Up Copy" showing all the changes made is also attached hereto (deleted matter is shown by strikethrough or double brackets and added matter is shown by underlining). This Substitute Specification includes no new matter.

In the Abstract

Please substitute the following amended Abstract for the Abstract as currently pending (deleted matter is shown by strikethrough and added matter is shown by underlining):

The invention pertains to a method for enhancing the determination, from a seismic image, of at least a portion of a seismic horizon in a three-dimensional domain, ~~wherein said~~ The method comprises: ~~receiving the seismic image; receiving a plurality of related control points; defining pseudo-rectangles; for each pseudo-rectangle~~ receiving the seismic image; receiving a plurality of related control points; defining pseudo-rectangles; for each pseudo-rectangle ~~applying a diffeomorphic transformation F; defining a new domain; transforming points of the seismic image; transforming said pseudo-rectangle into a corresponding rectangle; applying a horizon reconstruction algorithm to the transformed points, to determine a part of a transformed horizon, the reconstruction comprising solving a Poisson equation; and computing a part of the horizon, said computing comprising applying an inverse diffeomorphic transformation  $F^{-1}$  to the determined part of a transformed horizon.~~ applying a diffeomorphic transformation F; defining a new domain; transforming points of the seismic image; transforming said pseudo-rectangle into a corresponding rectangle; applying a horizon reconstruction algorithm to the transformed points, to determine a part of a transformed horizon, the reconstruction comprising solving a Poisson equation; and computing a part of the horizon, said computing comprising applying an inverse diffeomorphic transformation  $F^{-1}$  to the determined part of a transformed horizon.

AMENDMENTS TO THE CLAIMS

A detailed listing of all claims that are, or were, in the present application, irrespective of whether the claim(s) remain(s) under examination in the application is presented below. The claims are presented in ascending order and each includes one status identifier. Those claims not cancelled or withdrawn but amended by the current amendment utilize the following notations for amendment: 1. deleted matter is shown by strikethrough for six or more characters and double brackets for five or fewer characters; and 2. added matter is shown by underlining.

1. (Currently Amended) A [[M]] method for enhancing the determination, from a seismic image, of at least a portion of a seismic horizon in a three-dimensional domain (4) comprising axes  $\bar{X}$ ,  $\bar{Y}$ ,  $\bar{Z}$ , said seismic horizon being a function of coordinates along axes  $\bar{X}$ ,  $\bar{Y}$  in said three-dimensional domain (4),

wherein said method comprises:

[[ - ]] receiving (S1) the seismic image, the seismic image having points associated with coordinates along axes  $\bar{X}$ ,  $\bar{Y}$ ,  $\bar{Z}$ ;

[[ - ]] receiving (S2) a plurality of related control points (201, 202, 203, 204, 205, 206, 207, 208) associated with coordinates on axes  $\bar{X}$ ,  $\bar{Y}$ ,  $\bar{Z}$ ;

[[ - ]] in a reference plane (40) defined by axes  $\bar{X}$  and  $\bar{Y}$ , defining, for at least one related control point among the plurality of related control points (201, 202, 203, 204, 205, 206, 207, 208), an associated reference point with coordinates along axes  $\bar{X}$ ,  $\bar{Y}$ , among a plurality of reference points (210, 220, 230, 240, 250, 260, 270, 280), the reference point having coordinates on axes  $\bar{X}$  and  $\bar{Y}$  identical to coordinates on axes  $\bar{X}$  and  $\bar{Y}$  of the related control point,

[[ - ]] defining (S3) pseudo-rectangles in said reference plane (40), each pseudo-rectangle comprising a reference point among a plurality of reference points (210, 220, 230, 240, 250, 260, 270, 280);

[[ - ]] for each current pseudo-rectangle among the defined pseudo-rectangles:

- applying a diffeomorphic transformation  $F$  (S50), said diffeomorphic transformation  $F$ :

- [[ - ]] being a function of coordinates along  $\bar{X}$ ,  $\bar{Y}$  and defining a new domain comprising axes  $\bar{X}'$ ,  $\bar{Y}'$ ,  $\bar{Z}$ ;
- [[ - ]] transforming points of the seismic image having coordinates along axes  $\bar{X}$ ,  $\bar{Y}$  identical to coordinates along axes  $\bar{X}$ ,  $\bar{Y}$  of points in said current pseudo-rectangle, said points of the seismic image including the related control point associated with the current pseudo-rectangle;
- [[ - ]] transforming said current pseudo-rectangle into a corresponding rectangle;
- [[ - ]] applying ~~(S52, S53, S54, S55)~~ a horizon reconstruction algorithm to the transformed points, to determine a part of a transformed horizon ~~(7020)~~, said part of a transformed horizon ~~(7020)~~ comprising the transformed related control point ~~(602)~~, the reconstruction of the seismic horizon comprising solving ~~(S54)~~ the Poisson equation  $\Delta(\delta\tau) = -\text{div}(r)$ , where  $\delta\tau$  is an unknown function of coordinates along axes  $\bar{X}'$ ,  $\bar{Y}'$ ,  $\Delta$  denotes the Laplace operator in the new domain,  $\text{div}$  denotes the divergence vector operator in the new domain and  $r$  is a fixed function of coordinates along axes  $\bar{X}'$ ,  $\bar{Y}'$ ;
- [[ - ]] computing a part of the horizon ~~(720)~~, said computing of a part of the horizon ~~(720)~~ comprising applying ~~(S6)~~ an inverse diffeomorphic transformation  $F^{-1}$  to the determined part of a transformed horizon ~~(7020)~~.

2. (Currently Amended) ~~The m[[M]]ethod according to~~ of claim 1 wherein, a pseudo-rectangle is defined so that the reference point (220) comprised in a pseudo-rectangle (3220) belongs to a current reference edge (320) of said pseudo-rectangle (3220).

3. (Currently Amended) ~~The m[[M]]ethod according to~~ of claim 2, wherein prior to applying a diffeomorphic transformation F (S50), said method comprises applying, for each current pseudo-rectangle (3220) comprising a reference point (220) belonging to a current reference edge (320) of said pseudo-rectangle (3220) among the defined pseudo-rectangles, for each current reference edge of said current pseudo-rectangle (3220), a horizon reconstruction algorithm to edge points having coordinates along axes  $\bar{X}$ ,  $\bar{Y}$  identical to the coordinates along axes  $\bar{X}$ ,  $\bar{Y}$  of reference edge points of said current reference edge.

4. (Currently Amended) ~~The m[[M]]ethod according to any one of the preceding of~~ claim[[s]] 1, wherein at least one reference corner of each pseudo-rectangle among the defined pseudo-rectangles has coordinates along axes  $\bar{X}$ ,  $\bar{Y}$  identical to the coordinates along axes  $\bar{X}$ ,  $\bar{Y}$  of a related control point among the plurality of related control points (201, 202, 203, 204, 205, 206, 207, 208).

5. (Currently Amended) ~~The m[[M]]ethod according to any one of the preceding of~~ claim[[s]] 1, wherein the received plurality of related control points (201, 202, 203, 204, 205, 206, 207, 208) comprises at least three related control points (201, 202, 203), and wherein defining pseudo-rectangles comprises:

- [[ -]] identifying reference points in a reference plane-(10);
- [[ -]] identifying triangles having a first reference corner-(210), a second reference corner (220)-and a third reference corner (230)-among the identified reference points (210, 220, 230, 240, 250, 260, 270, 280)-using a triangulation, and
- [[ -]] in each of the identified triangles:
  - [[ -]] identifying a reference centroid (2123)-of said triangle,
  - [[ -]] identifying a first reference center (212)-of the segment defined by the first reference corner (210)-and the second reference corner(220);
  - [[ -]] identifying a second reference center (213)-of the segment defined by the first reference corner (210)-and the third reference corner-(230);

wherein a pseudo rectangle is defined by segments connecting the first reference corner (210) with the first reference center-(212), the first reference center (212)-with the reference centroid (2123), the reference centroid (2123)-with the second reference center (213)-and the second reference center (213)-with the first reference corner-(210).

6. (Currently Amended) The m[[M]]method according to of claim 5, wherein prior to applying a diffeomorphic transformation F-({S50}), the method comprises, for an identified triangle:

- [[ -]] identifying a first-(201), second-(202) and third-(203) related control point among the plurality of related control points associated with corresponding first-(210), second (220) and third-(230) reference corners of said identified triangle;

- [[{-]] applying a horizon reconstruction algorithm to points of a plane comprising axis  $\vec{Z}$  and comprising the first (201)-and second (202)-related control points to determine a first portion of a first local horizon;
- [[{-]] identifying a first related central point on the first portion of the first local horizon having coordinates along axes  $\vec{X}$  and  $\vec{Y}$  identical to coordinates along axes  $\vec{X}$  and  $\vec{Y}$  of the first reference center-(212);
- [[{-]] applying a horizon reconstruction algorithm to points of a plane comprising axis  $\vec{Z}$  and comprising the first (201)-and third (203)-related control points to determine a second portion of a second local horizon;
- [[{-]] identifying a second related central point on the second portion of the second local horizon having coordinates along axes  $\vec{X}$  and  $\vec{Y}$  identical to coordinates along axes  $\vec{X}$  and  $\vec{Y}$  of the second reference center-(213);
- [[{-]] computing a coordinate along axis  $\vec{Z}$  of a related middle point having coordinates along axes  $\vec{X}$  and  $\vec{Y}$  identical to coordinates along axes  $\vec{X}$  and  $\vec{Y}$  of the reference centroid (213)-of said identified triangle, the computation of said coordinate along axis  $\vec{Z}$  being a function of the coordinates of a point on said determined first or second local horizons.

7. (Currently Amended) The m[[M]]ethod according to of claim 6, wherein computing a coordinate along axis  $\vec{Z}$  of the related middle point of said identified triangle is achieved by applying a horizon reconstruction algorithm to points of a plane comprising axis  $\vec{Z}$  and

comprising the segment connecting the first (212)-reference center with the reference centroid or the segment connecting the second (213)-reference center with the reference centroid-(2123).

8. (Currently Amended) ~~The m[[M]]ethod according to of~~ claim 6, wherein computing a coordinate along axis  $\bar{Z}$  of the related middle point is achieved by calculating the mean value of the coordinates along axis  $\bar{Z}$  of at least the first (212)-and second (213)-related central points.

9. (Currently Amended) ~~The m[[M]]ethod according to any one of the preceding of~~ claim[[s]] 1, wherein the Poisson equation is solved (854)-using a Fourier transform algorithm.

10. (Currently Amended) ~~The m[[M]]ethod according to any one of the preceding of~~ claim[[s]] 1, wherein the defined pseudo-rectangles map a continuous portion of the reference plane-(10).

11. (Currently Amended) ~~The m[[M]]ethod according to any one of the preceding of~~ claim[[s]] 1, wherein the method further comprises computing a portion of a seismic horizon (800)-from at least the computed part of the horizon (720)-of each current pseudo-rectangle among the defined pseudo-rectangles.

12. (Currently Amended) ~~The m[[M]]ethod according to any one of~~ claim[[s]] 5-to-8-and-any of-claims-9-to-10, wherein the method further comprises computing a portion of a seismic horizon (800)-from at least the computed part of the horizon (720)-of each current pseudo-

rectangle among the defined pseudo-rectangles, and after computing a portion of a seismic horizon-(800), the method comprises:

- [[ - ]] receiving modification information relating to the related control points;
- [[ - ]] identifying pseudo-rectangles affected by said received modification information relating to the related control points;
- [[ - ]] defining a new set of pseudo-rectangles in a local area corresponding to the area occupied by said pseudo-rectangles affected by said received modification information relating to the related control points ;
- [[ - ]] for each current pseudo-rectangle among the new set of pseudo-rectangles:
  - [[ - ]] applying a diffeomorphic transformation  $F$ -(S50), said diffeomorphic transformation  $F$  :
    - [[ - ]] being a function of coordinates along  $\vec{X}$ ,  $\vec{Y}$  and defining a new domain comprising axes  $\vec{X}'$ ,  $\vec{Y}'$ ,  $\vec{Z}$ ;
    - [[ - ]] transforming points of the seismic image having coordinates along axes  $\vec{X}$ ,  $\vec{Y}$  identical to coordinates along axes  $\vec{X}$ ,  $\vec{Y}$  of points in said current pseudo-rectangle, said points of the seismic image including the related control point associated with the current pseudo-rectangle;
    - [[ - ]] transforming said current pseudo-rectangle into a corresponding rectangle;
  - [[ - ]] applying (S52, S53, S54, S55)-a horizon reconstruction algorithm to the transformed points, to determine a part of a transformed horizon-(7020), said part of a transformed horizon-(7020) comprising the transformed related control point

(602), the reconstruction of the seismic horizon comprising-(S54) solving the Poisson equation  $\Delta(\delta\tau) = -\text{div}(r)$ , where  $\delta\tau$  is an unknown function of coordinates along axes  $\bar{X}'$ ,  $\bar{Y}'$ ,  $\Delta$  denotes the Laplace operator in the new domain,  $\text{div}$  denotes the divergence vector operator in the new domain and  $r$  is a fixed function of coordinates along axes  $\bar{X}'$ ,  $\bar{Y}'$ ;

[[ - ]] computing a part of the horizon-(720), said computing of a part of the horizon-(720) comprising applying-(S6) an inverse diffeomorphic transformation  $F^{-1}$  to the determined part of a transformed horizon-(7020).

13. (Currently Amended) A [[D]] device-(1300) for enhancing the determination, from a seismic image, of at least a portion of a seismic horizon in a three-dimensional domain-(1) comprising axes  $\bar{X}$ ,  $\bar{Y}$ ,  $\bar{Z}$ , said seismic horizon being a function of coordinates along axes  $\bar{X}$ ,  $\bar{Y}$  in said three-dimensional domain-(1), wherein said device-(1300) comprises:

[[ - ]] an input interface-(1303) for receiving-(S1) the seismic image, the seismic image having points associated with coordinates along axes  $\bar{X}$ ,  $\bar{Y}$ ,  $\bar{Z}$ ; and for receiving-(S2) a plurality of related control points-(201, 202, 203, 204, 205, 206, 207, 208) associated with coordinates on axes  $\bar{X}$ ,  $\bar{Y}$ ,  $\bar{Z}$ ;

[[ - ]] a circuit-(1304) for defining, in a reference plane-(10) defined by axes  $\bar{X}$  and  $\bar{Y}$ , for at least one related control point among the plurality of related control points-(201, 202, 203, 204, 205, 206, 207, 208), an associated reference point with coordinates

along axes  $\bar{X}$ ,  $\bar{Y}$ , among a plurality of reference points (~~210, 220, 230, 240, 250, 260, 270, 280~~), the reference point having coordinates on axes  $\bar{X}$  and  $\bar{Y}$  identical to coordinates on axes  $\bar{X}$  and  $\bar{Y}$  of the related control point,

[[~~-~~]] a circuit(~~1304~~) for defining pseudo-rectangles in the reference plane(~~10~~), each pseudo-rectangle comprising a reference point among a plurality of reference points (~~210, 220, 230, 240, 250, 260, 270, 280~~);

[[~~-~~]] a circuit(~~1304~~) being adapted for, for each current pseudo-rectangle among the defined pseudo-rectangles:

[[~~-~~]] applying a diffeomorphic transformation F(~~S50~~), said diffeomorphic transformation F:

[[~~-~~]] being a function of coordinates along  $\bar{X}$ ,  $\bar{Y}$  and defining a new domain comprising axes  $\bar{X}'$ ,  $\bar{Y}'$ ,  $\bar{Z}$ ;

[[~~-~~]] transforming points of the seismic image having coordinates along axes  $\bar{X}$ ,  $\bar{Y}$  identical to coordinates along axes  $\bar{X}$ ,  $\bar{Y}$  of points in said current pseudo-rectangle, said points of the seismic image including the related control point associated with the current pseudo-rectangle;

[[~~-~~]] transforming said current pseudo-rectangle into a corresponding rectangle;

[[~~-~~]] applying(~~S52, S53, S54, S55~~) a horizon reconstruction algorithm to the transformed points, to determine a part of a transformed horizon(~~7020~~), said part of a transformed horizon(~~7020~~) comprising the transformed related control point

(602), the reconstruction of the seismic horizon comprising solving-(S54) the Poisson equation  $\Delta(\delta\tau) = -\text{div}(r)$ , where  $\delta\tau$  is an unknown function of coordinates along axes  $\bar{X}'$ ,  $\bar{Y}'$ ,  $\Delta$  denotes the Laplace operator in the new domain,  $\text{div}$  denotes the divergence vector operator in the new domain and  $r$  is a fixed function of coordinates along axes  $\bar{X}'$ ,  $\bar{Y}'$ ;

[[ -]] computing a part of the horizon-(720), said computing of a part of the horizon-(720) comprising applying-(S6) an inverse diffeomorphic transformation  $F^{-1}$  to the determined part of a transformed horizon-(7020).

14. (Currently Amended) A non-transitory computer readable storage medium, having stored thereon a computer program comprising program instructions, the computer program being loadable into a data-processing unit and adapted to cause the data-processing unit to carry out a method for enhancing the determination, from a seismic image, of at least a portion of a seismic horizon in a three-dimensional domain comprising axes  $\bar{X}_z$ ,  $\bar{Y}_z$ ,  $\bar{Z}_z$ , said seismic horizon being a function of coordinates along axes  $\bar{X}_z$ ,  $\bar{Y}_z$  in said three-dimensional domain, wherein said method comprises:

receiving the seismic image, the seismic image having points associated with coordinates

along axes  $\bar{X}_z$ ,  $\bar{Y}_z$ ,  $\bar{Z}_z$ ;

receiving a plurality of related control points associated with coordinates on axes  $\bar{X}_z$ ,  $\bar{Y}_z$ ,

$\bar{Z}_z$ ;

in a reference plane defined by axes  $\bar{X}$  and  $\bar{Y}$ , defining, for at least one related control point among the plurality of related control points, an associated reference point with coordinates along axes  $\bar{X}$ ,  $\bar{Y}$ , among a plurality of reference points, the reference point having coordinates on axes  $\bar{X}$  and  $\bar{Y}$  identical to coordinates on axes  $\bar{X}$  and  $\bar{Y}$  of the related control point,

defining pseudo-rectangles in said reference plane, each pseudo-rectangle comprising a reference point among a plurality of reference points;

for each current pseudo-rectangle among the defined pseudo-rectangles:

applying a diffeomorphic transformation  $F$ , said diffeomorphic transformation  $F$ ;

being a function of coordinates along  $\bar{X}$ ,  $\bar{Y}$  and defining a new domain comprising axes  $\bar{X}'$ ,  $\bar{Y}'$ ,  $\bar{Z}$ ;

transforming points of the seismic image having coordinates along axes  $\bar{X}$ ,  $\bar{Y}$  identical to coordinates along axes  $\bar{X}$ ,  $\bar{Y}$  of points in said current pseudo-rectangle, said points of the seismic image including the related control point associated with the current pseudo-rectangle;

transforming said current pseudo-rectangle into a corresponding rectangle;

applying a horizon reconstruction algorithm to the transformed points, to determine a part of a transformed horizon, said part of a transformed horizon comprising the transformed related control point, the reconstruction of the seismic horizon

comprising solving the Poisson equation  $\Delta(\delta\tau) = -\text{div}(r)$ , where  $\delta\tau$  is an unknown function of coordinates along axes  $\vec{X}'$ ,  $\vec{Y}'$ ,  $\Delta$  denotes the Laplace operator in the new domain,  $\text{div}$  denotes the divergence vector operator in the new domain and  $r$  is a fixed function of coordinates along axes  $\vec{X}'$ ,  $\vec{Y}'$ ;

computing a part of the horizon, said computing of a part of the horizon comprising applying an inverse diffeomorphic transformation  $F^{-1}$  to the determined part of a transformed horizon  
the steps of any of claims 1-12 when the computer program is run by the data processing device.

REMARKS

Claims 1-14 are pending. By this Amendment, no claims are cancelled, claims 1-14 are amended and no new claims are added.

In view of the foregoing, it is submitted that this application is in condition for allowance. Favorable consideration and prompt allowance of the application are respectfully requested.

The Examiner is invited to telephone the undersigned if the Examiner believes it would be useful to advance prosecution.

Respectfully submitted,



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5           **METHOD FOR ENHANCING THE DETERMINATION OF SEISMIC HORIZON**

RELATED APPLICATIONS

The present application is a National Phase entry of PCT Application No. PCT/EP2013/066492, filed August 6, 2013, which claims priority from U.S. Patent Application No. 61/681,005, filed August 8, 2012, said applications being hereby incorporated by reference herein in their entirety.

10

TECHNICAL FIELD

The invention pertains to the field of methods implemented in order to determine seismic horizons. The invention more specifically relates to a method that enhances the determination of a seismic horizon without suffering from some of the drawbacks of the prior art.

15

BACKGROUND OF THE INVENTION

Geological surveys involving generators of seismic waves and detectors of their reflections in the ground are often conducted to determine the position of oil reservoirs and/or to get to know the composition and thickness of the many layers that form the underground. Seismic reflection techniques consist in generating a seismic wave that propagates through the ground and reflects at the interfaces thereof. A precise measurement of these echoes and more specifically of their arrival times enables a determination of the shape, depth and composition of the layers that the seismic waves went through.

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In a first phase following the measurement of these data signals, image generation algorithms, well-known in the art, are used to reconstruct a raw picture of the underground in the form of seismic images, sometimes also referred to as echographic images. These images can be either two-dimensional in shape or three-dimensional. Such seismic images comprise pixels the intensity of which is correlated to a seismic wave amplitude, dependent on the local impedance variation.

Geophysicists are used to manipulating such seismic images displaying information relating to amplitude. By merely looking at such seismic images, a geophysicist is capable of identifying areas of the underground having distinct characteristics, and use these to determine the corresponding structure of the underground.

Automatic techniques for extracting structural information from seismic images are known. These generally involve seismic horizon reconstruction algorithms that analyze amplitude gradients in a seismic image and extract the tangent of the local dip in a direction that is transverse to that gradient. Examples of techniques used for reconstructing a seismic horizon using a seismic image are for example described in the French patent FR 2 869 693 and US application US 20130083973.

Sometimes the exact depth of a layer can be known due to other data inputs or because of reliable geological information. Therefore, it is sometimes useful to define fixed related control points on a seismic image which are known to belong to a seismic horizon. It is then useful to compute a seismic horizon by implementing a seismic reconstruction algorithm with imposed conditions on a certain limited number of related control points.

One method for reconstructing a seismic horizon with imposed conditions on a number of related control points is described in the article “Flattening with geological constraints” in *Annual Meeting Expanded Abstracts*, Society of Exploration Geophysicists (SEG), 2006, pp. 1053-1056 by J. Lomask and A. Guitton.

5           The method disclosed in this article considers a global approach by solving a two-dimensional nonlinear partial derivative equation relied on local dip. The partial derivative equation is solved using a Gauss-Newton approach by an iterative algorithm whose crucial step is the resolution of a Poisson equation. The approach is global in that it systematically computes a seismic horizon on the entire domain of the seismic image, no matter the number of related  
10 control points received as input.

          Even if it provides realistic seismic horizons, the method proposed by Lomask *et al.* suffers from two major drawbacks: its computational cost is often prohibitive for large data volumes, and it requires solving an iterative algorithm on the entire domain of the seismic image every time a change occurs in the number and/or position of the related control points received as  
15 input.

          The high computational cost of the horizon reconstruction algorithm implemented by Lomask is further increased by the computational means for solving the Poisson equation that forms the core step of the iterative algorithm. In general, another iterative algorithm may be used to solve the Poisson equation. The method disclosed by Lomask therefore comprises an iterative  
20 algorithm within another iterative algorithm.

To overcome these drawbacks, an enhancement of the determination of a seismic horizon that optimizes the computational speed of the horizon reconstruction algorithm is sought.

SUMMARY OF THE INVENTION

5 To achieve such an optimization and thereby overcome the drawbacks of the prior art, the invention provides a method for enhancing the determination, from a seismic image, of at least a portion of a seismic horizon in a three-dimensional domain comprising axes  $\vec{X}$ ,  $\vec{Y}$ ,  $\vec{Z}$ . In this three-dimensional domain, the seismic horizon is a function of coordinates along axes  $\vec{X}$ ,  $\vec{Y}$ . The method comprises:

- 10 - receiving the seismic image, the seismic image having points associated with coordinates along axes  $\vec{X}$ ,  $\vec{Y}$ ,  $\vec{Z}$ ;
- receiving a plurality of related control points associated with coordinates on axes  $\vec{X}$ ,  $\vec{Y}$ ,  $\vec{Z}$ ;
- in a reference plane defined by axes  $\vec{X}$  and  $\vec{Y}$ , defining, for at least one related control point among the plurality of related control points, an associated reference point with coordinates along axes  $\vec{X}$ ,  $\vec{Y}$ , among a plurality of reference points, the reference point having coordinates on axes  $\vec{X}$  and  $\vec{Y}$  identical to coordinates on axes  $\vec{X}$  and  $\vec{Y}$  of the related control point,
- 15
- defining pseudo-rectangles in said reference plane, each pseudo-rectangle comprising
- 20 a reference point among a plurality of reference points.

In a subsequent step, the invention consists in, for each current pseudo-rectangle among the defined pseudo-rectangles:

- applying a diffeomorphic transformation  $F$ , the diffeomorphic transformation  $F$  :
  - being a function of coordinates along  $\vec{X}$ ,  $\vec{Y}$  and defining a new domain comprising axes  $\vec{X}'$ ,  $\vec{Y}'$ ,  $\vec{Z}$ ;
  - transforming points of the seismic image having coordinates along axes  $\vec{X}$ ,  $\vec{Y}$  identical to coordinates along axes  $\vec{X}$ ,  $\vec{Y}$  of points in the current pseudo-rectangle, the points of the seismic image including the related control point associated with the current pseudo-rectangle;
  - transforming the current pseudo-rectangle into a corresponding rectangle;
- applying a horizon reconstruction algorithm to the transformed points, to determine a part of a transformed horizon, the part of a transformed horizon comprising the transformed related control point, the reconstruction of the seismic horizon comprising solving the Poisson equation  $\Delta(\delta\tau) = -\text{div}(r)$ , where  $\delta\tau$  is an unknown function of coordinates along axes  $\vec{X}'$ ,  $\vec{Y}'$ ,  $\Delta$  denotes the Laplace operator in the new domain,  $\text{div}$  denotes the divergence vector operator in the new domain and  $r$  is a fixed function of coordinates along axes  $\vec{X}'$ ,  $\vec{Y}'$ ;

- computing a part of the horizon, the computing of a part of the horizon comprising applying an inverse diffeomorphic transformation  $F^{-1}$  to the determined part of a transformed horizon.

The term pseudo-rectangle is used to refer to any quadrangle or quadrilateral that has a convex shape, that is to say that each of its inner angles is smaller than  $180^\circ$ . Simple diffeomorphic transformations can be used to transform a convex quadrangle into a rectangle.

Axes  $\vec{X}$ ,  $\vec{Y}$ ,  $\vec{Z}$  are used to define corresponding coordinates  $x$ ,  $y$  and  $z$  for each point in the three-dimensional domain.

For the sake of clarity, any point belonging to the reference plane will be referred to using the adjective reference, e.g. a reference center, and the corresponding points on the seismic horizon having the same  $x$  and  $y$  coordinates will be referred to using the adjective related, e.g. a related central point.

One advantageous feature of the invention resides in the definition of pseudo-rectangles that delimit portions of the three-dimensional domain. Each of these portions has a pseudo-rectangular section and comprises points in the vicinity of a related control point. A horizon reconstruction algorithm is applied to the points of these portions of the three-dimensional domain. The combined volume of these portions, corresponding to the sum of all the volumes of the portions defined by pseudo-rectangles, may be smaller than the volume of the domain corresponding to the entire seismic image. This reduction in volume provides a first enhancement of the computational speed of the horizon reconstruction algorithm.

A second advantageous feature of the invention is that it provides fast means for solving the Poisson equation, the latter generally implementing an iterative algorithm within the horizon reconstruction algorithm. To do so, the invention introduces for each previously defined pseudo-rectangle, a corresponding diffeomorphic transformation  $F$  which transforms each pseudo-rectangle into a corresponding rectangle in a transformed reference plane defined by axes  $\vec{X}'$  and  $\vec{Y}'$ . The same diffeomorphic transformation  $F$  also transforms the points of the corresponding portion of the three-dimensional domain into transformed points which are within a transformed portion of the three-dimensional domain delimited by the corresponding rectangle. The purpose of this transformation is to meet some conditions in which the Poisson equation can be solved in one step, i.e. using direct calculation techniques that do not rely on an iterative algorithm. It is known, by a man skilled in the art of solving Poisson equations on discrete systems, that at least two conditions can be met to enable such a fast computation:

- the portion of the three-dimensional domain on which the equation is solved advantageously has a rectangular or circular section and,
- either
  - at least one related control point belongs to the latter portion of the three-dimensional domain, this being also associated with specific conditions on the boundaries called Neumann condition, or
  - the boundary conditions along the edges of the portion of the three-dimensional domain are known, the latter condition being also referred to as Dirichlet boundary condition.

In the invention, the diffeomorphic transformation of pseudo-rectangles into rectangles ensures that the first condition is met. The diffeomorphic transformation associated with a pseudo-rectangle is applied to all the points of the seismic image whose coordinates along axes  $\vec{X}$  and  $\vec{Y}$  match those of points in the pseudo-rectangle. The coordinates along axis  $\vec{Z}$  are not affected by that transformation. The second condition is met by defining pseudo-rectangles that comprise reference points associated with related control points received as input and the coordinates of which are known.

Another original feature of the invention resides in the fact that each diffeomorphic transformation is applied to the portion of the seismic image comprising points having the same x and y coordinates as points in the pseudo-rectangles. Therefore, it may not be necessary to replace the Laplace operator of the Poisson equation by a differential operator with variable coefficients, which would render the resolution of the Poisson equation complex. In the invention, the divergence operator and the fixed function r are the ones that are transformed, thereby enabling the implementation of fast solvers and not necessarily matrix methods.

Finally, another original feature of this invention is the possibility of choosing pseudo-rectangles delimiting portions of the three-dimensional domain having any section suitable for encompassing the received related control points. This is particularly interesting in situations where the related control points are inhomogeneously scattered in the three-dimensional domain, with areas locally having higher concentrations of related control points. In such situations, defining a portion of the three-dimensional domain with a rectangular section may prove difficult insofar as it may require defining rectangles with small dimensions, sometimes referred to as

degenerated rectangles. Horizon reconstruction algorithms might suffer from an insufficient number of data points in portions delimited by such degenerated rectangles and provide less accurate results. The use of pseudo-rectangles gives more freedom in choosing shapes adapted to the local distribution of related control points without suffering from the disadvantages that arise  
5 when defining portions of the three-dimensional domain delimited by rectangles.

More specifically, it may be advantageous that a pseudo-rectangle is defined so that the reference point comprised in a pseudo-rectangle belongs to a current reference edge of said pseudo-rectangle.

In this embodiment, the portion of a seismic horizon is determined by first determining  
10 the boundaries of the portion of the domain delimited by the current pseudo-rectangle. Having a reference point on a current reference edge may increase the efficiency of the algorithm by providing means for calculating these boundaries of the seismic horizon. Indeed, when a reference point belongs to a current reference edge of a pseudo-rectangle, the associated related control point belongs to a related edge of the seismic horizon. It may then be possible to  
15 implement a calculation of the boundaries on the sought seismic horizon.

A further improvement of the method of the invention may consist in choosing advantageous methods for finding boundary conditions in the portion of the three-dimensional domain delimited by a pseudo-rectangle comprising reference points on a current reference edge.

To this end, prior to applying a diffeomorphic transformation  $F$ , the method may  
20 comprise applying, for each current pseudo-rectangle comprising a reference point belonging to a current reference edge of said pseudo-rectangle among the defined pseudo-rectangles, for each

current reference edge of said current pseudo-rectangle, a horizon reconstruction algorithm to edge points having coordinates along axes  $\vec{X}$ ,  $\vec{Y}$  identical to the coordinates along axes  $\vec{X}$ ,  $\vec{Y}$  of reference edge points of said current reference edge.

The horizon reconstruction algorithm implemented to compute these boundary conditions  
5 may be a simplified algorithm insofar as its solutions are functions that can be graphically represented in two dimensions as lines. A first current reference edge may advantageously be chosen as being the one comprising the reference point associated with the related control point. A first horizon line comprising said related control point and forming a first related edge associated with reference edge points of the first current reference edge may be determined. The  
10 extremities of this first related edge may be used to determine, respectively, a second and third related edge, by implementing horizon reconstruction algorithms in a similar fashion on points of faces of the portion of the three-dimensional domain delimited by the current pseudo-rectangle associated with reference edge points of a second and third current reference edge. Two extremities of the second and third related edge may correspond to extremities of a fourth related  
15 edge. Therefore the fourth related edge may be determined by implementing a horizon reconstruction algorithm on edge points of a face associated with a fourth current reference edge, with the condition that the horizon line passes through both extremities of the fourth related edge.

It may be advantageous to perform the calculation of the boundaries prior to applying a  
20 diffeomorphic transformation to each pseudo-rectangle, insofar as some pseudo-rectangles and therefore, the portions of the three-dimensional domain that is delimited by these pseudo-

rectangles, may share at least a portion of an edge. In this way, it may be possible to reduce the number of calculations that are performed to determine the boundary conditions by using the already calculated boundaries of portions of the three-dimensional domain delimited by adjacent pseudo-rectangles. It may however also be possible to perform these calculations individually for  
5 each pseudo-rectangle in the transformed domain after applying a diffeomorphic transformation  $F$ . In this alternative embodiment of the invention, it may be possible to use the corresponding inverse diffeomorphic transformation  $F^{-1}$  to reuse the portions of boundaries that are identical for the portions of the three-dimensional domain delimited by two adjacent pseudo-rectangles.

Some techniques for defining pseudo-rectangles may be particularly advantageous, may  
10 further reduce the computation time of the algorithm, and may be easy to implement.

For instance, it may be possible to define pseudo-rectangles such that at least one reference corner of each pseudo-rectangle among the defined pseudo-rectangles may have coordinates along axes  $\vec{X}$ ,  $\vec{Y}$  identical to the coordinates along axes  $\vec{X}$ ,  $\vec{Y}$  of a related control point among the plurality of related control points.

15 In such an embodiment, each pseudo-rectangle among the defined pseudo-rectangles may have a reference corner associated with a related control point, thus enabling an easy calculation of the boundary conditions, for example by applying successive horizon reconstruction algorithms to points of faces of the portion of the three-dimensional domain comprising a reference edge comprising said corner and axis  $\vec{Z}$ .

20

In a particularly advantageous configuration, the received plurality of related control points may comprise at least three related control points, and defining pseudo-rectangles comprises:

- identifying reference points in the reference plane;
- 5 - identifying triangles having a first reference corner, a second reference corner and a third reference corner among the identified reference points using a triangulation, and
- in each of the identified triangles:
  - identifying a reference centroid of said triangle,
  - identifying a first reference center of the segment defined by the first reference
  - 10 corner and the second reference corner;
  - identifying a second reference center of the segment defined by the first reference corner and the third reference corner;

wherein a pseudo-rectangle is defined by segments connecting the first reference corner with the first reference center, the first reference center with the reference centroid, the reference centroid

15 with the second reference center and the second reference center with the first reference corner.

Such a method of defining pseudo-rectangles may provide several advantages. First of all, it can be easily implemented by a computer program, no matter the distribution of the related control points. Secondly, this method may optimize the size distribution of the pseudo-rectangles, since the area of the pseudo-rectangles that are part of a given triangle is substantially

20 the same. Thirdly, this way of defining pseudo-rectangles may greatly facilitate the determination of boundary conditions, since a reference corner of each pseudo-rectangle is

associated with a related control point, and the triangles define lines joining reference points. These lines enable an easy calculation of the corresponding horizon line by applying a horizon reconstruction algorithm to points of a plane comprising axis  $\vec{Z}$  and two of the related control points.

5 More specifically, when pseudo-rectangles are defined in this way, the method of the invention may advantageously comprise, for an identified triangle, and prior to applying a diffeomorphic transformation  $F$  :

- identifying a first, second and third related control point among the plurality of related control points associated with corresponding first , second and third reference corners  
10 of said identified triangle;
- applying a horizon reconstruction algorithm to points of a plane comprising axis  $\vec{Z}$  and comprising the first and second related control points to determine a first portion of a first local horizon;
- identifying a first related central point on the first portion of the first local horizon  
15 having coordinates along axes  $\vec{X}$  and  $\vec{Y}$  identical to coordinates along axes  $\vec{X}$  and  $\vec{Y}$  of the first reference center;
- applying a horizon reconstruction algorithm to points of a plane comprising axis  $\vec{Z}$  and comprising the first and third related control points to determine a second portion of a second local horizon;

- identifying a second related central point on the second portion of the second local horizon having coordinates along axes  $\vec{X}$  and  $\vec{Y}$  identical to coordinates along axes  $\vec{X}$  and  $\vec{Y}$  of the second reference center;
- computing a coordinate along axis  $\vec{Z}$  of a related middle point having coordinates along axes  $\vec{X}$  and  $\vec{Y}$  identical to coordinates along axes  $\vec{X}$  and  $\vec{Y}$  of the reference centroid of said identified triangle, the computation of said coordinate along axis  $\vec{Z}$  being a function of the coordinates of a point on said determined first or second local horizons.

More specifically, the computation of the z coordinate of the related middle point can be a function of any point belonging to the first or second local horizon. For example, it could advantageously be a function of one of the extremities of the first or second local horizons, or either related central point.

The method described above may benefit from one major advantage: it may be particularly efficient from a computational point of view because many steps are implemented once for a first identified triangle, but can be skipped when applying the method to points associated with adjacent triangles. This more specifically concerns the portions of local horizons joining two related control points associated with two reference corners of a triangle. These portions of local horizons may be shared by two adjacent portions of the three-dimensional domain delimited by two adjacent triangles.

20

It may be possible to compute the coordinates along axis  $\vec{Z}$  of the related middle point of the identified triangle by applying a horizon reconstruction algorithm to points of a plane comprising axis  $\vec{Z}$ , and comprising the segment connecting the first reference center with the reference centroid or the segment connecting the second reference center with the reference  
5 centroid.

Doing so may increase the precision of the above mentioned method.

Alternatively, computing a coordinate along axis  $\vec{Z}$  of the related middle point can also be achieved by calculating the mean value of the coordinates along axis  $\vec{Z}$  of at least the first and second related central points.

10 This technique may be very quick and provide a good accuracy especially if the size of the triangle is small.

Several techniques may be foreseen to solve the Poisson equation that is computed in the horizon reconstruction algorithm. Once the conditions required for a one-step direct resolution of the equation are met, it may be advantageous to solve the Poisson equation using a Fourier  
15 transform algorithm.

The latter algorithms are well-known and easy to implement in a computer program for instance, due to the multitude of existing libraries for performing Fourier transforms on discrete data. Furthermore, Fourier transform algorithms are excellent alternatives to matrix methods, the latter being a lot more complex to compute.

20

The method described above can be implemented on portions of the three-dimensional domain comprising points having the same x and y coordinates as individualized pseudo-rectangles.

5 However it is possible to define pseudo-rectangles that map a continuous portion of the reference plane.

This may increase the computational speed of the method due to the fact that some of the computed data, for example the boundaries, can be reused on portions of the three-dimensional domain delimited by neighboring pseudo-rectangles.

10 In a final step, once two-dimensional portions of a horizon have been calculated for each of the defined pseudo-rectangles, the method may further comprise assembling all these portions of horizons to define a finalized portion of a reconstructed horizon.

To do so, the method may comprise computing a portion of a seismic horizon from at least the computed part of the horizon of each current pseudo-rectangle among the defined pseudo-rectangles.

15 When pseudo-rectangles were defined using a triangulation as described above, the method may further comprise computing a portion of a seismic horizon from at least the computed part of the horizon of each current pseudo-rectangle among the defined pseudo-rectangles, and after computing a portion of a seismic horizon, the method may comprise:

- receiving modification information relating to the related control points;
- 20 - identifying pseudo-rectangles affected by the received modification information relating to the related control points;

- defining a new set of pseudo-rectangles in a local area corresponding to the area occupied by the pseudo-rectangles affected by said received modification information relating to the related control points;
- for each current pseudo-rectangle among the new set of pseudo rectangles:
  - 5       - applying a diffeomorphic transformation  $F$ , said diffeomorphic transformation  $F$ :
    - being a function of coordinates along  $\vec{X}$ ,  $\vec{Y}$  and defining a new domain comprising axes  $\vec{X}'$ ,  $\vec{Y}'$ ,  $\vec{Z}$ ;
    - transforming points of the seismic image having coordinates along axes  $\vec{X}$ ,  $\vec{Y}$  identical to coordinates along axes  $\vec{X}$ ,  $\vec{Y}$  of points in said  
10       current pseudo-rectangle, said points of the seismic image including the related control point associated with the current pseudo-rectangle;
    - transforming said current pseudo-rectangle into a corresponding rectangle;
  - 15       - applying a horizon reconstruction algorithm to the transformed points, to determine a part of a transformed horizon, said part of a transformed horizon comprising the transformed related control point, the reconstruction of the seismic horizon comprising solving the Poisson equation  $\Delta(\delta\tau) = -\text{div}(r)$ , where  $\delta\tau$  is an unknown function of coordinates along axes  $\vec{X}'$ ,  $\vec{Y}'$ ,  $\Delta$  denotes the

Laplace operator in the new domain,  $\text{div}$  denotes the divergence vector operator in the new domain and  $r$  is a fixed function of coordinates along axes  $\vec{X}'$ ,  $\vec{Y}'$ ;

- computing a part of the horizon, said computing of a part of the horizon comprising applying an inverse diffeomorphic transformation  $F^{-1}$  to the determined part of a transformed horizon.

Therefore, whenever new related control points are added, or former related control points are removed, the method can efficiently limit the portion of the three-dimensional domain on which new calculations are performed to the portion of the three-dimensional domain concerned by the modifications that were performed.

The invention also pertains to a device for enhancing the determination, from a seismic image, of at least a portion of a seismic horizon in a three-dimensional domain comprising axes  $\vec{X}$ ,  $\vec{Y}$ ,  $\vec{Z}$ , said seismic horizon being a function of coordinates along axes  $\vec{X}$ ,  $\vec{Y}$  in said three-dimensional domain,

wherein said device comprises:

- an input interface for receiving the seismic image, the seismic image having points associated with coordinates along axes  $\vec{X}$ ,  $\vec{Y}$ ,  $\vec{Z}$ ; and for receiving a plurality of related control points associated with coordinates on axes  $\vec{X}$ ,  $\vec{Y}$ ,  $\vec{Z}$ ;
- a circuit for defining, in a reference plane defined by axes  $\vec{X}$  and  $\vec{Y}$ , for at least one related control point among the plurality of related control points, an associated reference point with coordinates along axes  $\vec{X}$ ,  $\vec{Y}$ , among a plurality of reference

points, the reference point having coordinates on axes  $\vec{X}$  and  $\vec{Y}$  identical to coordinates on axes  $\vec{X}$  and  $\vec{Y}$  of the related control point,

- a circuit for defining pseudo-rectangles in the reference plane, each pseudo-rectangle comprising a reference point among a plurality of reference points;
- 5 - a circuit being adapted for, for each current pseudo-rectangle among the defined pseudo-rectangles:

- applying a diffeomorphic transformation  $F$ , said diffeomorphic transformation  $F$ :

- being a function of coordinates along  $\vec{X}$ ,  $\vec{Y}$  and defining a new domain comprising axes  $\vec{X}'$ ,  $\vec{Y}'$ ,  $\vec{Z}$ ;
- 10 - transforming points of the seismic image having coordinates along axes  $\vec{X}$ ,  $\vec{Y}$  identical to coordinates along axes  $\vec{X}$ ,  $\vec{Y}$  of points in said current pseudo-rectangle, said points of the seismic image including the related control point associated with the current pseudo-rectangle;
- 15 - transforming said current pseudo-rectangle into a corresponding rectangle;
- applying a horizon reconstruction algorithm to the transformed points, to determine a part of a transformed horizon, said part of a transformed horizon comprising the transformed related control point, the reconstruction of the seismic horizon comprising solving the Poisson equation  $\Delta(\delta\tau) = -\text{div}(r)$ , where
- 20

$\delta\tau$  is an unknown function of coordinates along axes  $\vec{X}'$ ,  $\vec{Y}'$ ,  $\Delta$  denotes the Laplace operator in the new domain,  $\text{div}$  denotes the divergence vector operator in the new domain and  $r$  is a fixed function of coordinates along axes  $\vec{X}'$ ,  $\vec{Y}'$ ;

- computing a part of the horizon, said computing of a part of the horizon comprising applying an inverse diffeomorphic transformation  $F^{-1}$  to the determined part of a transformed horizon.

5 The invention also pertains to a non-transitory computer readable storage medium, having stored thereon a computer program comprising program instructions, the computer program being loadable into a data-processing unit and adapted to cause the data-processing unit to carry out the sequence of operations of the method described above when the computer program is run by the data-processing device.

### BRIEF DESCRIPTION OF THE DRAWINGS

15 The method of the invention will be better understood by reading the detailed description of exemplary embodiments presented below. These embodiments are illustrative and by no means limitative. They are provided with the appended figures and drawings on which:

[[ - f ]] Figure 1 is a schematic representation of a seismic image in a three-dimensional domain; and

20 1 comprising related control points and their associated reference points in the reference plane; and

Figure 3 is a schematic representation of the reference plane of Figure 2; and

Figure 4 is a schematic representation of a plane pointed at on Figure 3 and comprising axis  $\vec{Z}$ , a portion of seismic image, a current reference edge of a pseudo-rectangle and a related control point associated with a reference point on the current reference edge; and

5 Figure 5 is a schematic representation of the three-dimensional domain of Figure 1 comprising one related control point the associated current pseudo-rectangle and the boundaries of the sought seismic horizon delimited by the current pseudo-rectangle; and

Figure 6 presents schematic representations (A and B) of the transformation operated by the diffeomorphic transformation  $F$  associated with the pseudo-rectangle of Figure 5; and

10 Figure 7 presents schematic representations (A and B) of the transformation operated by the inverse diffeomorphic transformation  $F^{-1}$  associated with the pseudo-rectangle of Figures 5, 6 element A and 6 element B; and

15 Figure 8 is a schematic representation of the three-dimensional domain of Figure 1 comprising related control points and their associated portions of a reconstructed seismic horizon; and

Figure 9 is a schematic representation of the reference plane of Figure 2 according to a second embodiment; and

Figure 10 is a schematic representation of the reference plane of Figure 9 with three pseudo-rectangles defined in accordance with the second embodiment; and

20 Figure 11 is a schematic representation of the reference plane of Figure 9 illustrating the pseudo-rectangles affected by the addition of a related control point; and

Figure 12 is a flow chart illustrating the main steps implemented by the horizon reconstruction method; and

Figure 13 is a possible embodiment for a device that enables the present invention.

For the sake of clarity, the dimensions of features represented on these figures may not necessarily correspond to the real-size proportions of the corresponding elements. Like reference numerals on the figures correspond to similar elements or items.

### DETAILED DESCRIPTION OF THE INVENTION

Figure 1 represents an exemplary seismic image in a three-dimensional domain **1** associated with axes  $\vec{X}$ ,  $\vec{Y}$ ,  $\vec{Z}$ . Such an image comprises dark regions **101**, **102**, **103** alternating with brighter regions **110**, **120**, **130**. From the data contained in the seismic image of Figure 1, geophysicists may extract the tangent of the local dip  $p$  associated with every data point of the seismic image. The tangent of the local dip is expressed as a function of class  $C^1$  of  $x$ ,  $y$ ,  $z$  coordinates. The aim of a horizon reconstruction method is to find a two-dimensional surface in the three-dimensional domain **1**, that can be numerically represented as a function of class  $C^2$ :

$$\tau: (x,y) \rightarrow \tau(x,y)$$

of  $x$ ,  $y$  coordinates and verifying the condition :

$$\tau = \arg \min_{f \in C^2} \int_{\Omega} \|\nabla f(x,y) - p[x,y;f(x,y)]\|^2 d\Omega$$

where  $\|\ \|$  denotes a norm, for example the absolute value,  $\nabla$  denotes the gradient operator and  $\Omega$  the portion of the three-dimensional domain **1** on which the seismic horizon is calculated.

Iterative horizon reconstruction algorithms to solve the above equation are well-known from the existing prior art, such as for example from the above-cited article by Lomask *et al.*

In the process of implementing a horizon reconstruction algorithm, one constraint resides in the fact that any calculated horizon must pass through all the related control points received as  
5 input.

Several key steps are implemented in such an algorithm. Generally, a first horizon corresponding to a function  $\tau = \tau_0$  is initialized. Then, a residual term  $r$  is calculated. This term  $r$  is another function of coordinates  $x, y$ , verifying the condition  $r(x; y) = \nabla\tau(x; y) - \rho[x; y; \tau(x; y)]$ , which corresponds to the difference between the tangent of the local dip of the seismic image  
10 and the gradient of the horizon.

While implementing the iterative horizon reconstruction algorithm, the main challenge resides in minimizing this residual term  $r$ . This is done by progressively correcting function  $\tau$ , so that after each step  $k$  of the horizon reconstruction algorithm,  $\tau_{k+1} = \tau_k + \delta\tau_k$ . At each step, an update term  $\delta\tau$  is computed, the latter verifying:

15 
$$\delta\tau = \operatorname{argmin}_{f \in C^2} \int_{\Omega} \|\nabla f(x; y) + r(x; y)\|^2 d\Omega$$

This update term, later added to function  $\tau$ , is numerically obtained by solving the Poisson equation:

$$\Delta(\delta\tau) = -\operatorname{div}(r)$$

As mentioned above, the invention resides in the way this Poisson equation is calculated.

As illustrated on Figure 2, the method comprises receiving related control points **201**, **202**, **203**, **204**, **205**, **206**, **207**, **208** in the three-dimensional domain **1**. These related control points **201**, **202**, **203**, **204**, **205**, **206**, **207**, **208** may for example be points that are known to belong to a given horizon because of drills realized in the ground or because of reliable geological data. The horizon reconstruction algorithm relies on using the x and y coordinates of the points of the three-dimensional domain **1** as input, and calculating a corresponding coordinate along axis  $\vec{Z}$  to determine a reconstructed horizon. The method of the invention involves transformations on these points, that only affect their x and y coordinates, but do not change their z coordinate. To simplify the process of defining pseudo-rectangles and diffeomorphic transformations that are part of this invention, reference points **210**, **220**, **230**, **240**, **250**, **260**, **270**, **280** associated with said related control points are defined in a reference plane **10**, this reference plane being defined by axes  $\vec{X}$  and  $\vec{Y}$ . The reference points **210**, **220**, **230**, **240**, **250**, **260**, **270**, **280** have the same x and y coordinates along axes  $\vec{X}$  and  $\vec{Y}$  as the related control points **201**, **202**, **203**, **204**, **205**, **206**, **207**, **208** i.e. the point **210** (respectively **220**, **230**, **240**, **250**, **260**, **270**, **280**) is a projection of the related control point **201** (respectively **202**, **203**, **204**, **205**, **206**, **207**, **208**) on a plane surface  $(\vec{X}, \vec{Y})$ .

As illustrated on Figure 3, the invention then consists in defining pseudo-rectangles in the reference plane **10** comprising the reference points **210**, **220**, **230**, **240**, **250**, **260**, **270**, **280** associated with related control points. This may be done in many different ways, some of which are illustrated on Figures 3, 9 and 10. On Figure 3, pseudo-rectangles with random

shapes map a portion of the reference plane **10**. Each of these pseudo-rectangles contains one of the reference points **210, 220, 230, 240, 250, 260, 270, 280**. The latter points can be located anywhere on a current pseudo-rectangle. For example, reference point **280** belongs to a reference corner of a current pseudo-rectangle, and reference point **220** belongs to a current reference edge  
5 of a current pseudo-rectangle **3220**.

The pseudo-rectangles comprising reference points **210, 220, 230, 240, 250, 260, 270, 280** verify the boundary conditions called Neumann conditions, which state that for a unique point of fixed coordinates on the horizon, the derivative of the update term along the exterior normal  $\vec{\omega}$  to the boundary is assumed to be equal to zero and its mean value fixed to zero. In  
10 other words, for any value of coordinates  $x$  and  $y$  along the edges of the horizon in the portion  $\Omega$  of the three-dimensional domain **1** delimited by the current pseudo-rectangle, the following scalar product is equal to zero:  $\nabla\delta\tau(x;y).\vec{\omega}(x;y)=0$ . In such pseudo-rectangles, it is advantageous to avoid calculating the boundary conditions since these boundaries are not required to rapidly solve the horizon reconstruction algorithm. It may also be advantageous to  
15 verify that adjacent calculated portions of a seismic horizon form a continuous surface, and implement corrections to ensure that there is no discontinuity at their shared boundary.

In another embodiment, it may be advantageous to compute the boundary conditions on the edges of the horizon in the portion  $\Omega$  of the three-dimensional domain **1** delimited by the current pseudo-rectangle, to verify the Dirichlet conditions and in order to be sure that the  
20 different determined horizons for each pseudo-rectangle are continuous. On [Figure 3](#), a plane **20** defined by axis  $\vec{Z}$  and containing reference point **220** and reference corners **2220, 2210** is

represented. This plane **20** comprises the current reference edge **320** of the current pseudo-rectangle **3220**. On [Figure 3](#), this plane **20** appears as a line.

On [Figure 4](#), the same plane **20** is represented with the points from the seismic image having the same coordinates in the three-dimensional domain **1** as points from the plane **20**, reference point **220**, the related control point **202**, and the reference corners **2220**, **2210**. To find the related edge **302** comprising related control point **202** and belonging to the seismic horizon, a horizon reconstruction algorithm can be applied to points of plane **20**. This horizon reconstruction algorithm is easier to implement since it resolves the Poisson equation in two-dimensions, that is to say, it computes a function  $\tau$  which can be expressed as a function of one variable and which can be graphically represented in a plane. As can be seen on [Figure 4](#), the reconstructed horizon line **302** tends to follow the tangent of the dip of the points from the seismic image.

The boundaries of the sought horizon are represented on [Figure 5](#). Figure 5 represents the portion of the three-dimensional domain **1** delimited by pseudo-rectangle **3220**. This portion comprises four faces: face **501** appears on the left side, face **504** on the right side, face **502** at the back and face **503** at the front of the illustration on [Figure 5](#). Knowing a related edge **302**, corresponding to a horizon line of the sought horizon, comprised in face **501**, it is possible to compute the boundaries **420**. The horizon line **302** can be used to compute the other horizon lines along the adjacent faces **502**, **503** of the current portion of the three-dimensional domain **1** delimited by the current pseudo-rectangle **3220**. To do so, the extremities **2201** and **2202** of the horizon line are used in two horizon reconstruction algorithms to determine a second and third

horizon lines. The second horizon line passes through extremity **2202**, comprises another extremity **2203** and is comprised in face **502**. The third horizon line passes through extremity **2201**, comprises another extremity **2204** and is comprised in face **503**. The horizon line comprised in the remaining face **504** is determined by applying a horizon reconstruction  
5 algorithm to points of the remaining face **504**, so that the horizon line passes through extremities **2203** of the second and **2204** third horizon line.

This step by step approach leads to the determination of the boundary conditions in the portion  $\Omega$  of the three-dimensional domain **1** delimited by the current pseudo-rectangle, thereby fulfilling the Dirichlet boundary conditions. Figure 5 illustrates the determined boundaries **420** in  
10 the current portion  $\Omega$  of the three-dimensional domain **1** delimited by the current pseudo-rectangle associated with related control point **202**.

It is to be noted that although the above description and illustrations describe a way of determining the boundary conditions in the current portion  $\Omega$ , it is possible to skip this step and proceed with the method described below. Indeed, the method of this invention is also efficient  
15 in the case where a single related control point is contained in the current portion  $\Omega$ . Alternatives such as the configuration in which a related control point has the same x and y coordinates as a reference corner of the current pseudo-rectangle, as is the case for related control point **208**, is also compatible with the invention. As long as any one of the boundary conditions is met, the method of the invention further proceeds by identifying, for a current pseudo-rectangle, a  
20 diffeomorphic transformation  $F$  which transforms the current pseudo-rectangle into a

corresponding rectangle. For a current pseudo-rectangle, such a diffeomorphic transformation  $F$  is a function which transforms coordinates  $(x;y)$  into corresponding coordinates  $(x',y')$  so that:

$$\begin{bmatrix} x' \\ y' \end{bmatrix} = F(x;y) = \begin{bmatrix} F_{x'}(x;y) \\ F_{y'}(x;y) \end{bmatrix}$$

Figure 6 (element A) illustrates a current portion  $\Omega$  of the three-dimensional domain **1** delimited by the current pseudo-rectangle associated with related control point **202**, for which the Dirichlet conditions, represented by boundaries **420**, have been computed. All the points of this current portion  $\Omega$  are transformed using diffeomorphic transformation  $F$  to obtain the corresponding rectangle and the new domain  $\Omega'$  delimited by the corresponding rectangle illustrated on Figure 6 element B. The boundary conditions **620** in the new domain as well the transformed related control point **602** are also represented. The new domain is associated with the transformed axes  $\vec{X}'$ ,  $\vec{Y}'$ ,  $\vec{Z}$ . In addition to transforming the current portion  $\Omega$  into the new domain  $\Omega'$ , the method of the invention also transforms the corresponding portion of the seismic image, to obtain a set of transformed points in the new domain. The gradient field of the function  $\tau$  is therefore relied on a vector field by a partial differential equation:

$$\nabla\tau(x';y') = p' [x';y';\tau(x';y')] \tag{15}$$

where  $p'$  is the tangent of the transformed local dip  $p$ . It can be expressed as:

$$p' = J_F^{-1}p$$

where  $J_F^{-1}$  is the inverse of the transformation Jacobian matrix  $J_F$  defined by:

$$J_F = \begin{bmatrix} \frac{\partial x'}{\partial x} & \frac{\partial y'}{\partial x} \\ \frac{\partial x'}{\partial y} & \frac{\partial y'}{\partial y} \end{bmatrix}$$

The diffeomorphic transformation  $F$  transforming a current pseudo-rectangle into a corresponding rectangle is a homography defined by a 3x3 matrix  $H = [h_{ij}]$ . This transformation is given, for any  $x, y$  coordinates in the current portion  $\Omega$  by:

$$\begin{bmatrix} x' \\ y' \end{bmatrix} = \begin{bmatrix} \frac{h_{11}x + h_{12}y + h_{13}}{h_{31}x + h_{32}y + h_{33}} \\ \frac{h_{21}x + h_{22}y + h_{23}}{h_{31}x + h_{32}y + h_{33}} \end{bmatrix}$$

5 The four terms of the Jacobian are then defined by:

$$\frac{\partial x'}{\partial x}(x; y) = \frac{(h_{11}h_{32} - h_{31}h_{12})y + h_{11}h_{33} - h_{31}h_{13}}{(h_{31}x + h_{32}y + h_{33})^2}$$

$$\frac{\partial y'}{\partial x}(x; y) = \frac{(h_{21}h_{32} - h_{31}h_{22})y + h_{21}h_{33} - h_{31}h_{23}}{(h_{31}x + h_{32}y + h_{33})^2}$$

$$\frac{\partial x'}{\partial y}(x; y) = \frac{(h_{12}h_{31} - h_{31}h_{121})x + h_{21}h_{33} - h_{31}h_{23}}{(h_{31}x + h_{32}y + h_{33})^2}$$

$$\frac{\partial y'}{\partial y}(x; y) = \frac{(h_{22}h_{31} - h_{32}h_{21})x + h_{22}h_{33} - h_{31}h_{23}}{(h_{31}x + h_{32}y + h_{33})^2}$$

10 It is therefore possible to compute, for each point of the new domain, a transformed residual term  $r$  and solve the Poisson equation in the transformed domain.

With the elements obtained so far, two conditions are met to allow a direct and one-step resolution of the Poisson equation: the domain on which a solution is searched corresponds to points having  $x$  and  $y$  coordinates identical to those of a rectangle, and either at least one related control point is within this new domain, or the boundary conditions of the solution are known.

The determination of the update term, the solution of the Poisson equation, can be calculated using fast Fourier transform algorithms, for example by solving the equation:

$$\delta\tau = \text{FT}^{-1} \left[ \frac{\text{FT}[-\text{div}(r)]}{\text{FT}[\Delta]} \right]$$

where FT denotes a Fourier transform and  $\text{FT}^{-1}$  denotes an inverse Fourier transform.

Advantageously, the Fourier transform is a discrete Fourier transform, and even more  
5 advantageously a fast Fourier transform. If the size of the new domain can be expressed as a  
number verifying  $2^a 3^b 5^c 7^d 11^e 13^f$ , where a, b, c, d, e and f are positive integers and e+f is smaller  
than 1, then a particularly efficient fast Fourier transform can be implemented to further reduce  
the computation time of the method of the invention.

As represented on Figure 7 element A, once the transformed part of a reconstructed  
10 horizon **7020** is obtained, the method comprises applying the inverse diffeomorphic  
transformation  $F^{-1}$  to the transformed part of a reconstructed horizon to obtain a part of a  
reconstructed horizon **720**, as represented on Figure 7 element B.

Finally, the invention advantageously comprises assembling all the parts of a  
reconstructed horizon to obtain a reconstructed horizon on a portion of the three-dimensional  
15 domain **1** as represented on Figure 8.

Besides the general method described above, the invention may advantageously benefit  
from substantial optimizations that allow it to be performed faster and be easily programmed to  
be executed with minimal input from the user.

To this end, Figure 9 represents a method for defining pseudo-rectangles that have a  
20 substantially similar shape and which allows a fast and reliable calculation of the boundary  
conditions in each pseudo-rectangle.

On **Figure 9** reference points **210, 220, 230, 240, 250, 260, 270, 280** associated with related control points **201, 202, 203, 204, 205, 206, 207, 208** are represented in the reference plane **10**. A triangulation, advantageously a Delaunay triangulation, connecting all these reference points to form triangles is implemented. Then, as represented on **Figure 10**, the center of each side of an identified triangle is selected. **Figure 10** represents the triangle identified by corners corresponding to reference points **210, 220** and **230**. The reference centers **223, 212** and **213** of the sides of this triangle are also used to determine the centroid **2123** of this triangle, the centroid being the point where the median lines of the triangle cross. In this manner, the obtained three pseudo-rectangles have substantially the same area in each triangle, and the method can systematically be implemented by a computer program.

Other advantages arise from the method of defining pseudo-rectangles represented on **Figures 9 and 10**. The sides of each triangle are lines joining two reference points having the same x and y coordinates as related control points, and boundary conditions can be easily computed in the plane comprising axis  $\vec{Z}$  and comprising two related control points by using a horizon reconstruction algorithm to obtain a horizon line. Since it may occur, as seen on **Figure 9**, that several triangles share a common side, the calculation of boundary conditions may not have to be computed for each triangle in the portion of the three-dimensional domain **1** delimited by a triangle. Indeed the results obtained in the portion of the three-dimensional domain **1** delimited by a previously identified triangle may be reused in the portion of the three-dimensional domain **1** delimited by subsequent triangles.

The centroid of each triangle, called reference centroid **2123**, shares the same x and y coordinates as a related middle point of the horizon. This related middle point is shared by three portions of horizon in three adjacent portions of the three-dimensional domain **1**. There are several options for determining the z coordinate of that middle point of the horizon.

5           It is for example possible to make realistic approximations that are likely to be valid for triangles having a small area compared to the size of the three-dimensional domain **1**. One of these consists in calculating the mean value of the z coordinate of related central points of the horizon, associated with reference centers **212**, **223**, **213** of at least two of the three sides of a current triangle. Another consists in assuming the z coordinate of that related middle point is  
10          equal to the z coordinate of any related point of the horizon associated with a reference point of the triangle, for example a reference corner **220**, **230**, **210** or a reference center **212**, **223**, **213** of a side of the triangle. Another method consists in applying a horizon reconstruction algorithm to points of the plane comprising axis  $\vec{Z}$  and comprising one of the segments connecting a reference center **212**, **223**, **213** of a side of the triangle, and the reference centroid **2123**, to obtain  
15          a horizon line.

In an alternative embodiment, it is possible to define pseudo-rectangles by combining the identified triangles two by two. Two adjacent triangles are combined by removing the segment they have in common. This embodiment is advantageous in that it makes it even easier to determine the boundary conditions of the portion  $\Omega$  of the three-dimensional domain **1** delimited  
20          by a pseudo-rectangle, since every reference corner of each pseudo-rectangle is associated with a

related control point. In this embodiment, horizon lines passing through the related control points define the boundary conditions of each pseudo-rectangle.

The method of the invention nonetheless also offers another major advantage over the existing prior art. Indeed, it is very efficient for computing portions of a seismic horizon when a  
5 related control point is added to or removed from a set of related control points.

Figure 11 represents reference plane **10** containing reference points **210, 220, 230, 240, 250, 260, 270, 280** associated with related control points **201, 202, 203, 204, 205, 206, 207, 208**. First, modification information relating to the related control points is received, for example the addition of a related control point. Then, the reference point **1100** in the reference plane **10**  
10 associated with the added related control point requires locally redefining pseudo-rectangles. Nevertheless, the effect is only local as shown on Figure 11, on which the darkest pseudo-rectangles correspond to the affected area that is chosen for a recalculation of the local horizon. In general, adding a related control point only affects the pseudo-rectangle or pseudo-rectangles to which the added reference point associated with the added related control point belongs.  
15 Nevertheless, it is advantageous to identify an affected area by identifying the triangle or triangles to which the reference point belongs. This may enable defining new pseudo-rectangles having substantially the same size as already defined surrounding pseudo-rectangles. Since the pseudo-rectangles comprising the added reference point may share boundaries with neighboring pseudo-rectangles, two of which may belong to neighboring triangles, it is advantageous to  
20 include these neighboring triangles into the affected area and triangulate a new set of pseudo-rectangles on this affected area. On Figure 11, the area affected by the addition of reference

point **1100** implies a new triangulation giving rise to twelve new pseudo-rectangles. Similar conclusions arise when a related control point is removed.

For the above reason, the invention is very efficient in terms of computation time required to determine a horizon, for example when a user decides to add several related control  
5 points in a portion of the three-dimensional domain **1** which requires a finer resolution in the reconstructed horizon.

Figure 12 is a flow-chart schematically illustrating the different steps that are implemented by the method of this invention.

In a first step S1, a seismic image SEISM\_IMG **1** is received. The seismic image **1** can  
10 for example be received from a raw seismic data treatment program that outputs the data points in the three-dimensional domain **1**.

In a second step S2, related control points CTRL.\_PTs **201, 202, 203, 204, 205, 206, 207, 208** are received. The x, y, z coordinates of these points are fixed and they all belong to the same horizon.

15 In a subsequent step S3, pseudo-rectangles PSEUD.\_RECT. are defined, in such a way that each pseudo-rectangle is in a reference plane and comprises at least one reference point **210, 220, 230, 240, 250, 260, 270, 280**.

In step S4, it is possible to apply, for each pseudo-rectangle PSEUD.\_RECT. one or several horizon reconstruction algorithms to points of an edge of a portion of the three-  
20 dimensional domain **1** delimited by the current pseudo-rectangle, in order to find the boundaries  
**420**.

In step S50, a diffeomorphic transformation  $F$  is identified for each pseudo-rectangle. An identified diffeomorphic transformation  $F$  is applied to a current pseudo-rectangle to transform it into a corresponding rectangle. By doing so, the method generates conditions in which solving the Poisson equation can be greatly simplified.

5           Step S50 also comprises applying said transformation to the points of the seismic image having the same  $x$  and  $y$  coordinates as points of the pseudo-rectangle.

The invention further comprises the horizon reconstruction algorithm per se. It starts with step S51 which comprises identifying a horizon corresponding to an initialization function  $\tau_k$  at  $k=0$  and proceeding iteratively as follows:

10           - comparing the number of iterations to a preset value  $N$ . It is assumed that the calculated horizon converges to a reliable solution typically after a few tens of iterations. In case the number of iterations is smaller than the preset value  $N$ , the method proceeds by;

- computing a residual term  $r_k$  using the horizon  $\tau_k$  and the tangent of the transformed local dip  $p$  at step S54;

15           - applying a horizon reconstruction algorithm using Fourier transforms to solve the Poisson equation in the new domain  $\Omega'$  at step S54;

- incrementing  $k$  by one digit at step S55 and returning to step S52. When the number  $k$  of iterations reaches the target value  $N$ , the method proceeds with step S6 by applying the inverse diffeomorphic transformation  $F^{-1}$  that can transform the corresponding rectangle into the current

20           pseudo-rectangle, to the computed horizon  $\tau_k$ .

Finally, all the portions of a reconstructed horizon obtained for each pseudo-rectangle can be assembled to form the portion of a reconstructed horizon represented on [Figure 8](#).

A comparison of the method of the invention and the global optimization method disclosed by Lomask *et al.* was performed on real seismic data defining a volume of 1750m by 4000m by 1600m. Complex geometries and convergent structures of the treated data resulted in an extremely noisy estimated dip, so a set of twenty seven related control points were sequentially received in critical regions corresponding for example to peaks or basins of the horizon to be reconstructed, starting from an initial set of thirteen related control points.

The number of iterations in the horizon reconstruction algorithm to reach convergence of both methods was set to thirty. For the method of the invention, each identified triangle is subdivided in three pseudo-rectangles as described above. The twenty seven related control points then lead to one hundred and twenty six pseudo-rectangles. For the global optimization method disclosed by Lomask *et al.* each update term  $\delta\tau$  computation through a direction descent approach required three hundred iterations and the algorithm had to be initialized with a function  $\tau_0$  close to the solution. This function  $\tau_0$  was obtained from a horizon reconstructed over the entire domain by assuming that only one particular related control point was known.

Table 1 resumes the computation time in seconds that was measured using both methods. The time in parentheses corresponds to the time measured for the calculations dedicated to the Fourier transforms.

Size of rectangular domain (new domain)	Method of the invention		Method disclosed by Lomask <i>et al.</i>
	Normal size	Optimal size	

smallest	3.3 s (1.41 s)	2.7 s (0.561 s)	79.1 s
largest	9.98 s (5.47 s)	6.43 s (2.41 s)	
arithmetic mean	5.82 s (2.9 s)	4.26 s (1.56 s)	
geometric mean	5.4 s (2.54 s)	3.78 s (1.4 s)	

Table 1

Table 1 shows the time required to do calculations on the portions of the three-dimensional domain **1** based on the size of the domain. The column labeled normal size gives the measured time that elapsed during the implementation of the method of the invention on portions of a domain that did not have a size optimized for fast Fourier transforms. The column labeled optimal size gives the same data but measured on portions of a domain that had a size suitable for implementing a fast Fourier transform algorithm. The line labeled smallest corresponds to the smallest defined portions of domains, the line labeled largest corresponds to the largest defined portions of domains, and the arithmetic and geometric means give times calculated based on a mean value of the size of the rectangular domains. It arises from the data of table 1 that the method of the invention enables reducing the computation time by as much as thirty times when compared to global approaches like the one disclosed by Lomask *et al.* .

Another test was conducted to determine the time that can be saved using the method of the invention when modification instructions regarding the related control points are received. Table 2 summarizes the times in seconds measured for implementing the method of the invention when increasing the number of related control points from thirteen to twenty-seven. The time in parentheses corresponds to the time measured for the calculations dedicated to the Fourier transforms. In the column labeled entire reconstruction, the measured times are substantially the

same, since the volume on which the computation is implemented is the entire three-dimensional domain **1**. In the column labeled incremental reconstruction, the method is only applied to the portion of the three-dimensional domain **1** which is affected by the addition of new related control points.

Number of related control points	Entire reconstruction	Incremental reconstruction
13	3.8 s (1.4 s)	
18	3.73 s (1.4 s)	0.627 s (0.219 s)
23	3.72 s (1.38 s)	0.603 s (0.233 s)
27	3.78 s (1.4 s)	0.5 s (0.184 s)

5 Table 2

It appears from table 2 that the selective computation of portions of a horizon on only those parts that are affected by the addition or removal of related control points further enhances the computational speed of the method.

Figure 13 is a possible embodiment for a device that enables the present invention.

10 In this embodiment, the device **1300** comprises a computer, this computer comprising a memory **1305** to store program instructions loadable into a circuit and adapted to cause circuit **1304** to carry out the steps of the present invention when the program instructions are run by the circuit **1304**.

15 The memory **1305** may also store data and useful information for carrying the steps of the present invention as described above.

The circuit **1304** may be for instance:

- a processor or a processing unit adapted to interpret instructions in a computer language, the processor or the processing unit may comprise, may be associated with or be attached to a memory comprising the instructions, or
- the association of a processor / processing unit and a memory, the processor or the processing unit adapted to interpret instructions in a computer language, the memory comprising said instructions, or
- an electronic card wherein the steps of the invention are described within silicon, or
- a programmable electronic chip such as a FPGA chip (for « Field-Programmable Gate Array »).

5

10

This computer comprises an input interface **1303** for the reception of data used for the above method according to the invention and an output interface **1306** for providing a stacked model.

To ease the interaction with the computer, a screen **1301** and a keyboard **1302** may be provided and connected to the computer circuit **1304**.

15

The invention is not limited to the embodiments described above and may encompass equivalent embodiments.

For example, it is possible to define non quadrangular surfaces in the reference plane. Instead of defining pseudo-rectangles, it may for example be possible to define surfaces for which diffeomorphic transformations, transforming these surfaces into circles, can be obtained.

20

Indeed, a rapid resolution of the Poisson equation in a domain having a circular section, instead of a rectangular section, is possible.

It is possible to apply the diffeomorphic transformation  $F$  to a current pseudo-rectangle before calculating boundary conditions associated with the current pseudo-rectangle.

It is also possible to define some pseudo-rectangles which are not associated with any related control point. Although doing so might seem less advantageous from a computational point of view, it may be interesting in the case in which large gaps exist between local concentrations of related control points. Defining pseudo-rectangles that are not associated with any related control point may allow mapping a continuous portion of the three-dimensional domain **1** without having a high dispersion in the size of the pseudo-rectangles. It is also possible to have pseudo-rectangles that are not associated with any related control point, but which are adjacent to other pseudo-rectangles which are. Thereby, it is possible to use the boundary conditions of the neighboring pseudo-rectangles to meet the conditions enabling a direct resolution of the Poisson equation.

The method described above may also be implemented in a domain comprising more than three dimensions.

One may also define quadrangles that are not pseudo-rectangles, although this may render the calculation of the diffeomorphic transformations more complicated.

The embodiments above are intended to be illustrative and not limiting. Additional embodiments may be within the claims. Although the present invention has been described with reference to particular embodiments, workers skilled in the art will recognize that changes may be made in form and detail without departing from the spirit and scope of the invention.

Various modifications to the invention may be apparent to one of skill in the art upon reading this disclosure. For example, persons of ordinary skill in the relevant art will recognize that the various features described for the different embodiments of the invention can be suitably combined, un-combined, and re-combined with other features, alone, or in different combinations, within the spirit of the invention. Likewise, the various features described above should all be regarded as example embodiments, rather than limitations to the scope or spirit of the invention. Therefore, the above is not contemplated to limit the scope of the present invention.

5

5           **METHOD FOR ENHANCING THE DETERMINATION OF SEISMIC HORIZON**

**RELATED APPLICATIONS**

The present application is a National Phase entry of PCT Application No. PCT/EP2013/066492, filed August 6, 2013, which claims priority from U.S. Patent Application  
10 No. 61/681,005, filed August 8, 2012, said applications being hereby incorporated by reference herein in their entirety.

**TECHNICAL FIELD**

The invention pertains to the field of methods implemented in order to determine seismic  
15 horizons. The invention more specifically relates to a method that enhances the determination of a seismic horizon without suffering from some of the drawbacks of the prior art.

**BACKGROUND OF THE INVENTION**

Geological surveys involving generators of seismic waves and detectors of their  
20 reflections in the ground are often conducted to determine the position of oil reservoirs and/or to get to know the composition and thickness of the many layers that form the underground. Seismic reflection techniques consist in generating a seismic wave that propagates through the ground and reflects at the interfaces thereof. A precise measurement of these echoes and more specifically of their arrival times enables a determination of the shape, depth and composition of  
25 the layers that the seismic waves went through.

In a first phase following the measurement of these data signals, image generation algorithms, well-known in the art, are used to reconstruct a raw picture of the underground in the form of seismic images, sometimes also referred to as echographic images. These images can be either two-dimensional in shape or three-dimensional. Such seismic images comprise pixels the intensity of which is correlated to a seismic wave amplitude, dependent on the local impedance variation.

Geophysicists are used to manipulating such seismic images displaying information relating to amplitude. By merely looking at such seismic images, a geophysicist is capable of identifying areas of the underground having distinct characteristics, and use these to determine the corresponding structure of the underground.

Automatic techniques for extracting structural information from seismic images are known. These generally involve seismic horizon reconstruction algorithms that analyze amplitude gradients in a seismic image and extract the tangent of the local dip in a direction that is transverse to that gradient. Examples of techniques used for reconstructing a seismic horizon using a seismic image are for example described in the French patent FR 2 869 693 and US application US 20130083973.

Sometimes the exact depth of a layer can be known due to other data inputs or because of reliable geological information. Therefore, it is sometimes useful to define fixed related control points on a seismic image which are known to belong to a seismic horizon. It is then useful to compute a seismic horizon by implementing a seismic reconstruction algorithm with imposed conditions on a certain limited number of related control points.

One method for reconstructing a seismic horizon with imposed conditions on a number of related control points is described in the article “Flattening with geological constraints” in *Annual Meeting Expanded Abstracts*, Society of Exploration Geophysicists (SEG), 2006, pp. 1053-1056 by J. Lomask and A. Guitton.

5           The method disclosed in this article considers a global approach by solving a two-dimensional nonlinear partial derivative equation relied on local dip. The partial derivative equation is solved using a Gauss-Newton approach by an iterative algorithm whose crucial step is the resolution of a Poisson equation. The approach is global in that it systematically computes a seismic horizon on the entire domain of the seismic image, no matter the number of related  
10 control points received as input.

          Even if it provides realistic seismic horizons, the method proposed by Lomask *et al.* suffers from two major drawbacks: its computational cost is often prohibitive for large data volumes, and it requires solving an iterative algorithm on the entire domain of the seismic image every time a change occurs in the number and/or position of the related control points received as  
15 input.

          The high computational cost of the horizon reconstruction algorithm implemented by Lomask is further increased by the computational means for solving the Poisson equation that forms the core step of the iterative algorithm. In general, another iterative algorithm may be used to solve the Poisson equation. The method disclosed by Lomask therefore comprises an iterative  
20 algorithm within another iterative algorithm.

To overcome these drawbacks, an enhancement of the determination of a seismic horizon that optimizes the computational speed of the horizon reconstruction algorithm is sought.

### SUMMARY OF THE INVENTION

5 To achieve such an optimization and thereby overcome the drawbacks of the prior art, the invention provides a method for enhancing the determination, from a seismic image, of at least a portion of a seismic horizon in a three-dimensional domain comprising axes  $\vec{X}$ ,  $\vec{Y}$ ,  $\vec{Z}$ . In this three-dimensional domain, the seismic horizon is a function of coordinates along axes  $\vec{X}$ ,  $\vec{Y}$ . The method comprises:

- 10
- receiving the seismic image, the seismic image having points associated with coordinates along axes  $\vec{X}$ ,  $\vec{Y}$ ,  $\vec{Z}$ ;
  - receiving a plurality of related control points associated with coordinates on axes  $\vec{X}$ ,  $\vec{Y}$ ,  $\vec{Z}$ ;
  - in a reference plane defined by axes  $\vec{X}$  and  $\vec{Y}$ , defining, for at least one related control point among the plurality of related control points, an associated reference point with coordinates along axes  $\vec{X}$ ,  $\vec{Y}$ , among a plurality of reference points, the reference point having coordinates on axes  $\vec{X}$  and  $\vec{Y}$  identical to coordinates on axes  $\vec{X}$  and  $\vec{Y}$  of the related control point,
  - defining pseudo-rectangles in said reference plane, each pseudo-rectangle comprising
- 15
- 20 a reference point among a plurality of reference points.

In a subsequent step, the invention consists in, for each current pseudo-rectangle among the defined pseudo-rectangles:

- applying a diffeomorphic transformation  $F$ , the diffeomorphic transformation  $F$  :
  - being a function of coordinates along  $\vec{X}$ ,  $\vec{Y}$  and defining a new domain comprising axes  $\vec{X}'$ ,  $\vec{Y}'$ ,  $\vec{Z}$ ;
  - transforming points of the seismic image having coordinates along axes  $\vec{X}$ ,  $\vec{Y}$  identical to coordinates along axes  $\vec{X}$ ,  $\vec{Y}$  of points in the current pseudo-rectangle, the points of the seismic image including the related control point associated with the current pseudo-rectangle;
  - transforming the current pseudo-rectangle into a corresponding rectangle;
- applying a horizon reconstruction algorithm to the transformed points, to determine a part of a transformed horizon, the part of a transformed horizon comprising the transformed related control point, the reconstruction of the seismic horizon comprising solving the Poisson equation  $\Delta(\delta\tau) = -\text{div}(r)$ , where  $\delta\tau$  is an unknown function of coordinates along axes  $\vec{X}'$ ,  $\vec{Y}'$ ,  $\Delta$  denotes the Laplace operator in the new domain,  $\text{div}$  denotes the divergence vector operator in the new domain and  $r$  is a fixed function of coordinates along axes  $\vec{X}'$ ,  $\vec{Y}'$ ;

- computing a part of the horizon, the computing of a part of the horizon comprising applying an inverse diffeomorphic transformation  $F^{-1}$  to the determined part of a transformed horizon.

The term pseudo-rectangle is used to refer to any quadrangle or quadrilateral that has a convex shape, that is to say that each of its inner angles is smaller than  $180^\circ$ . Simple diffeomorphic transformations can be used to transform a convex quadrangle into a rectangle.

Axes  $\vec{X}$ ,  $\vec{Y}$ ,  $\vec{Z}$  are used to define corresponding coordinates  $x$ ,  $y$  and  $z$  for each point in the three-dimensional domain.

For the sake of clarity, any point belonging to the reference plane will be referred to using the adjective reference, e.g. a reference center, and the corresponding points on the seismic horizon having the same  $x$  and  $y$  coordinates will be referred to using the adjective related, e.g. a related central point.

One advantageous feature of the invention resides in the definition of pseudo-rectangles that delimit portions of the three-dimensional domain. Each of these portions has a pseudo-rectangular section and comprises points in the vicinity of a related control point. A horizon reconstruction algorithm is applied to the points of these portions of the three-dimensional domain. The combined volume of these portions, corresponding to the sum of all the volumes of the portions defined by pseudo-rectangles, may be smaller than the volume of the domain corresponding to the entire seismic image. This reduction in volume provides a first enhancement of the computational speed of the horizon reconstruction algorithm.

A second advantageous feature of the invention is that it provides fast means for solving the Poisson equation, the latter generally implementing an iterative algorithm within the horizon reconstruction algorithm. To do so, the invention introduces for each previously defined pseudo-rectangle, a corresponding diffeomorphic transformation  $F$  which transforms each pseudo-rectangle into a corresponding rectangle in a transformed reference plane defined by axes  $\vec{X}'$  and  $\vec{Y}'$ . The same diffeomorphic transformation  $F$  also transforms the points of the corresponding portion of the three-dimensional domain into transformed points which are within a transformed portion of the three-dimensional domain delimited by the corresponding rectangle. The purpose of this transformation is to meet some conditions in which the Poisson equation can be solved in one step, i.e. using direct calculation techniques that do not rely on an iterative algorithm. It is known, by a man skilled in the art of solving Poisson equations on discrete systems, that at least two conditions can be met to enable such a fast computation:

- the portion of the three-dimensional domain on which the equation is solved advantageously has a rectangular or circular section and,
- either
  - at least one related control point belongs to the latter portion of the three-dimensional domain, this being also associated with specific conditions on the boundaries called Neumann condition, or
  - the boundary conditions along the edges of the portion of the three-dimensional domain are known, the latter condition being also referred to as Dirichlet boundary condition.

In the invention, the diffeomorphic transformation of pseudo-rectangles into rectangles ensures that the first condition is met. The diffeomorphic transformation associated with a pseudo-rectangle is applied to all the points of the seismic image whose coordinates along axes  $\vec{X}$  and  $\vec{Y}$  match those of points in the pseudo-rectangle. The coordinates along axis  $\vec{Z}$  are not affected by that transformation. The second condition is met by defining pseudo-rectangles that comprise reference points associated with related control points received as input and the coordinates of which are known.

Another original feature of the invention resides in the fact that each diffeomorphic transformation is applied to the portion of the seismic image comprising points having the same x and y coordinates as points in the pseudo-rectangles. Therefore, it may not be necessary to replace the Laplace operator of the Poisson equation by a differential operator with variable coefficients, which would render the resolution of the Poisson equation complex. In the invention, the divergence operator and the fixed function r are the ones that are transformed, thereby enabling the implementation of fast solvers and not necessarily matrix methods.

Finally, another original feature of this invention is the possibility of choosing pseudo-rectangles delimiting portions of the three-dimensional domain having any section suitable for encompassing the received related control points. This is particularly interesting in situations where the related control points are inhomogeneously scattered in the three-dimensional domain, with areas locally having higher concentrations of related control points. In such situations, defining a portion of the three-dimensional domain with a rectangular section may prove difficult insofar as it may require defining rectangles with small dimensions, sometimes referred to as

degenerated rectangles. Horizon reconstruction algorithms might suffer from an insufficient number of data points in portions delimited by such degenerated rectangles and provide less accurate results. The use of pseudo-rectangles gives more freedom in choosing shapes adapted to the local distribution of related control points without suffering from the disadvantages that arise  
5 when defining portions of the three-dimensional domain delimited by rectangles.

More specifically, it may be advantageous that a pseudo-rectangle is defined so that the reference point comprised in a pseudo-rectangle belongs to a current reference edge of said pseudo-rectangle.

In this embodiment, the portion of a seismic horizon is determined by first determining  
10 the boundaries of the portion of the domain delimited by the current pseudo-rectangle. Having a reference point on a current reference edge may increase the efficiency of the algorithm by providing means for calculating these boundaries of the seismic horizon. Indeed, when a reference point belongs to a current reference edge of a pseudo-rectangle, the associated related control point belongs to a related edge of the seismic horizon. It may then be possible to  
15 implement a calculation of the boundaries on the sought seismic horizon.

A further improvement of the method of the invention may consist in choosing advantageous methods for finding boundary conditions in the portion of the three-dimensional domain delimited by a pseudo-rectangle comprising reference points on a current reference edge.

To this end, prior to applying a diffeomorphic transformation  $F$ , the method may  
20 comprise applying, for each current pseudo-rectangle comprising a reference point belonging to a current reference edge of said pseudo-rectangle among the defined pseudo-rectangles, for each

current reference edge of said current pseudo-rectangle, a horizon reconstruction algorithm to edge points having coordinates along axes  $\vec{X}$ ,  $\vec{Y}$  identical to the coordinates along axes  $\vec{X}$ ,  $\vec{Y}$  of reference edge points of said current reference edge.

The horizon reconstruction algorithm implemented to compute these boundary conditions  
5 may be a simplified algorithm insofar as its solutions are functions that can be graphically represented in two dimensions as lines. A first current reference edge may advantageously be chosen as being the one comprising the reference point associated with the related control point. A first horizon line comprising said related control point and forming a first related edge associated with reference edge points of the first current reference edge may be determined. The  
10 extremities of this first related edge may be used to determine, respectively, a second and third related edge, by implementing horizon reconstruction algorithms in a similar fashion on points of faces of the portion of the three-dimensional domain delimited by the current pseudo-rectangle associated with reference edge points of a second and third current reference edge. Two extremities of the second and third related edge may correspond to extremities of a fourth related  
15 edge. Therefore the fourth related edge may be determined by implementing a horizon reconstruction algorithm on edge points of a face associated with a fourth current reference edge, with the condition that the horizon line passes through both extremities of the fourth related edge.

It may be advantageous to perform the calculation of the boundaries prior to applying a  
20 diffeomorphic transformation to each pseudo-rectangle, insofar as some pseudo-rectangles and therefore, the portions of the three-dimensional domain that is delimited by these pseudo-

rectangles, may share at least a portion of an edge. In this way, it may be possible to reduce the number of calculations that are performed to determine the boundary conditions by using the already calculated boundaries of portions of the three-dimensional domain delimited by adjacent pseudo-rectangles. It may however also be possible to perform these calculations individually for  
5 each pseudo-rectangle in the transformed domain after applying a diffeomorphic transformation  $F$ . In this alternative embodiment of the invention, it may be possible to use the corresponding inverse diffeomorphic transformation  $F^{-1}$  to reuse the portions of boundaries that are identical for the portions of the three-dimensional domain delimited by two adjacent pseudo-rectangles.

Some techniques for defining pseudo-rectangles may be particularly advantageous, may  
10 further reduce the computation time of the algorithm, and may be easy to implement.

For instance, it may be possible to define pseudo-rectangles such that at least one reference corner of each pseudo-rectangle among the defined pseudo-rectangles may have coordinates along axes  $\vec{X}$ ,  $\vec{Y}$  identical to the coordinates along axes  $\vec{X}$ ,  $\vec{Y}$  of a related control point among the plurality of related control points.

15 In such an embodiment, each pseudo-rectangle among the defined pseudo-rectangles may have a reference corner associated with a related control point, thus enabling an easy calculation of the boundary conditions, for example by applying successive horizon reconstruction algorithms to points of faces of the portion of the three-dimensional domain comprising a reference edge comprising said corner and axis  $\vec{Z}$ .

20

In a particularly advantageous configuration, the received plurality of related control points may comprise at least three related control points, and defining pseudo-rectangles comprises:

- identifying reference points in the reference plane;
- 5 - identifying triangles having a first reference corner, a second reference corner and a third reference corner among the identified reference points using a triangulation, and
- in each of the identified triangles:
  - identifying a reference centroid of said triangle,
  - identifying a first reference center of the segment defined by the first reference
  - 10 corner and the second reference corner;
  - identifying a second reference center of the segment defined by the first reference corner and the third reference corner;

wherein a pseudo-rectangle is defined by segments connecting the first reference corner with the first reference center, the first reference center with the reference centroid, the reference centroid

15 with the second reference center and the second reference center with the first reference corner.

Such a method of defining pseudo-rectangles may provide several advantages. First of all, it can be easily implemented by a computer program, no matter the distribution of the related control points. Secondly, this method may optimize the size distribution of the pseudo-rectangles, since the area of the pseudo-rectangles that are part of a given triangle is substantially

20 the same. Thirdly, this way of defining pseudo-rectangles may greatly facilitate the determination of boundary conditions, since a reference corner of each pseudo-rectangle is

associated with a related control point, and the triangles define lines joining reference points. These lines enable an easy calculation of the corresponding horizon line by applying a horizon reconstruction algorithm to points of a plane comprising axis  $\vec{Z}$  and two of the related control points.

5 More specifically, when pseudo-rectangles are defined in this way, the method of the invention may advantageously comprise, for an identified triangle, and prior to applying a diffeomorphic transformation F :

- identifying a first, second and third related control point among the plurality of related control points associated with corresponding first , second and third reference corners  
10 of said identified triangle;
- applying a horizon reconstruction algorithm to points of a plane comprising axis  $\vec{Z}$  and comprising the first and second related control points to determine a first portion of a first local horizon;
- identifying a first related central point on the first portion of the first local horizon  
15 having coordinates along axes  $\vec{X}$  and  $\vec{Y}$  identical to coordinates along axes  $\vec{X}$  and  $\vec{Y}$  of the first reference center;
- applying a horizon reconstruction algorithm to points of a plane comprising axis  $\vec{Z}$  and comprising the first and third related control points to determine a second portion of a second local horizon;

- identifying a second related central point on the second portion of the second local horizon having coordinates along axes  $\vec{X}$  and  $\vec{Y}$  identical to coordinates along axes  $\vec{X}$  and  $\vec{Y}$  of the second reference center;
- computing a coordinate along axis  $\vec{Z}$  of a related middle point having coordinates along axes  $\vec{X}$  and  $\vec{Y}$  identical to coordinates along axes  $\vec{X}$  and  $\vec{Y}$  of the reference centroid of said identified triangle, the computation of said coordinate along axis  $\vec{Z}$  being a function of the coordinates of a point on said determined first or second local horizons.

More specifically, the computation of the z coordinate of the related middle point can be a function of any point belonging to the first or second local horizon. For example, it could advantageously be a function of one of the extremities of the first or second local horizons, or either related central point.

The method described above may benefit from one major advantage: it may be particularly efficient from a computational point of view because many steps are implemented once for a first identified triangle, but can be skipped when applying the method to points associated with adjacent triangles. This more specifically concerns the portions of local horizons joining two related control points associated with two reference corners of a triangle. These portions of local horizons may be shared by two adjacent portions of the three-dimensional domain delimited by two adjacent triangles.

It may be possible to compute the coordinates along axis  $\vec{Z}$  of the related middle point of the identified triangle by applying a horizon reconstruction algorithm to points of a plane comprising axis  $\vec{Z}$ , and comprising the segment connecting the first reference center with the reference centroid or the segment connecting the second reference center with the reference  
5 centroid.

Doing so may increase the precision of the above mentioned method.

Alternatively, computing a coordinate along axis  $\vec{Z}$  of the related middle point can also be achieved by calculating the mean value of the coordinates along axis  $\vec{Z}$  of at least the first and second related central points.

10 This technique may be very quick and provide a good accuracy especially if the size of the triangle is small.

Several techniques may be foreseen to solve the Poisson equation that is computed in the horizon reconstruction algorithm. Once the conditions required for a one-step direct resolution of the equation are met, it may be advantageous to solve the Poisson equation using a Fourier  
15 transform algorithm.

The latter algorithms are well-known and easy to implement in a computer program for instance, due to the multitude of existing libraries for performing Fourier transforms on discrete data. Furthermore, Fourier transform algorithms are excellent alternatives to matrix methods, the latter being a lot more complex to compute.

20

The method described above can be implemented on portions of the three-dimensional domain comprising points having the same x and y coordinates as individualized pseudo-rectangles.

5 However it is possible to define pseudo-rectangles that map a continuous portion of the reference plane.

This may increase the computational speed of the method due to the fact that some of the computed data, for example the boundaries, can be reused on portions of the three-dimensional domain delimited by neighboring pseudo-rectangles.

10 In a final step, once two-dimensional portions of a horizon have been calculated for each of the defined pseudo-rectangles, the method may further comprise assembling all these portions of horizons to define a finalized portion of a reconstructed horizon.

To do so, the method may comprise computing a portion of a seismic horizon from at least the computed part of the horizon of each current pseudo-rectangle among the defined pseudo-rectangles.

15 When pseudo-rectangles were defined using a triangulation as described above, the method may further comprise computing a portion of a seismic horizon from at least the computed part of the horizon of each current pseudo-rectangle among the defined pseudo-rectangles, and after computing a portion of a seismic horizon, the method may comprise:

- receiving modification information relating to the related control points;
- 20 - identifying pseudo-rectangles affected by the received modification information relating to the related control points;

- defining a new set of pseudo-rectangles in a local area corresponding to the area occupied by the pseudo-rectangles affected by said received modification information relating to the related control points;
- for each current pseudo-rectangle among the new set of pseudo rectangles:
  - 5       - applying a diffeomorphic transformation  $F$ , said diffeomorphic transformation  $F$ :
    - being a function of coordinates along  $\vec{X}$ ,  $\vec{Y}$  and defining a new domain comprising axes  $\vec{X}'$ ,  $\vec{Y}'$ ,  $\vec{Z}$ ;
    - transforming points of the seismic image having coordinates along axes  $\vec{X}$ ,  $\vec{Y}$  identical to coordinates along axes  $\vec{X}$ ,  $\vec{Y}$  of points in said  
10       current pseudo-rectangle, said points of the seismic image including the related control point associated with the current pseudo-rectangle;
    - transforming said current pseudo-rectangle into a corresponding rectangle;
  - 15       - applying a horizon reconstruction algorithm to the transformed points, to determine a part of a transformed horizon, said part of a transformed horizon comprising the transformed related control point, the reconstruction of the seismic horizon comprising solving the Poisson equation  $\Delta(\delta\tau) = -\text{div}(r)$ , where  $\delta\tau$  is an unknown function of coordinates along axes  $\vec{X}'$ ,  $\vec{Y}'$ ,  $\Delta$  denotes the

Laplace operator in the new domain,  $\text{div}$  denotes the divergence vector operator in the new domain and  $r$  is a fixed function of coordinates along axes  $\vec{X}'$ ,  $\vec{Y}'$ ;

- computing a part of the horizon, said computing of a part of the horizon comprising applying an inverse diffeomorphic transformation  $F^{-1}$  to the determined part of a transformed horizon.

Therefore, whenever new related control points are added, or former related control points are removed, the method can efficiently limit the portion of the three-dimensional domain on which new calculations are performed to the portion of the three-dimensional domain concerned by the modifications that were performed.

The invention also pertains to a device for enhancing the determination, from a seismic image, of at least a portion of a seismic horizon in a three-dimensional domain comprising axes  $\vec{X}$ ,  $\vec{Y}$ ,  $\vec{Z}$ , said seismic horizon being a function of coordinates along axes  $\vec{X}$ ,  $\vec{Y}$  in said three-dimensional domain,

wherein said device comprises:

- an input interface for receiving the seismic image, the seismic image having points associated with coordinates along axes  $\vec{X}$ ,  $\vec{Y}$ ,  $\vec{Z}$ ; and for receiving a plurality of related control points associated with coordinates on axes  $\vec{X}$ ,  $\vec{Y}$ ,  $\vec{Z}$ ;
- a circuit for defining, in a reference plane defined by axes  $\vec{X}$  and  $\vec{Y}$ , for at least one related control point among the plurality of related control points, an associated reference point with coordinates along axes  $\vec{X}$ ,  $\vec{Y}$ , among a plurality of reference

points, the reference point having coordinates on axes  $\vec{X}$  and  $\vec{Y}$  identical to coordinates on axes  $\vec{X}$  and  $\vec{Y}$  of the related control point,

- a circuit for defining pseudo-rectangles in the reference plane, each pseudo-rectangle comprising a reference point among a plurality of reference points;
- 5 - a circuit being adapted for, for each current pseudo-rectangle among the defined pseudo-rectangles:

- applying a diffeomorphic transformation  $F$ , said diffeomorphic transformation  $F$ :

- being a function of coordinates along  $\vec{X}$ ,  $\vec{Y}$  and defining a new domain comprising axes  $\vec{X}'$ ,  $\vec{Y}'$ ,  $\vec{Z}$ ;
- 10 - transforming points of the seismic image having coordinates along axes  $\vec{X}$ ,  $\vec{Y}$  identical to coordinates along axes  $\vec{X}$ ,  $\vec{Y}$  of points in said current pseudo-rectangle, said points of the seismic image including the related control point associated with the current pseudo-rectangle;
- 15 - transforming said current pseudo-rectangle into a corresponding rectangle;

- applying a horizon reconstruction algorithm to the transformed points, to determine a part of a transformed horizon, said part of a transformed horizon comprising the transformed related control point, the reconstruction of the seismic horizon comprising solving the Poisson equation  $\Delta(\delta\tau) = -\text{div}(\mathbf{r})$ , where
- 20

$\delta\tau$  is an unknown function of coordinates along axes  $\vec{X}'$ ,  $\vec{Y}'$ ,  $\Delta$  denotes the Laplace operator in the new domain,  $\text{div}$  denotes the divergence vector operator in the new domain and  $r$  is a fixed function of coordinates along axes  $\vec{X}'$ ,  $\vec{Y}'$ ;

- computing a part of the horizon, said computing of a part of the horizon comprising applying an inverse diffeomorphic transformation  $F^{-1}$  to the determined part of a transformed horizon.

5 The invention also pertains to a non-transitory computer readable storage medium, having stored thereon a computer program comprising program instructions, the computer program being loadable into a data-processing unit and adapted to cause the data-processing unit to carry out the sequence of operations of the method described above when the computer program is run by the data-processing device.

### BRIEF DESCRIPTION OF THE DRAWINGS

15 The method of the invention will be better understood by reading the detailed description of exemplary embodiments presented below. These embodiments are illustrative and by no means limitative. They are provided with the appended figures and drawings on which:

Figure 1 is a schematic representation of a seismic image in a three-dimensional domain; and

20 Figure 2 is a schematic representation of the three-dimensional domain of Figure 1 comprising related control points and their associated reference points in the reference plane; and

Figure 3 is a schematic representation of the reference plane of Figure 2; and

Figure 4 is a schematic representation of a plane pointed at on Figure 3 and comprising axis  $\vec{Z}$ , a portion of seismic image, a current reference edge of a pseudo-rectangle and a related control point associated with a reference point on the current reference edge; and

5 Figure 5 is a schematic representation of the three-dimensional domain of Figure 1 comprising one related control point the associated current pseudo-rectangle and the boundaries of the sought seismic horizon delimited by the current pseudo-rectangle; and

Figure 6 presents schematic representations (A and B) of the transformation operated by the diffeomorphic transformation  $F$  associated with the pseudo-rectangle of Figure 5; and

10 Figure 7 presents schematic representations (A and B) of the transformation operated by the inverse diffeomorphic transformation  $F^{-1}$  associated with the pseudo-rectangle of Figures 5, 6 element A and 6 element B; and

Figure 8 is a schematic representation of the three-dimensional domain of Figure 1 comprising related control points and their associated portions of a reconstructed seismic horizon; and

15 Figure 9 is a schematic representation of the reference plane of Figure 2 according to a second embodiment; and

Figure 10 is a schematic representation of the reference plane of Figure 9 with three pseudo-rectangles defined in accordance with the second embodiment; and

20 Figure 11 is a schematic representation of the reference plane of Figure 9 illustrating the pseudo-rectangles affected by the addition of a related control point; and

Figure 12 is a flow chart illustrating the main steps implemented by the horizon reconstruction method; and

Figure 13 is a possible embodiment for a device that enables the present invention.

For the sake of clarity, the dimensions of features represented on these figures may not necessarily correspond to the real-size proportions of the corresponding elements. Like reference numerals on the figures correspond to similar elements or items.

#### DETAILED DESCRIPTION OF THE INVENTION

Figure 1 represents an exemplary seismic image in a three-dimensional domain **1** associated with axes  $\vec{X}$ ,  $\vec{Y}$ ,  $\vec{Z}$ . Such an image comprises dark regions **101**, **102**, **103** alternating with brighter regions **110**, **120**, **130**. From the data contained in the seismic image of Figure 1, geophysicists may extract the tangent of the local dip  $p$  associated with every data point of the seismic image. The tangent of the local dip is expressed as a function of class  $C^1$  of  $x$ ,  $y$ ,  $z$  coordinates. The aim of a horizon reconstruction method is to find a two-dimensional surface in the three-dimensional domain **1**, that can be numerically represented as a function of class  $C^2$ :

$$\tau: (x,y) \rightarrow \tau(x,y)$$

of  $x$ ,  $y$  coordinates and verifying the condition :

$$\tau = \arg \min_{f \in C^2} \int_{\Omega} \|\nabla f(x,y) - p[x,y;f(x,y)]\|^2 d\Omega$$

where  $\|\ \|$  denotes a norm, for example the absolute value,  $\nabla$  denotes the gradient operator and  $\Omega$  the portion of the three-dimensional domain **1** on which the seismic horizon is calculated.

Iterative horizon reconstruction algorithms to solve the above equation are well-known from the existing prior art, such as for example from the above-cited article by Lomask *et al.*

In the process of implementing a horizon reconstruction algorithm, one constraint resides in the fact that any calculated horizon must pass through all the related control points received as  
5 input.

Several key steps are implemented in such an algorithm. Generally, a first horizon corresponding to a function  $\tau = \tau_0$  is initialized. Then, a residual term  $r$  is calculated. This term  $r$  is another function of coordinates  $x, y$ , verifying the condition  $r(x; y) = \nabla\tau(x; y) - \rho[x; y; \tau(x; y)]$ , which corresponds to the difference between the tangent of the local dip of the seismic image  
10 and the gradient of the horizon.

While implementing the iterative horizon reconstruction algorithm, the main challenge resides in minimizing this residual term  $r$ . This is done by progressively correcting function  $\tau$ , so that after each step  $k$  of the horizon reconstruction algorithm,  $\tau_{k+1} = \tau_k + \delta\tau_k$ . At each step, an update term  $\delta\tau$  is computed, the latter verifying:

15 
$$\delta\tau = \operatorname{argmin}_{f \in C^2} \int_{\Omega} \|\nabla f(x; y) + r(x; y)\|^2 d\Omega$$

This update term, later added to function  $\tau$ , is numerically obtained by solving the Poisson equation:

$$\Delta(\delta\tau) = -\operatorname{div}(r)$$

As mentioned above, the invention resides in the way this Poisson equation is calculated.

As illustrated on Figure 2, the method comprises receiving related control points **201**, **202**, **203**, **204**, **205**, **206**, **207**, **208** in the three-dimensional domain **1**. These related control points **201**, **202**, **203**, **204**, **205**, **206**, **207**, **208** may for example be points that are known to belong to a given horizon because of drills realized in the ground or because of reliable geological data. The horizon reconstruction algorithm relies on using the x and y coordinates of the points of the three-dimensional domain **1** as input, and calculating a corresponding coordinate along axis  $\vec{Z}$  to determine a reconstructed horizon. The method of the invention involves transformations on these points, that only affect their x and y coordinates, but do not change their z coordinate. To simplify the process of defining pseudo-rectangles and diffeomorphic transformations that are part of this invention, reference points **210**, **220**, **230**, **240**, **250**, **260**, **270**, **280** associated with said related control points are defined in a reference plane **10**, this reference plane being defined by axes  $\vec{X}$  and  $\vec{Y}$ . The reference points **210**, **220**, **230**, **240**, **250**, **260**, **270**, **280** have the same x and y coordinates along axes  $\vec{X}$  and  $\vec{Y}$  as the related control points **201**, **202**, **203**, **204**, **205**, **206**, **207**, **208** i.e. the point **210** (respectively **220**, **230**, **240**, **250**, **260**, **270**, **280**) is a projection of the related control point **201** (respectively **202**, **203**, **204**, **205**, **206**, **207**, **208**) on a plane surface  $(\vec{X}, \vec{Y})$ .

As illustrated on Figure 3, the invention then consists in defining pseudo-rectangles in the reference plane **10** comprising the reference points **210**, **220**, **230**, **240**, **250**, **260**, **270**, **280** associated with related control points. This may be done in many different ways, some of which are illustrated on Figures 3, 9 and 10. On Figure 3, pseudo-rectangles with random shapes map a

portion of the reference plane **10**. Each of these pseudo-rectangles contains one of the reference points **210, 220, 230, 240, 250, 260, 270, 280**. The latter points can be located anywhere on a current pseudo-rectangle. For example, reference point **280** belongs to a reference corner of a current pseudo-rectangle, and reference point **220** belongs to a current reference edge of a  
5 current pseudo-rectangle **3220**.

The pseudo-rectangles comprising reference points **210, 220, 230, 240, 250, 260, 270, 280** verify the boundary conditions called Neumann conditions, which state that for a unique point of fixed coordinates on the horizon, the derivative of the update term along the exterior normal  $\vec{\omega}$  to the boundary is assumed to be equal to zero and its mean value fixed to zero. In  
10 other words, for any value of coordinates  $x$  and  $y$  along the edges of the horizon in the portion  $\Omega$  of the three-dimensional domain **1** delimited by the current pseudo-rectangle, the following scalar product is equal to zero:  $\nabla\delta\tau(x;y).\vec{\omega}(x;y)=0$ . In such pseudo-rectangles, it is advantageous to avoid calculating the boundary conditions since these boundaries are not required to rapidly solve the horizon reconstruction algorithm. It may also be advantageous to  
15 verify that adjacent calculated portions of a seismic horizon form a continuous surface, and implement corrections to ensure that there is no discontinuity at their shared boundary.

In another embodiment, it may be advantageous to compute the boundary conditions on the edges of the horizon in the portion  $\Omega$  of the three-dimensional domain **1** delimited by the current pseudo-rectangle, to verify the Dirichlet conditions and in order to be sure that the  
20 different determined horizons for each pseudo-rectangle are continuous. On Figure 3, a plane **20** defined by axis  $\vec{Z}$  and containing reference point **220** and reference corners **2220, 2210** is

represented. This plane **20** comprises the current reference edge **320** of the current pseudo-rectangle **3220**. On Figure 3, this plane **20** appears as a line.

On Figure 4, the same plane **20** is represented with the points from the seismic image having the same coordinates in the three-dimensional domain **1** as points from the plane **20**, reference point **220**, the related control point **202**, and the reference corners **2220**, **2210**. To find the related edge **302** comprising related control point **202** and belonging to the seismic horizon, a horizon reconstruction algorithm can be applied to points of plane **20**. This horizon reconstruction algorithm is easier to implement since it resolves the Poisson equation in two-dimensions, that is to say, it computes a function  $\tau$  which can be expressed as a function of one variable and which can be graphically represented in a plane. As can be seen on Figure 4, the reconstructed horizon line **302** tends to follow the tangent of the dip of the points from the seismic image.

The boundaries of the sought horizon are represented on Figure 5. Figure 5 represents the portion of the three-dimensional domain **1** delimited by pseudo-rectangle **3220**. This portion comprises four faces: face **501** appears on the left side, face **504** on the right side, face **502** at the back and face **503** at the front of the illustration on Figure 5. Knowing a related edge **302**, corresponding to a horizon line of the sought horizon, comprised in face **501**, it is possible to compute the boundaries **420**. The horizon line **302** can be used to compute the other horizon lines along the adjacent faces **502**, **503** of the current portion of the three-dimensional domain **1** delimited by the current pseudo-rectangle **3220**. To do so, the extremities **2201** and **2202** of the horizon line are used in two horizon reconstruction algorithms to determine a second and third

horizon lines. The second horizon line passes through extremity **2202**, comprises another extremity **2203** and is comprised in face **502**. The third horizon line passes through extremity **2201**, comprises another extremity **2204** and is comprised in face **503**. The horizon line comprised in the remaining face **504** is determined by applying a horizon reconstruction  
5 algorithm to points of the remaining face **504**, so that the horizon line passes through extremities **2203** of the second and **2204** third horizon line.

This step by step approach leads to the determination of the boundary conditions in the portion  $\Omega$  of the three-dimensional domain **1** delimited by the current pseudo-rectangle, thereby fulfilling the Dirichlet boundary conditions. Figure 5 illustrates the determined boundaries **420** in  
10 the current portion  $\Omega$  of the three-dimensional domain **1** delimited by the current pseudo-rectangle associated with related control point **202**.

It is to be noted that although the above description and illustrations describe a way of determining the boundary conditions in the current portion  $\Omega$ , it is possible to skip this step and proceed with the method described below. Indeed, the method of this invention is also efficient  
15 in the case where a single related control point is contained in the current portion  $\Omega$ . Alternatives such as the configuration in which a related control point has the same x and y coordinates as a reference corner of the current pseudo-rectangle, as is the case for related control point **208**, is also compatible with the invention. As long as any one of the boundary conditions is met, the method of the invention further proceeds by identifying, for a current pseudo-rectangle, a  
20 diffeomorphic transformation  $F$  which transforms the current pseudo-rectangle into a

corresponding rectangle. For a current pseudo-rectangle, such a diffeomorphic transformation  $F$  is a function which transforms coordinates  $(x;y)$  into corresponding coordinates  $(x',y')$  so that:

$$\begin{bmatrix} x' \\ y' \end{bmatrix} = F(x;y) = \begin{bmatrix} F_{x'}(x;y) \\ F_{y'}(x;y) \end{bmatrix}$$

Figure 6 (element A) illustrates a current portion  $\Omega$  of the three-dimensional domain **1** delimited by the current pseudo-rectangle associated with related control point **202**, for which the Dirichlet conditions, represented by boundaries **420**, have been computed. All the points of this current portion  $\Omega$  are transformed using diffeomorphic transformation  $F$  to obtain the corresponding rectangle and the new domain  $\Omega'$  delimited by the corresponding rectangle illustrated on Figure 6 element B. The boundary conditions **620** in the new domain as well the transformed related control point **602** are also represented. The new domain is associated with the transformed axes  $\vec{X}'$ ,  $\vec{Y}'$ ,  $\vec{Z}$ . In addition to transforming the current portion  $\Omega$  into the new domain  $\Omega'$ , the method of the invention also transforms the corresponding portion of the seismic image, to obtain a set of transformed points in the new domain. The gradient field of the function  $\tau$  is therefore relied on a vector field by a partial differential equation:

$$\nabla \tau(x';y') = p' [x';y';\tau(x';y')] \tag{15}$$

where  $p'$  is the tangent of the transformed local dip  $p$ . It can be expressed as:

$$p' = J_F^{-1} p$$

where  $J_F^{-1}$  is the inverse of the transformation Jacobian matrix  $J_F$  defined by:

$$J_F = \begin{bmatrix} \frac{\partial x'}{\partial x} & \frac{\partial y'}{\partial x} \\ \frac{\partial x'}{\partial y} & \frac{\partial y'}{\partial y} \end{bmatrix}$$

The diffeomorphic transformation  $F$  transforming a current pseudo-rectangle into a corresponding rectangle is a homography defined by a 3x3 matrix  $H = [h_{ij}]$ . This transformation is given, for any  $x, y$  coordinates in the current portion  $\Omega$  by:

$$\begin{bmatrix} x' \\ y' \end{bmatrix} = \begin{bmatrix} \frac{h_{11}x + h_{12}y + h_{13}}{h_{31}x + h_{32}y + h_{33}} \\ \frac{h_{21}x + h_{22}y + h_{23}}{h_{31}x + h_{32}y + h_{33}} \end{bmatrix}$$

5 The four terms of the Jacobian are then defined by:

$$\frac{\partial x'}{\partial x}(x; y) = \frac{(h_{11}h_{32} - h_{31}h_{12})y + h_{11}h_{33} - h_{31}h_{13}}{(h_{31}x + h_{32}y + h_{33})^2}$$

$$\frac{\partial y'}{\partial x}(x; y) = \frac{(h_{21}h_{32} - h_{31}h_{22})y + h_{21}h_{33} - h_{31}h_{23}}{(h_{31}x + h_{32}y + h_{33})^2}$$

$$\frac{\partial x'}{\partial y}(x; y) = \frac{(h_{12}h_{31} - h_{31}h_{121})x + h_{21}h_{33} - h_{31}h_{23}}{(h_{31}x + h_{32}y + h_{33})^2}$$

$$\frac{\partial y'}{\partial y}(x; y) = \frac{(h_{22}h_{31} - h_{32}h_{21})x + h_{22}h_{33} - h_{31}h_{23}}{(h_{31}x + h_{32}y + h_{33})^2}$$

10 It is therefore possible to compute, for each point of the new domain, a transformed residual term  $r$  and solve the Poisson equation in the transformed domain.

With the elements obtained so far, two conditions are met to allow a direct and one-step resolution of the Poisson equation: the domain on which a solution is searched corresponds to points having  $x$  and  $y$  coordinates identical to those of a rectangle, and either at least one related control point is within this new domain, or the boundary conditions of the solution are known.

The determination of the update term, the solution of the Poisson equation, can be calculated using fast Fourier transform algorithms, for example by solving the equation:

$$\delta\tau = \text{FT}^{-1} \left[ \frac{\text{FT}[-\text{div}(r)]}{\text{FT}[\Delta]} \right]$$

where FT denotes a Fourier transform and  $\text{FT}^{-1}$  denotes an inverse Fourier transform.

Advantageously, the Fourier transform is a discrete Fourier transform, and even more  
5 advantageously a fast Fourier transform. If the size of the new domain can be expressed as a  
number verifying  $2^a 3^b 5^c 7^d 11^e 13^f$ , where a, b, c, d, e and f are positive integers and e+f is smaller  
than 1, then a particularly efficient fast Fourier transform can be implemented to further reduce  
the computation time of the method of the invention.

As represented on Figure 7 element A, once the transformed part of a reconstructed  
10 horizon **7020** is obtained, the method comprises applying the inverse diffeomorphic  
transformation  $F^{-1}$  to the transformed part of a reconstructed horizon to obtain a part of a  
reconstructed horizon **720**, as represented on Figure 7 element B.

Finally, the invention advantageously comprises assembling all the parts of a  
reconstructed horizon to obtain a reconstructed horizon on a portion of the three-dimensional  
15 domain **1** as represented on Figure 8.

Besides the general method described above, the invention may advantageously benefit  
from substantial optimizations that allow it to be performed faster and be easily programmed to  
be executed with minimal input from the user.

To this end, Figure 9 represents a method for defining pseudo-rectangles that have a  
20 substantially similar shape and which allows a fast and reliable calculation of the boundary  
conditions in each pseudo-rectangle.

On Figure 9 reference points **210, 220, 230, 240, 250, 260, 270, 280** associated with related control points **201, 202, 203, 204, 205, 206, 207, 208** are represented in the reference plane **10**. A triangulation, advantageously a Delaunay triangulation, connecting all these reference points to form triangles is implemented. Then, as represented on Figure 10, the center of each side of an identified triangle is selected. Figure 10 represents the triangle identified by corners corresponding to reference points **210, 220** and **230**. The reference centers **223, 212** and **213** of the sides of this triangle are also used to determine the centroid **2123** of this triangle, the centroid being the point where the median lines of the triangle cross. In this manner, the obtained three pseudo-rectangles have substantially the same area in each triangle, and the method can systematically be implemented by a computer program.

Other advantages arise from the method of defining pseudo-rectangles represented on [[f]]Figures 9 and 10. The sides of each triangle are lines joining two reference points having the same x and y coordinates as related control points, and boundary conditions can be easily computed in the plane comprising axis  $\vec{Z}$  and comprising two related control points by using a horizon reconstruction algorithm to obtain a horizon line. Since it may occur, as seen on Figure 9, that several triangles share a common side, the calculation of boundary conditions may not have to be computed for each triangle in the portion of the three-dimensional domain **1** delimited by a triangle. Indeed the results obtained in the portion of the three-dimensional domain **1** delimited by a previously identified triangle may be reused in the portion of the three-dimensional domain **1** delimited by subsequent triangles.

The centroid of each triangle, called reference centroid **2123**, shares the same x and y coordinates as a related middle point of the horizon. This related middle point is shared by three portions of horizon in three adjacent portions of the three-dimensional domain **1**. There are several options for determining the z coordinate of that middle point of the horizon.

5 It is for example possible to make realistic approximations that are likely to be valid for triangles having a small area compared to the size of the three-dimensional domain **1**. One of these consists in calculating the mean value of the z coordinate of related central points of the horizon, associated with reference centers **212**, **223**, **213** of at least two of the three sides of a current triangle. Another consists in assuming the z coordinate of that related middle point is  
10 equal to the z coordinate of any related point of the horizon associated with a reference point of the triangle, for example a reference corner **220**, **230**, **210** or a reference center **212**, **223**, **213** of a side of the triangle. Another method consists in applying a horizon reconstruction algorithm to points of the plane comprising axis  $\vec{Z}$  and comprising one of the segments connecting a reference center **212**, **223**, **213** of a side of the triangle, and the reference centroid **2123**, to obtain  
15 a horizon line.

In an alternative embodiment, it is possible to define pseudo-rectangles by combining the identified triangles two by two. Two adjacent triangles are combined by removing the segment they have in common. This embodiment is advantageous in that it makes it even easier to determine the boundary conditions of the portion  $\Omega$  of the three-dimensional domain **1** delimited  
20 by a pseudo-rectangle, since every reference corner of each pseudo-rectangle is associated with a

related control point. In this embodiment, horizon lines passing through the related control points define the boundary conditions of each pseudo-rectangle.

The method of the invention nonetheless also offers another major advantage over the existing prior art. Indeed, it is very efficient for computing portions of a seismic horizon when a related control point is added to or removed from a set of related control points.

Figure 11 represents reference plane **10** containing reference points **210, 220, 230, 240, 250, 260, 270, 280** associated with related control points **201, 202, 203, 204, 205, 206, 207, 208**. First, modification information relating to the related control points is received, for example the addition of a related control point. Then, the reference point **1100** in the reference plane **10** associated with the added related control point requires locally redefining pseudo-rectangles. Nevertheless, the effect is only local as shown on Figure 11, on which the darkest pseudo-rectangles correspond to the affected area that is chosen for a recalculation of the local horizon. In general, adding a related control point only affects the pseudo-rectangle or pseudo-rectangles to which the added reference point associated with the added related control point belongs. Nevertheless, it is advantageous to identify an affected area by identifying the triangle or triangles to which the reference point belongs. This may enable defining new pseudo-rectangles having substantially the same size as already defined surrounding pseudo-rectangles. Since the pseudo-rectangles comprising the added reference point may share boundaries with neighboring pseudo-rectangles, two of which may belong to neighboring triangles, it is advantageous to include these neighboring triangles into the affected area and triangulate a new set of pseudo-rectangles on this affected area. On Figure 11, the area affected by the addition of reference point

**1100** implies a new triangulation giving rise to twelve new pseudo-rectangles. Similar conclusions arise when a related control point is removed.

For the above reason, the invention is very efficient in terms of computation time required to determine a horizon, for example when a user decides to add several related control  
5 points in a portion of the three-dimensional domain **1** which requires a finer resolution in the reconstructed horizon.

Figure 12 is a flow-chart schematically illustrating the different steps that are implemented by the method of this invention.

In a first step S1, a seismic image SEISM\_IMG **1** is received. The seismic image **1** can  
10 for example be received from a raw seismic data treatment program that outputs the data points in the three-dimensional domain **1**.

In a second step S2, related control points CTRL.\_PTs **201, 202, 203, 204, 205, 206, 207, 208** are received. The x, y, z coordinates of these points are fixed and they all belong to the same horizon.

15 In a subsequent step S3, pseudo-rectangles PSEUD.\_RECT. are defined, in such a way that each pseudo-rectangle is in a reference plane and comprises at least one reference point **210, 220, 230, 240, 250, 260, 270, 280**.

In step S4, it is possible to apply, for each pseudo-rectangle PSEUD.\_RECT. one or several horizon reconstruction algorithms to points of an edge of a portion of the three-  
20 dimensional domain **1** delimited by the current pseudo-rectangle, in order to find the boundaries  
**420**.

In step S50, a diffeomorphic transformation  $F$  is identified for each pseudo-rectangle. An identified diffeomorphic transformation  $F$  is applied to a current pseudo-rectangle to transform it into a corresponding rectangle. By doing so, the method generates conditions in which solving the Poisson equation can be greatly simplified.

5           Step S50 also comprises applying said transformation to the points of the seismic image having the same  $x$  and  $y$  coordinates as points of the pseudo-rectangle.

The invention further comprises the horizon reconstruction algorithm per se. It starts with step S51 which comprises identifying a horizon corresponding to an initialization function  $\tau_k$  at  $k=0$  and proceeding iteratively as follows:

10           - comparing the number of iterations to a preset value  $N$ . It is assumed that the calculated horizon converges to a reliable solution typically after a few tens of iterations. In case the number of iterations is smaller than the preset value  $N$ , the method proceeds by;

- computing a residual term  $r_k$  using the horizon  $\tau_k$  and the tangent of the transformed local dip  $p$  at step S54;

15           - applying a horizon reconstruction algorithm using Fourier transforms to solve the Poisson equation in the new domain  $\Omega'$  at step S54;

- incrementing  $k$  by one digit at step S55 and returning to step S52. When the number  $k$  of iterations reaches the target value  $N$ , the method proceeds with step S6 by applying the inverse diffeomorphic transformation  $F^{-1}$  that can transform the corresponding rectangle into the current

20           pseudo-rectangle, to the computed horizon  $\tau_k$ .

Finally, all the portions of a reconstructed horizon obtained for each pseudo-rectangle can be assembled to form the portion of a reconstructed horizon represented on Figure 8.

A comparison of the method of the invention and the global optimization method disclosed by Lomask *et al.* was performed on real seismic data defining a volume of 1750m by 4000m by 1600m. Complex geometries and convergent structures of the treated data resulted in an extremely noisy estimated dip, so a set of twenty seven related control points were sequentially received in critical regions corresponding for example to peaks or basins of the horizon to be reconstructed, starting from an initial set of thirteen related control points.

The number of iterations in the horizon reconstruction algorithm to reach convergence of both methods was set to thirty. For the method of the invention, each identified triangle is subdivided in three pseudo-rectangles as described above. The twenty seven related control points then lead to one hundred and twenty six pseudo-rectangles. For the global optimization method disclosed by Lomask *et al.* each update term  $\delta\tau$  computation through a direction descent approach required three hundred iterations and the algorithm had to be initialized with a function  $\tau_0$  close to the solution. This function  $\tau_0$  was obtained from a horizon reconstructed over the entire domain by assuming that only one particular related control point was known.

Table 1 resumes the computation time in seconds that was measured using both methods. The time in parentheses corresponds to the time measured for the calculations dedicated to the Fourier transforms.

Size of rectangular domain (new domain)	Method of the invention		Method disclosed by Lomask <i>et al.</i>
	Normal size	Optimal size	

smallest	3.3 s (1.41 s)	2.7 s (0.561 s)	79.1 s
largest	9.98 s (5.47 s)	6.43 s (2.41 s)	
arithmetic mean	5.82 s (2.9 s)	4.26 s (1.56 s)	
geometric mean	5.4 s (2.54 s)	3.78 s (1.4 s)	

Table 1

Table 1 shows the time required to do calculations on the portions of the three-dimensional domain **1** based on the size of the domain. The column labeled normal size gives the measured time that elapsed during the implementation of the method of the invention on portions of a domain that did not have a size optimized for fast Fourier transforms. The column labeled optimal size gives the same data but measured on portions of a domain that had a size suitable for implementing a fast Fourier transform algorithm. The line labeled smallest corresponds to the smallest defined portions of domains, the line labeled largest corresponds to the largest defined portions of domains, and the arithmetic and geometric means give times calculated based on a mean value of the size of the rectangular domains. It arises from the data of table 1 that the method of the invention enables reducing the computation time by as much as thirty times when compared to global approaches like the one disclosed by Lomask *et al.* .

Another test was conducted to determine the time that can be saved using the method of the invention when modification instructions regarding the related control points are received. Table 2 summarizes the times in seconds measured for implementing the method of the invention when increasing the number of related control points from thirteen to twenty-seven. The time in parentheses corresponds to the time measured for the calculations dedicated to the Fourier transforms. In the column labeled entire reconstruction, the measured times are substantially the

same, since the volume on which the computation is implemented is the entire three-dimensional domain **1**. In the column labeled incremental reconstruction, the method is only applied to the portion of the three-dimensional domain **1** which is affected by the addition of new related control points.

Number of related control points	Entire reconstruction	Incremental reconstruction
13	3.8 s (1.4 s)	
18	3.73 s (1.4 s)	0.627 s (0.219 s)
23	3.72 s (1.38 s)	0.603 s (0.233 s)
27	3.78 s (1.4 s)	0.5 s (0.184 s)

5 Table 2

It appears from table 2 that the selective computation of portions of a horizon on only those parts that are affected by the addition or removal of related control points further enhances the computational speed of the method.

Figure 13 is a possible embodiment for a device that enables the present invention.

10 In this embodiment, the device **1300** comprises a computer, this computer comprising a memory **1305** to store program instructions loadable into a circuit and adapted to cause circuit **1304** to carry out the steps of the present invention when the program instructions are run by the circuit **1304**.

15 The memory **1305** may also store data and useful information for carrying the steps of the present invention as described above.

The circuit **1304** may be for instance:

- a processor or a processing unit adapted to interpret instructions in a computer language, the processor or the processing unit may comprise, may be associated with or be attached to a memory comprising the instructions, or
- the association of a processor / processing unit and a memory, the processor or the processing unit adapted to interpret instructions in a computer language, the memory comprising said instructions, or
- an electronic card wherein the steps of the invention are described within silicon, or
- a programmable electronic chip such as a FPGA chip (for « Field-Programmable Gate Array »).

5

10

This computer comprises an input interface **1303** for the reception of data used for the above method according to the invention and an output interface **1306** for providing a stacked model.

To ease the interaction with the computer, a screen **1301** and a keyboard **1302** may be provided and connected to the computer circuit **1304**.

15

The invention is not limited to the embodiments described above and may encompass equivalent embodiments.

For example, it is possible to define non quadrangular surfaces in the reference plane. Instead of defining pseudo-rectangles, it may for example be possible to define surfaces for which diffeomorphic transformations, transforming these surfaces into circles, can be obtained.

20

Indeed, a rapid resolution of the Poisson equation in a domain having a circular section, instead of a rectangular section, is possible.

It is possible to apply the diffeomorphic transformation  $F$  to a current pseudo-rectangle before calculating boundary conditions associated with the current pseudo-rectangle.

It is also possible to define some pseudo-rectangles which are not associated with any related control point. Although doing so might seem less advantageous from a computational point of view, it may be interesting in the case in which large gaps exist between local concentrations of related control points. Defining pseudo-rectangles that are not associated with any related control point may allow mapping a continuous portion of the three-dimensional domain **1** without having a high dispersion in the size of the pseudo-rectangles. It is also possible to have pseudo-rectangles that are not associated with any related control point, but which are adjacent to other pseudo-rectangles which are. Thereby, it is possible to use the boundary conditions of the neighboring pseudo-rectangles to meet the conditions enabling a direct resolution of the Poisson equation.

The method described above may also be implemented in a domain comprising more than three dimensions.

One may also define quadrangles that are not pseudo-rectangles, although this may render the calculation of the diffeomorphic transformations more complicated.

The embodiments above are intended to be illustrative and not limiting. Additional embodiments may be within the claims. Although the present invention has been described with reference to particular embodiments, workers skilled in the art will recognize that changes may be made in form and detail without departing from the spirit and scope of the invention.

Various modifications to the invention may be apparent to one of skill in the art upon reading this disclosure. For example, persons of ordinary skill in the relevant art will recognize that the various features described for the different embodiments of the invention can be suitably combined, un-combined, and re-combined with other features, alone, or in different combinations, within the spirit of the invention. Likewise, the various features described above should all be regarded as example embodiments, rather than limitations to the scope or spirit of the invention. Therefore, the above is not contemplated to limit the scope of the present invention.

PATENT APPLICATION

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

In re the application of:

Attorney Docket No.: 4229.108WOUS01

Guillaume ZINCK et al.

Confirmation No.:

Application No.:

Examiner:

Filed: Concurrent herewith

Group Art Unit:

For: METHOD FOR ENHANCING THE DETERMINATION OF A SEISMIC HORIZON

---

INFORMATION DISCLOSURE STATEMENT

Mail Stop Amendment  
Commissioner for Patents  
P.O. Box 1450  
Alexandria, VA 22313-1450

Commissioner:

Pursuant to 37 CFR § 1.56, the attention of the Patent and Trademark Office is hereby directed to the references listed on the attached Form PTO-1449. It is respectfully requested that the information be expressly considered during the prosecution of the above-referenced application, and be made of record therein and appear among the "References Cited" on any patent to issue therefrom.

The listing of a reference herein is not an admission that the reference is prior art or is material to patentability. 37 CFR § 1.97(h). Applicant reserves the right to establish the patentability of any claimed invention over any of the information provided herewith, and/or prove that this information may not be prior art, and/or prove that this information may not be enabling for any aspect of the information provided herewith.

This Information Disclosure Statement is being filed without a certification or fee because this Information Disclosure Statement is being filed with the application. No certification or fee is required. 37 CFR § 1.97(b)(1)(2).

This Information Disclosure Statement includes one or more non-English language references for which the relevance of the non-English language reference is discussed in the present specification. 37 CFR § 1.98(a)(3)(i).

Some of the references were cited in a counterpart foreign application. A copy of the International Search Report for PCT/EP2013/066492 is attached herewith for the Examiner's information.

This Information Disclosure Statement includes one or more non-English language references for which a copy of the translation of the non-English language reference is attached hereto. 37 CFR § 1.98(a)(3)(ii).

Respectfully submitted,



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Customer No. 24113  
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*Please grant any extension of time necessary for entry; charge any fee due to Deposit Account No. 16-0631.*

Substitute for form 1449/PTO  <b>INFORMATION DISCLOSURE STATEMENT BY APPLICANT</b> <i>(Use as many sheets as necessary)</i>				<i>Complete if Known</i>			
				Application Number			
				Filing Date			
				First Named Inventor		Guillaume ZINCK	
				Art Unit			
				Examiner Name			
Sheet	1	of	2	Attorney Docket Number	4229.108WOUS01		

U.S. PATENT DOCUMENTS				
EXAMINER INITIAL <sup>2</sup>	Cite No. <sup>1</sup>	Document Number	Publication Date MM-DD-YYYY	Name of Patentee or Applicant of Cited Document
		Number-Kind Code <sup>3</sup> (if known)		
		US-2013/0083973 A1	04-04-2013	Guillon et al.
		US-		

FOREIGN PATENT DOCUMENTS					
EXAMINER INITIAL <sup>2</sup>	Cite No. <sup>1</sup>	Foreign Patent Document	Publication Date MM-DD-YYYY	Name of Patentee or Applicant of Cited Document	T <sup>5</sup>
		Country Code <sup>3</sup> Number <sup>4</sup> Kind Code <sup>5</sup> (if known)			
		FR 2 869 693 A1	11-04-2005	Total France SA	√

EXAMINER SIGNATURE	DATE CONSIDERED
--------------------	-----------------

<sup>1</sup>EXAMINER: Initial if reference considered, whether or not citation is in conformance with MPEP 609. Draw line through citation if not in conformance and not considered. Include copy of this form with next communication to applicant.

<sup>2</sup>Applicant's unique citation designation number (optional). <sup>3</sup>See Kinds Codes of USPTO Patent Documents at [www.uspto.gov](http://www.uspto.gov) or MPEP 901.04. <sup>4</sup>Enter Office that issued the document, by the two-letter code (WIPO Standard ST.3). <sup>5</sup>For Japanese patent documents, the indication of the year of the reign of the Emperor must precede the serial number of the patent document. <sup>6</sup>Kind of document by the appropriate symbols as indicated on the document under WIPO Standard ST. 16 if possible. <sup>7</sup>Applicant is to place a check mark here if English language Translation is attached.

This collection of information is required by 37 CFR 1.97 and 1.98. The information is required to obtain or retain a benefit by the public which is to file (and by the USPTO in process) an application. Confidentiality is governed by 35 U.S.C. 122 and 37 CFR 1.14. This collection is estimated to take 2 hours to complete, including gathering, preparing, and submitting the completed application form to the USPTO. Time will vary depending upon the individual case. Any comments on the amount of time you require to complete this form and/or suggestions for reducing this burden, should be sent to the Chief Information Officer, U.S. Patent and Trademark Office, U.S. Department of Commerce, Washington, DC 20251. DO NOT SEND FEES OR COMPLETED FORMS TO THIS ADDRESS. SEND TO: Commissioner for Patents, P.O. Box 1450 Alexandria, VA 22313-1450.

Substitute for form 1449/PTO  <b>INFORMATION DISCLOSURE STATEMENT BY APPLICANT</b> <i>(Use as many sheets as necessary)</i>				<i>Complete if Known</i>			
				Application Number			
				Filing Date			
				First Named Inventor		Guillaume ZINCK	
				Art Unit			
Examiner Name							
Sheet	2	of	2	Attorney Docket Number	4229.108WOUS01		
<b>NON PATENT LITERATURE DOCUMENTS</b>							
EXAMINER INITIAL <sup>7</sup>	Cite No. <sup>1</sup>	Include name of the author (in CAPITAL LETTERS), title of the article (when appropriate), title of the item (book, magazine, journal, serial, symposium, catalog, etc.), date, page(s), volume-issue number(s), publisher, city and/or country where published			T <sup>2</sup>		
		J. LOMASK, ET AL., "Flattening with geological constraints", <i>Annual Meeting Expanded Abstracts</i> , Society of Exploration Geophysicists (SEG), 1 January 2006, pp. 1053-1056.					
		J. LOMASK, ET AL., "Flattening without picking", Society of Exploration Geophysicists (SEG), Vol. 71, No. 4, 1 July 2006, pp. P13-P20.					
		G. ZINCK, ET AL., "Discontinuous seismic horizon tracking based on a poisson equation with incremental dirichlet boundary conditions", <i>Image Processing (ICIP), 2011 18<sup>th</sup> IEEE International Conference On, IEEE</i> , 11 September 2011, pp. 3385-3388.					
		HONGZHI ZHONG, ET AL., "Solution of Poisson and Laplace equations by quadrilateral quadrature element", <i>International Journal of Solids and Structures</i> , Vol. 35, No. 21, 1 January 1998, pp. 2805-2819.					
		JACK HOYES, ET AL., "A review of "global" interpretation methods for automated 3D horizon picking", <i>The Leading Edge</i> , 1 January 2011, pp. 39-47.					
		GUILLAUME ZINCK, ET AL., "Fast seismic horizon reconstructions based on local dip transformation", <i>Journal of Applied Geophysics</i> , Vol. 96, 1 September 2013, pp. 11-18.					
		GUILLAUME ZINCK, ET AL., "Reconstruction d'hypersurfaces de champs de normales sous contraintes - Application à l'analyse stratigraphique des images sismiques", 18 December 2012, Chapter 1, Section 1.2.4; Chapter 3, Section 3.3.					
		PCT International Search Report for PCT/EP2013/066492, mailed March 3, 2014, 3 pgs.					
		PCT Written Opinion for PCT/EP2013/066492, mailed March 3, 2014, 7 pgs.					
EXAMINER SIGNATURE		DATE CONSIDERED					
<p>*EXAMINER: Initial if reference considered, whether or not citation is in conformance with MPEP 609. Draw line through citation if not in conformance and not considered. Include copy of this form with next communication to applicant. <sup>1</sup>Applicant's unique citation designation number (optional). <sup>2</sup>Applicant is to place a check mark here if English language Translation is attached.</p> <p>This collection of information is required by 37 CFR 1.98. The information is required to obtain or retain a benefit by the public which is to file (and by the USPTO to process) an application. Confidentiality is governed by 35 U.S.C. 122 and 37 CFR 1.14. This collection is estimated to take 120 minutes to complete, including gathering, preparing, and submitting the completed application form to the USPTO. Time will vary depending upon the individual case. Any comments on the amount of time you require to complete this form and/or suggestions for reducing this burden, should be sent to the Chief Information Officer, U.S. Patent and Trademark Office, U.S. Department of Commerce, Washington, DC 20231. DO NOT SEND FEES OR COMPLETED FORMS TO THIS ADDRESS. SEND TO: Commissioner for Patents, P.O. Box 1450 Alexandria, VA 22313-1450.</p> <p style="text-align: center;"><i>If you need assistance in completing the form, call 1-800-PTO-9199 (1-800-786-9199) and select option 2.</i></p>							

**PATENT COOPERATION TREATY**

**PCT**

**INTERNATIONAL SEARCH REPORT**

(PCT Article 18 and Rules 43 and 44)

Applicant's or agent's file reference BCT1301770D	<b>FOR FURTHER ACTION</b> see Form PCT/ISA/220 as well as, where applicable, item 5 below.	
International application No. PCT/EP2013/066492	International filing date ( <i>day/month/year</i> ) 6 August 2013 (06-08-2013)	(Earliest) Priority Date ( <i>day/month/year</i> ) 8 August 2012 (08-08-2012)
Applicant  TOTAL SA		

This international search report has been prepared by this International Searching Authority and is transmitted to the applicant according to Article 18. A copy is being transmitted to the International Bureau.

This international search report consists of a total of 3 sheets.

It is also accompanied by a copy of each prior art document cited in this report.

**1. Basis of the report**

a. With regard to the **language**, the international search was carried out on the basis of:

- the international application in the language in which it was filed  
 a translation of the international application into \_\_\_\_\_, which is the language of a translation furnished for the purposes of international search (Rules 12.3(a) and 23.1(b))

b.  This international search report has been established taking into account the **rectification of an obvious mistake** authorized by or notified to this Authority under Rule 91 (Rule 43.6**bis**(a)).

c.  With regard to any **nucleotide and/or amino acid sequence** disclosed in the international application, see Box No. I.

2.  **Certain claims were found unsearchable** (See Box No. II)

3.  **Unity of invention is lacking** (see Box No III)

4. With regard to the **title**,

- the text is approved as submitted by the applicant  
 the text has been established by this Authority to read as follows:

5. With regard to the **abstract**,

- the text is approved as submitted by the applicant  
 the text has been established, according to Rule 38.2, by this Authority as it appears in Box No. IV. The applicant may, within one month from the date of mailing of this international search report, submit comments to this Authority

6. With regard to the **drawings**,

- a. the figure of the **drawings** to be published with the abstract is Figure No. 6  
 as suggested by the applicant  
 as selected by this Authority, because the applicant failed to suggest a figure  
 as selected by this Authority, because this figure better characterizes the invention
- b.  none of the figures is to be published with the abstract

INTERNATIONAL SEARCH REPORT

International application No  
PCT/EP2013/066492

A. CLASSIFICATION OF SUBJECT MATTER  
INV. G01V1/30  
ADD.  
  
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED  
Minimum documentation searched (classification system followed by classification symbols)  
G01V  
  
Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)  
EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	LOMASK J ET AL: "FLATTENING WITHOUT PICKING", GEOPHYSICS, SOCIETY OF EXPLORATION GEOPHYSICISTS, US, vol. 71, no. 4, 1 July 2006 (2006-07-01), pages P13-P20, XP001245370, ISSN: 0016-8033, DOI: 10.1190/1.2210848 the whole document	1-14
A	JESSE LOMASK ET AL: "Flattening with geological constraints", SEG TECHNICAL PROGRAM EXPANDED ABSTRACTS 2006, 1 January 2006 (2006-01-01), pages 1053-1057, XP055103785, DOI: 10.1190/1.2369693 cited in the application the whole document	1-14

Further documents are listed in the continuation of Box C.

See patent family annex.

\* Special categories of cited documents :

- "A" document defining the general state of the art which is not considered to be of particular relevance
- "E" earlier application or patent but published on or after the international filing date
- "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
- "O" document referring to an oral disclosure, use, exhibition or other means
- "P" document published prior to the international filing date but later than the priority date claimed

- "T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
- "X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
- "Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
- "&" document member of the same patent family

Date of the actual completion of the international search

24 February 2014

Date of mailing of the international search report

03/03/2014

Name and mailing address of the ISA/  
European Patent Office, P.B. 5818 Patentlaan 2  
NL - 2280 HV Rijswijk  
Tel. (+31-70) 340-2040,  
Fax: (+31-70) 340-3016

Authorized officer

Scappazzoni, E

## INTERNATIONAL SEARCH REPORT

International application No  
PCT/EP2013/066492

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	ZINCK G ET AL: "Discontinuous seismic horizon tracking based on a poisson equation with incremental dirichlet boundary conditions", IMAGE PROCESSING (ICIP), 2011 18TH IEEE INTERNATIONAL CONFERENCE ON, IEEE, 11 September 2011 (2011-09-11), pages 3385-3388, XP032080418, DOI: 10.1109/ICIP.2011.6116436 ISBN: 978-1-4577-1304-0 the whole document	1-14
A	----- HONGZHI ZHONG ET AL: "Solution of Poisson and Laplace equations by quadrilateral quadrature element", INTERNATIONAL JOURNAL OF SOLIDS AND STRUCTURES, vol. 35, no. 21, 1 January 1998 (1998-01-01), pages 2805-2819, XP055103787, the whole document	1-14
A	----- JACK HOYES ET AL: "A review of "global" interpretation methods for automated 3D horizon picking", THE LEADING EDGE, 1 January 2011 (2011-01-01), pages 39-47, XP055103790, the whole document	1-14
A,P	----- GUILLAUME ZINCK ET AL: "Fast seismic horizon reconstruction based on local dip transformation", JOURNAL OF APPLIED GEOPHYSICS, vol. 96, 1 September 2013 (2013-09-01), pages 11-18, XP055103792, ISSN: 0926-9851, DOI: 10.1016/j.jappgeo.2013.06.010 the whole document	1-14
A,P	----- Guillaume Zinck: "Reconstruction d'hypersurfaces de champs de normales sous contraintes - Application à l'analyse stratigraphique des images sismiques",  18 December 2012 (2012-12-18), XP055103793, Retrieved from the Internet: URL:http://ori-oai.u-bordeaux1.fr/pdf/2012/ZINCK_GUILLAUME_2012.pdf [retrieved on 2014-02-21] section 1.2.4; chapter 3; section 3.3 -----	1-14

# PATENT COOPERATION TREATY

# PCT

From the INTERNATIONAL SEARCHING AUTHORITY

NOTIFICATION OF TRANSMITTAL OF  
THE INTERNATIONAL SEARCH REPORT AND  
THE WRITTEN OPINION OF THE INTERNATIONAL  
SEARCHING AUTHORITY, OR THE DECLARATION

To: Ameline, Jean-Paul Cabinet Plasseraud 52, Rue de la Victoire 75440 Paris Cedex 09 FRANCE
---

(PCT Rule 44.1)

Applicant's or agent's file reference BCT130177OD	Date of mailing <i>(day/month/year)</i> 3 March 2014 (03-03-2014)
International application No. PCT/EP2013/066492	International filing date <i>(day/month/year)</i> 6 August 2013 (06-08-2013)
Applicant TOTAL SA	

1.  The applicant is hereby notified that the international search report and the written opinion of the International Searching Authority have been established and are transmitted herewith.

**Filing of amendments and statement under Article 19:**  
 The applicant is entitled, if he so wishes, to amend the claims of the International Application (see Rule 46):

**When?** The time limit for filing such amendments is normally two months from the date of transmittal of the International Search Report.

**Where?** Directly to the International Bureau of WIPO, 34 chemin des Colombettes  
 1211 Geneva 20, Switzerland, Facsimile No.: (41-22) 338.82.70

**For more detailed instructions, see PCT Applicant's Guide, International Phase, paragraphs 9.004 - 9.011.**

2.  The applicant is hereby notified that no international search report will be established and that the declaration under Article 17(2)(a) to that effect and the written opinion of the International Searching Authority are transmitted herewith.

3.  **With regard to any protest** against payment of (an) additional fee(s) under Rule 40.2, the applicant is notified that:

the protest together with the decision thereon has been transmitted to the International Bureau together with any request to forward the texts of both the protest and the decision thereon to the designated Offices.

no decision has been made yet on the protest; the applicant will be notified as soon as a decision is made.

4. **Reminders**

The applicant may submit comments on an informal basis on the written opinion of the International Searching Authority to the International Bureau. The International Bureau will send a copy of such comments to all designated Offices unless an international preliminary examination report has been or is to be established. Following the expiration of 30 months from the priority date, these comments will also be made available to the public.

Shortly after the expiration of **18 months** from the priority date, the international application will be published by the International Bureau. If the applicant wishes to avoid or postpone publication, a notice of withdrawal of the international application, or of the priority claim, must reach the International Bureau before completion of the technical preparations for international publication (Rules 90*bis*.1 and 90*bis*.3).

Within **19 months** from the priority date, but only in respect of some designated Offices, a demand for international preliminary examination must be filed if the applicant wishes to postpone the entry into the national phase **until 30 months** from the priority date (in some Offices even later); otherwise, the applicant must, **within 20 months** from the priority date, perform the prescribed acts for entry into the national phase before those designated Offices.

In respect of other designated Offices, the time limit of **30 months** (or later) will apply even if no demand is filed within 19 months.

For details about the applicable time limits, Office by Office, see [www.wipo.int/pct/en/texts/time\\_limits.html](http://www.wipo.int/pct/en/texts/time_limits.html) and the *PCT Applicant's Guide*, National Chapters.

Name and mailing address of the International Searching Authority European Patent Office, P.B. 5818 Patentlaan 2 NL-2280 HV Rijswijk Tel. (+31-70) 340-2040 Fax: (+31-70) 340-3016	Authorized officer PAREDES SANCHEZ, Luis-Miguel Tel: +31 (0)70 340-3650
--	---

# PATENT COOPERATION TREATY

From the  
INTERNATIONAL SEARCHING AUTHORITY

# PCT

## WRITTEN OPINION OF THE INTERNATIONAL SEARCHING AUTHORITY (PCT Rule 43bis.1)

To:

see form PCT/ISA/220

Date of mailing  
(day/month/year) see form PCT/ISA/210 (second sheet)

Applicant's or agent's file reference  
see form PCT/ISA/220

**FOR FURTHER ACTION**  
See paragraph 2 below

International application No.  
PCT/EP2013/066492

International filing date (day/month/year)  
06.08.2013

Priority date (day/month/year)  
08.08.2012

International Patent Classification (IPC) or both national classification and IPC  
INV. G01V1/30

Applicant  
TOTAL SA

1. This opinion contains indications relating to the following items:

- Box No. I Basis of the opinion
- Box No. II Priority
- Box No. III Non-establishment of opinion with regard to novelty, inventive step and industrial applicability
- Box No. IV Lack of unity of invention
- Box No. V Reasoned statement under Rule 43bis.1(a)(i) with regard to novelty, inventive step and industrial applicability; citations and explanations supporting such statement
- Box No. VI Certain documents cited
- Box No. VII Certain defects in the international application
- Box No. VIII Certain observations on the international application

2. **FURTHER ACTION**

If a demand for international preliminary examination is made, this opinion will usually be considered to be a written opinion of the International Preliminary Examining Authority ("IPEA") except that this does not apply where the applicant chooses an Authority other than this one to be the IPEA and the chosen IPEA has notified the International Bureau under Rule 66.1bis(b) that written opinions of this International Searching Authority will not be so considered.

If this opinion is, as provided above, considered to be a written opinion of the IPEA, the applicant is invited to submit to the IPEA a written reply together, where appropriate, with amendments, before the expiration of 3 months from the date of mailing of Form PCT/ISA/220 or before the expiration of 22 months from the priority date, whichever expires later.

For further options, see Form PCT/ISA/220.

Name and mailing address of the ISA:



European Patent Office  
P.B. 5818 Patentlaan 2  
NL-2280 HV Rijswijk - Pays Bas  
Tel. +31 70 340 - 2040  
Fax: +31 70 340 - 3016

Date of completion of  
this opinion

see form  
PCT/ISA/210

Authorized Officer

Scappazzoni, E

Telephone No. +31 70 340-9441



---

**Box No. I Basis of the opinion**

---

1. With regard to the **language**, this opinion has been established on the basis of:
  - the international application in the language in which it was filed
  - a translation of the international application into , which is the language of a translation furnished for the purposes of international search (Rules 12.3(a) and 23.1 (b)).
2.  This opinion has been established taking into account the **rectification of an obvious mistake** authorized by or notified to this Authority under Rule 91 (Rule 43bis.1(a))
3. With regard to any **nucleotide and/or amino acid sequence** disclosed in the international application, this opinion has been established on the basis of a sequence listing filed or furnished:
  - a. (means)
    - on paper
    - in electronic form
  - b. (time)
    - in the international application as filed
    - together with the international application in electronic form
    - subsequently to this Authority for the purposes of search
4.  In addition, in the case that more than one version or copy of a sequence listing has been filed or furnished, the required statements that the information in the subsequent or additional copies is identical to that in the application as filed or does not go beyond the application as filed, as appropriate, were furnished.
5. Additional comments:

---

**Box No. II Priority**

---

1.  The validity of the priority claim has not been considered because the International Searching Authority does not have in its possession a copy of the earlier application whose priority has been claimed or, where required, a translation of that earlier application. This opinion has nevertheless been established on the assumption that the relevant date (Rules 43*bis*.1 and 64.1) is the claimed priority date.
2.  This opinion has been established as if no priority had been claimed due to the fact that the priority claim has been found invalid (Rules 43*bis*.1 and 64.1). Thus for the purposes of this opinion, the international filing date indicated above is considered to be the relevant date.
3. Additional observations, if necessary:

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**Box No. V Reasoned statement under Rule 43bis.1(a)(i) with regard to novelty, inventive step or industrial applicability; citations and explanations supporting such statement**

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1. Statement

Novelty (N)	Yes: Claims	<u>1-14</u>
	No: Claims	
Inventive step (IS)	Yes: Claims	<u>1-14</u>
	No: Claims	
Industrial applicability (IA)	Yes: Claims	<u>1-14</u>
	No: Claims	

2. Citations and explanations

**see separate sheet**

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**Box No. VI Certain documents cited**

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1. Certain published documents (Rules 43bis.1 and 70.10)

and / or

2. Non-written disclosures (Rules 43bis.1 and 70.9)

**see form 210**

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**Box No. VIII Certain observations on the international application**

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The following observations on the clarity of the claims, description, and drawings or on the question whether the claims are fully supported by the description, are made:

**see separate sheet**

**RE ITEM VIII: Certain observations on the international application**

**The application does not meet the requirements of Article 6 PCT, because independent claim 1, mutatis mutandis claims 12 to 14, is not clear.** The reasons are as follows:

**a.** It is clear from the description that it is essential to the definition of the invention that:

- all the control points are all from the same horizon to be enhanced; and
- the inverse diffeomorphic transformation  $F^{-1}$  is the inverse of  $F$ .

Since independent claim 1 does not contain these features it does not meet the requirement following from Article 6 PCT taken in combination with Rule 6.3(b) PCT that any independent claim must contain all the technical features essential to the definition of the invention.

**b.** The description gives the definition of the adjective "related": "*For the sake of clarity, any point belonging to the reference plane will be referred to using the adjective reference [...] and the corresponding points on the seismic horizon having the same x and y coordinates will be referred to using the adjective related [...].*" This definition provided in the description however leads to a lack of clarity in the wording of the claims: in the expression "receiving a plurality of related control points", one therefore understand that the control points all have the same x and y coordinates. This is however not the case (see for instance figure 2).

**c.** It is further essential to the definition of the invention to indicated on which elements the transformation  $F$  is applied. From the wording of the claims, it is not clear on which elements the diffeomorphic transformation  $F$  is applied. The reason being that claim 1 indicates that:

*"- for each current pseudo-rectangle among the defined pseudo-rectangles:*

- *applying a diffeomorphic transformation  $F$  (S50), said diffeomorphic transformation  $F$ :*

*[i.] being a function of coordinates along  $X, Y$  and defining a new domain comprising axes  $X', Y', Z$ ;*

*[ii.] transforming points of the seismic image having coordinates along axes  $X, Y$  identical to coordinates along axes  $X, Y$  of points in said current pseudo- rectangle, said points of the seismic image including the related control point associated with the current pseudo- rectangle;*

*[iii.] transforming said current pseudo-rectangle into a corresponding rectangle"*

This wording does not allow to know on which elements the transformation F is applied because points [i.], [ii.] and [iii.] are only defining the characterizing features of F and do not define steps or sub-steps of the claimed method.

**d.** Functions  $\delta\tau$  and  $\mathbf{r}$  are indicated in the claims as "an unknown function" and "a fixed function". This however renders the scope of claim 1 broader than justified by the description and drawings as these two functions have a specific technical meaning essential to the definition of the invention.

**RE ITEM V: Reasoned statement with regard to novelty, inventive step or industrial applicability; citations and explanations supporting such statement.**

**The subject-matter of all claims is new (Article 33(2) PCT) and involves an inventive step (Article 33(3) PCT).**

**A. PRIOR ART - RULE 64 PCT**

Reference is made to the following documents:

Reference is made to the following documents:

D1: Lomask J *et al*: "Flattening without Picking" in Geophysics, SEG, vol. 71, no. 4, July 2006, pp. P13-P20

D2: Lomask J *et al*: "Flattening with geological constraints", SEG Technical Program Expanded Abstracts 2006, pp. 1053-1057, cited in the application

D3: Zinck G *et al*: "Discontinuous seismic horizon tracking based on a poisson equation with incremental dirichlet boundary conditions", 18<sup>th</sup> IEEE International Conference on Image Processing, September 2011, pp. 3385-3388

D4: Zhong Z *et al*: "Solution of Poisson and Laplace equations by quadrilateral quadrature element", international Journal of Solids and Structures, vol. 35, no. 21, 1998, pp. 2805-2819

**B. NOVELTY AND INVENTIVE STEP - ARTICLES 33(2) AND 33(3) PCT**

Each of the documents D1 to D3 discloses methods for determining horizon by resolving the Poisson's equation for three-dimensional domains without the use of pseudo-rectangles and transformation. **The subject-matter of independent claim 1 is therefore new (Article 33(2) PCT).**

The problem solved by the present invention may be regarded as improving the time of computation of the horizon.

Document D4 discloses a general efficient method for solving the Poisson's equation in a two-dimensional domain with the use of pseudo-rectangles and transformation.

It is however firstly not straightforward to the skilled person to combine this document D4 to one of the documents D1 to D3 as there is no hint to this specific method. Secondly, even when combining D4 with one of the document D1 to D3, the combination would not result in the use of a reference plan and in the use of the projection of the control points on the reference plan. **The subject-matter of independent claim 1 does therefore involve an inventive step (Article 33(3) PCT).**

The same reasoning applies mutatis mutandis to independent claims 13 and 14. As being dependent on claim 1, the subject-matter of claims 2 to 12 are considered as new and involving an inventive step. **The subject-matter of independent claims 13 and 14 and of dependent claims 2 to 12 is therefore new (Article 33(2) PCT) and involves an inventive step (Article 33(3) PCT).**

**RE ITEM VI: Certain documents cited**

The following documents

D6: Zinck G *et al*: "Fast seismic horizon reconstruction based on local dip transformation", Journal of Applied Geophysics, vol. 96, September 2013, pp. 11-18

D7: Zinck G: "Reconstruction d'hypersurfaces de champs de normales sous contraintes - Application à l'analyse stratigraphique des images sismiques", PhD thesis, 18 December 2012

are cited according to Rule 64.3 PCT. These documents do not show the entirety of the features of the independent claims of the present application. These documents are however considered relevant for the assessment of inventive step in case the priority claim would be found invalid.

## Electronic Patent Application Fee Transmittal

<b>Application Number:</b>				
<b>Filing Date:</b>				
<b>Title of Invention:</b>	METHOD FOR ENHANCING THE DETERMINATION OF A SEISMIC HORIZON			
<b>First Named Inventor/Applicant Name:</b>	Guillaume Zinck			
<b>Filer:</b>	Thomas G. Dickson/Nicole Landree			
<b>Attorney Docket Number:</b>	4229.108WOUS01			
Filed as Large Entity				
<b>Filing Fees for U.S. National Stage under 35 USC 371</b>				
Description	Fee Code	Quantity	Amount	Sub-Total in USD(\$)
<b>Basic Filing:</b>				
National Stage Fee	1631	1	280	280
Natl Stage Search Fee - Report provided	1642	1	480	480
National Stage Exam - all other cases	1633	1	720	720
<b>Pages:</b>				
<b>Claims:</b>				
<b>Miscellaneous-Filing:</b>				
Oath/Decl > 30 Mos From 371 commencement	1617	1	140	140
<b>Petition:</b>				

Description	Fee Code	Quantity	Amount	Sub-Total in USD(\$)
<b>Patent-Appeals-and-Interference:</b>				
<b>Post-Allowance-and-Post-Issuance:</b>				
<b>Extension-of-Time:</b>				
<b>Miscellaneous:</b>				
			<b>Total in USD (\$)</b>	<b>1620</b>

## Electronic Acknowledgement Receipt

<b>EFS ID:</b>	21429252
<b>Application Number:</b>	14420267
<b>International Application Number:</b>	PCT/EP2013/066492
<b>Confirmation Number:</b>	7275
<b>Title of Invention:</b>	METHOD FOR ENHANCING THE DETERMINATION OF A SEISMIC HORIZON
<b>First Named Inventor/Applicant Name:</b>	Guillaume Zinck
<b>Customer Number:</b>	24113
<b>Filer:</b>	Thomas G. Dickson/Nicole Landree
<b>Filer Authorized By:</b>	Thomas G. Dickson
<b>Attorney Docket Number:</b>	4229.108WOUS01
<b>Receipt Date:</b>	06-FEB-2015
<b>Filing Date:</b>	
<b>Time Stamp:</b>	17:23:59
<b>Application Type:</b>	U.S. National Stage under 35 USC 371

### Payment information:

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Payment Type	Credit Card
Payment was successfully received in RAM	\$1620
RAM confirmation Number	4714
Deposit Account	160631
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The Director of the USPTO is hereby authorized to charge indicated fees and credit any overpayment as follows:

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Charge any Additional Fees required under 37 C.F.R. Section 1.17 (Patent application and reexamination processing fees)

Charge any Additional Fees required under 37 C.F.R. Section 1.19 (Document supply fees)

Charge any Additional Fees required under 37 C.F.R. Section 1.20 (Post Issuance fees)

Charge any Additional Fees required under 37 C.F.R. Section 1.21 (Miscellaneous fees and charges)

### File Listing:

Document Number	Document Description	File Name	File Size(Bytes)/ Message Digest	Multi Part /.zip	Pages (if appl.)
1	Transmittal of New Application	4229_108WOUS01_PTO1390.pdf	1471656	no	4
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<b>Warnings:</b>					
<b>Information:</b>					
2	Application Data Sheet	ADS.pdf	1895491	no	11
			156873385f0e6e6450cd35fafa081c620d6d 2248		
<b>Warnings:</b>					
<b>Information:</b>					
3	Documents submitted with 371 Applications	INTL_PUB_PAGE.pdf	87743	no	2
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<b>Warnings:</b>					
<b>Information:</b>					
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<b>Warnings:</b>					
<b>Information:</b>					
5	Documents submitted with 371 Applications	PCTIB304.pdf	244475	no	1
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<b>Warnings:</b>					
<b>Information:</b>					
6	Documents submitted with 371 Applications	PCTIB306.pdf	163988	no	1
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<b>Warnings:</b>					
<b>Information:</b>					
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<b>Warnings:</b>					
<b>Information:</b>					

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	Specification		2	2	
	Abstract		3	3	
	Claims		4	16	
	Applicant Arguments/Remarks Made in an Amendment		17	17	
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<b>Information:</b>					
16	Information Disclosure Statement (IDS) Form (SB08)	4229_108WOUS01_1449.pdf	828677 38bc1ecbd0a13cce92639799de0f0ca0ea442fbc	no	2
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<b>Information:</b>					
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17	Non Patent Literature	NPL1_Lomask_FlatteningWith GeologicalConstraints.pdf	77896 bb5b902e935ea6b29701397a8dbbf34c9e04be9	no	8
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<b>Information:</b>					
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<b>Information:</b>					
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<b>Information:</b>					
22	Non Patent Literature	NPL6_ZINCK_FAST_SEISMIC.pdf	2819947 869eb67495637250877cc1a69a9fbc1b66876e1d	no	8

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<b>Information:</b>					
23	Non Patent Literature	NPL7_Zinck_ReconstructionDHypersurfaces.pdf	4224279 4e69223b39010fa9895557c3f6c079cc63dbe857	no	51
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<b>Warnings:</b>					
<b>Information:</b>					
25	Non Patent Literature	NPL9_PCTISA237_WRITTEN_OPINION.pdf	316586 9bdd60bdf8c55373a57704749e15eb8e02533b65	no	7
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<b>Information:</b>					
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<b>Information:</b>					
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<b>Information:</b>					
<b>Total Files Size (in bytes):</b>			31984044		

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**National Stage of an International Application under 35 U.S.C. 371**

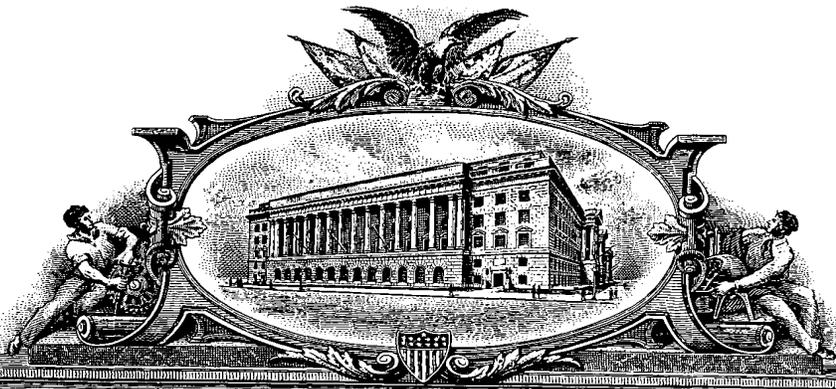
**If a timely submission to enter the national stage of an international application is compliant with the conditions of 35 U.S.C. 371 and other applicable requirements a Form PCT/DO/EO/903 indicating acceptance of the application as a national stage submission under 35 U.S.C. 371 will be issued in addition to the Filing Receipt, in due course.**

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**If a new international application is being filed and the international application includes the necessary components for an international filing date (see PCT Article 11 and MPEP 1810), a Notification of the International Application Number and of the International Filing Date (Form PCT/RO/105) will be issued in due course, subject to prescriptions concerning national security, and the date shown on this Acknowledgement Receipt will establish the international filing date of the application.**

EP13/66492

PA 7422381



# THE UNITED STATES OF AMERICA

**TO ALL TO WHOM THESE PRESENTS SHALL COME:**

**UNITED STATES DEPARTMENT OF COMMERCE**

**United States Patent and Trademark Office**

**June 11, 2013**

**THIS IS TO CERTIFY THAT ANNEXED HERETO IS A TRUE COPY FROM THE RECORDS OF THE UNITED STATES PATENT AND TRADEMARK OFFICE OF THOSE PAPERS OF THE BELOW IDENTIFIED PATENT APPLICATION THAT MET THE REQUIREMENTS TO BE GRANTED A FILING DATE UNDER 35 USC 111.**

**APPLICATION NUMBER: 61/681,005**

**FILING DATE: August 08, 2012**

**THE COUNTRY CODE AND NUMBER OF YOUR PRIORITY APPLICATION, TO BE USED FOR FILING ABROAD UNDER THE PARIS CONVENTION, IS US61/681,005**

**By Authority of the  
Under Secretary of Commerce for Intellectual Property  
and Director of the United States Patent and Trademark Office**



*T. Wallace*  
**T. WALLACE**  
Certifying Officer

## Electronic Acknowledgement Receipt

<b>EFS ID:</b>	13451372
<b>Application Number:</b>	61681005
<b>International Application Number:</b>	
<b>Confirmation Number:</b>	9590
<b>Title of Invention:</b>	FAST SEISMIC HORIZON RECONSTRUCTION BASED ON LOCAL DIP TRANSFORMATION
<b>First Named Inventor/Applicant Name:</b>	Guillaume Zinck
<b>Customer Number:</b>	24113
<b>Filer:</b>	Thomas G. Dickson/Rachel Gagliardi
<b>Filer Authorized By:</b>	Thomas G. Dickson
<b>Attorney Docket Number:</b>	4229.30US01P1
<b>Receipt Date:</b>	08-AUG-2012
<b>Filing Date:</b>	
<b>Time Stamp:</b>	17:52:43
<b>Application Type:</b>	Provisional

### Payment information:

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Payment was successfully received in RAM	\$ 250
RAM confirmation Number	4856
Deposit Account	
Authorized User	

### File Listing:

Document Number	Document Description	File Name	File Size(Bytes)/ Message Digest	Multi Part /.zip	Pages (if appl.)
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1		422930US01P1_Application.pdf	274875 4a67d0cf163fdea42ba4db095727720d57c1e5a	yes	6
<b>Multipart Description/PDF files in .zip description</b>					
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		Specification	1		4
		Drawings-only black and white line drawings	5		5
		Claims	6		6
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<b>Information:</b>					
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<b>Warnings:</b>					
<b>Information:</b>					
3	Fee Worksheet (SB06)	fee-info.pdf	29822 1b52c817dbbecf8c36870e00b5ead9e4554b0a92	no	2
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<b>Total Files Size (in bytes):</b>			1712057		
<p><b>This Acknowledgement Receipt evidences receipt on the noted date by the USPTO of the indicated documents, characterized by the applicant, and including page counts, where applicable. It serves as evidence of receipt similar to a Post Card, as described in MPEP 503.</b></p> <p><b><u>New Applications Under 35 U.S.C. 111</u></b>  <b>If a new application is being filed and the application includes the necessary components for a filing date (see 37 CFR 1.53(b)-(d) and MPEP 506), a Filing Receipt (37 CFR 1.54) will be issued in due course and the date shown on this Acknowledgement Receipt will establish the filing date of the application.</b></p> <p><b><u>National Stage of an International Application under 35 U.S.C. 371</u></b>  <b>If a timely submission to enter the national stage of an international application is compliant with the conditions of 35 U.S.C. 371 and other applicable requirements a Form PCT/DO/EO/903 indicating acceptance of the application as a national stage submission under 35 U.S.C. 371 will be issued in addition to the Filing Receipt, in due course.</b></p> <p><b><u>New International Application Filed with the USPTO as a Receiving Office</u></b>  <b>If a new international application is being filed and the international application includes the necessary components for an international filing date (see PCT Article 11 and MPEP 1810), a Notification of the International Application Number and of the International Filing Date (Form PCT/RO/105) will be issued in due course, subject to prescriptions concerning national security, and the date shown on this Acknowledgement Receipt will establish the international filing date of the application.</b></p>					

# Fast seismic horizon reconstruction based on local dip transformation

G. Zinck, M. Donias, J. Daniel, S. Guillon and O. Laviaille

**Abstract**—We propose a fast method to reconstruct a seismic horizon with respect to a set of picked input points. The reconstruction domain is subdivided in quadrilateral domains which are determined from input points while the entire horizon is obtained part by part by juxtaposing independent partial reconstructions. Each quadrilateral domain is mapped onto a rectangular domain on which a non linear partial derivative equation relied on local dip is solved by an iterative process based on a Poisson equation. The key point is the transformation of the local dip, which allows to carry out a direct Fourier method with a low computational cost.

**Index Terms**—Seismic horizon reconstruction, Poisson equation, Fast Fourier method, Local dip transformation.

## I. INTRODUCTION

To improve seismic data interpretation and understand geological processes, many recent numerical frameworks have been dedicated to seismic horizon reconstruction. Applications scopes are various, like geological model building, reservoir characterization [1] or chrono-stratigraphic interpretation [2], for instance by flattening [3]. Some authors [4] [5] perform the reconstruction by an integration of the estimated local dip along three-dimensional (3-D) seismic data. Lomask *et al.* [6] consider a global approach through a two-dimensional (2-D) non linear partial derivative equation (PDE) relied on local dip. The PDE is solved using a Gauss-Newton approach by an iterative algorithm whose crucial step is the resolution of a Poisson equation. In the case of complex geometries, Lomask and Guillon [7] have proposed to take into account geological constraints such as picked points. Nevertheless, the proposed method carries out an iterative algorithm which implies that the computational cost is often prohibitive for large data volume.

In this paper, we present a fast approach based on Lomask's iterative algorithm [6] to reconstruct a horizon with respect to a set of picked input points. Considering the input points as corners of quadrangles, the reconstruction domain of the horizon is subdivided in quadrilateral areas. Parts of the horizon are then reconstructed independently from each other on subdomains while the entire horizon is obtained by juxtaposing all reconstructed parts. Each quadrilateral domain is mapped onto a rectangular domain through a geometrical transformation. Instead of modifying the Poisson equation

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S. Guillon is with TOTAL CSTJF, Avenue Larribau, 64018 Pau, France (e-mail: sebastien.guillon@total.com).

Manuscript received ...; revised ...

as described in standard methods [8] [9], the key point of our approach is the transformation of local dip: the Poisson equation is therefore solved by a direct Fourier method which guarantees a low computational cost.

This article is organized as follows: section 2 introduces Lomask's horizon reconstruction algorithm, section 3 deals with a new fast reconstruction method on non-rectangular domains while the last section describes the part by part horizon reconstruction and exhibits results.

## II. HORIZON RECONSTRUCTION ALGORITHM

A seismic horizon can be considered as a curved segment in a 2-D space or as a surface in a 3-D space and is represented by a function  $\tau$  defined on a domain  $\Omega$ . The function  $\tau$  is connected to the tangent  $\mathbf{p}$  of the local dip<sup>1</sup> by a PDE:

$$\forall \mathbf{x} \in \Omega, \quad \nabla \tau(\mathbf{x}) = \mathbf{p}(\mathbf{x}, \tau(\mathbf{x})), \quad (1)$$

where  $\nabla$  denotes the gradient operator [6]. In a 2-D (resp. 3-D) space,  $\mathbf{x}$  denotes a one-dimensional (1-D) variable  $x$  (resp. a 2-D variable  $(x, y)$ ) while the local dip is a known one (resp. two)-dimensional vector giving the slope of the horizon tangent line (resp. plane) compared to the space axis  $\vec{x}$  (resp.  $\vec{x}$  and  $\vec{y}$ )<sup>2</sup>. The functions  $\tau$  and  $\mathbf{p}$  are respectively considered of class  $C^2$  and  $C^1$ .

The horizon is obtained by solving a constrained optimization problem:

$$\tau = \arg \min_{f \in C^2} \int_{\Omega} \|\nabla f(\mathbf{x}) - \mathbf{p}(\mathbf{x}, f(\mathbf{x}))\|^2 d\mathbf{x}, \quad (2)$$

assuming that either the horizon boundary or points belonging to the horizon are known. Equation (2) is non linear, thus an iterative algorithm is used to solve it [6]. The horizon is initialized with a function  $\tau_0$  and the iterative step is made of three parts : residual computation, update term computation and updating.

- *Residual computation:*

$$\forall \mathbf{x} \in \Omega, \quad \mathbf{r}_k(\mathbf{x}) = \nabla \tau_k(\mathbf{x}) - \mathbf{p}(\mathbf{x}, \tau_k(\mathbf{x})). \quad (3)$$

<sup>1</sup>The tangent  $\mathbf{p}$  is previously estimated over the entire seismic data by a gradient field principal component analysis [10].

<sup>2</sup>It can be noted that (1) is valid outside the seismic application scope to reconstruct a surface in a  $n$ -dimensional space in which  $\tau$  is an explicit function.

• *Update term computation:*

$$\delta\tau_k = \arg \min_{f \in C^2} \int_{\Omega} \|\nabla f(x) + r_k(x)\|^2 dx. \quad (4)$$

The solution of (4) is obtained by solving a Poisson equation

$$\Delta(\delta\tau_k) = -\text{div}(r_k), \quad (5)$$

where  $\Delta$  denotes the Laplace operator and  $\text{div}$  is the divergence vector operator.

If the horizon boundary is known, the Poisson equation is associated with boundary values called Dirichlet conditions which ensure the uniqueness of the solution:

$$\forall x \in \partial\Omega, \quad \delta\tau_k(x) = 0, \quad (6)$$

where  $\partial\Omega$  denotes the boundary of the domain.

If a unique point belonging to the horizon is known [6], the derivative of the update term along the exterior normal  $\vec{w}$  to the boundary are assumed to be equal to zero and its mean value is fixed to zero. The Poisson equation is then associated with boundary values called Neumann conditions which ensure the uniqueness of the solution:

$$\forall x \in \partial\Omega, \quad \nabla\delta\tau_k(x) \cdot \vec{w}(x) = 0, \quad (7)$$

where  $\cdot$  denotes the dot product operator. The problems (5)-(6) and (5)-(7) are called boundary problems.

If several points belonging to the horizon are known [7], the Poisson equation is associated with "inner" conditions:

$$\forall x \in \Omega_c, \quad \delta\tau_k(x) = 0, \quad (8)$$

where  $\Omega_c$  denotes the union set of all known points. The problem (5)-(8) is called inner problem.

• *Updating:*

$$\forall x \in \Omega, \quad \tau_{k+1}(x) = \tau_k(x) + \delta\tau_k(x). \quad (9)$$

If a unique point belonging to the horizon is known with coordinates  $(x^P, \tau(x^P))$ , the value  $\delta\tau_k(x^P)$  is moreover subtracted from  $\tau_{k+1}$  such as  $\tau_{k+1}(x^P) = \tau(x^P)$ .

Convergence is assumed to be reached after a number  $K$  of iterations.

The ability to compute the update term determines the computational efficiency of the reconstruction method, so the major step of the algorithm is the solving of the boundary and inner problems. On a 1-D domain and a 2-D rectangular domain, fast Fourier algorithms [11] can be applied to solve the boundary problems. The update term is computed in one step:

$$\delta\tau_k = \text{FT}^{-1} \left[ \frac{\text{FT}[-\text{div}(r_k)]}{\text{FT}[\Delta]} \right], \quad (10)$$

where  $\text{FT}$  and  $\text{FT}^{-1}$  denote respectively the Fourier transform and the inverse Fourier transform in dimension one or two<sup>3</sup>. However, the Fourier algorithms can not be carried out to

<sup>3</sup>It can be noted that (10) is valid on a hyperrectangular domain of a  $n$ -dimensional space.

solve the inner problem on the aforementioned domains. Iterative methods like descent direction approaches and relaxation algorithms are therefore proposed in the literature [12]. On 2-D non-rectangular domains (excepted on a disk), both problems lead to complex matrix inversions. For some particular domains diffeomorphic to a rectangular domain and called in this paper pseudo-rectangular domains, an alternative method is to map the physical domain  $\Omega$  onto a rectangular computational domain  $\Omega'$  by introducing a diffeomorphic transformation [8] [9]. On the domain  $\Omega'$ , a differential operator with variable coefficients takes place of the Laplace operator in (5). Although less complex than those described previously on  $\Omega$ , matrix methods to solve (5) on  $\Omega'$  [13] [14] are relatively slow whereas Fourier algorithms are irrelevant.

### III. FAST RECONSTRUCTION ON PSEUDO-RECTANGULAR DOMAINS

#### A. Local dip transformation

In this section, we present a fast horizon reconstruction on a pseudo-rectangular domain, assuming that either the horizon boundary or a unique point belonging to the horizon is known. Instead of replacing the Laplace operator in (5), the right term  $-\text{div}(r_k)$  is modified by a local dip transformation. The boundary problems can then be solved by a Fourier algorithm.

We propose to apply on (1) the diffeomorphic transformation  $\mathcal{F}$  which maps the pseudo-rectangular domain  $\Omega$  onto a rectangular domain  $\Omega'$ . The transformation is defined by

$$\forall (x, y) \in \Omega, \quad \begin{bmatrix} \xi \\ \eta \end{bmatrix} = \mathcal{F}(x, y) = \begin{bmatrix} \mathcal{F}_{\xi}(x, y) \\ \mathcal{F}_{\eta}(x, y) \end{bmatrix} \in \Omega'. \quad (11)$$

The gradient field of the function  $\tau$  is consequently relied on a vector field by a PDE:

$$\forall x' \in \Omega', \quad \nabla\tau(x') = \mathbf{p}'(x', \tau(x')), \quad (12)$$

where  $x'$  denotes the 2-D variable  $(\xi, \eta)$ . The 2-D vector  $\mathbf{p}'$  is the tangent of the transformed local dip, which gives the slope of the horizon tangent plane compared to the axis  $\vec{\xi}$  and  $\vec{\eta}$  of  $\Omega'$ . It is expressed by

$$\mathbf{p}' = J_{\mathcal{F}}^{-1} \mathbf{p}, \quad (13)$$

where  $J_{\mathcal{F}}^{-1}$  is the inverse of the transformation Jacobian matrix  $J_{\mathcal{F}}$  defined by

$$J_{\mathcal{F}} = \begin{bmatrix} \frac{\partial \xi}{\partial x} & \frac{\partial \eta}{\partial x} \\ \frac{\partial \xi}{\partial y} & \frac{\partial \eta}{\partial y} \end{bmatrix}. \quad (14)$$

*Proof:* Derivatives on  $\Omega$  and  $\Omega'$  [8] [9] are connected by the relation

$$\begin{bmatrix} \frac{\partial \tau}{\partial x} \\ \frac{\partial \tau}{\partial y} \end{bmatrix} = [J_{\mathcal{F}}] \begin{bmatrix} \frac{\partial \tau}{\partial \xi} \\ \frac{\partial \tau}{\partial \eta} \end{bmatrix}. \quad (15)$$

According to equations (1) and (15),

$$[J_{\mathcal{F}}] \begin{bmatrix} \frac{\partial \tau}{\partial \xi} \\ \frac{\partial \tau}{\partial \eta} \end{bmatrix} = \mathbf{p}. \quad (16)$$

Multiplying both sides of (16) by  $J_{\mathcal{F}}^{-1}$  leads to (13). ■

**B. Example of the quadrilateral domain**

A quadrilateral domain is an example of pseudo-rectangular domain. The diffeomorphic transformation  $\mathcal{F}$  introduced to map a quadrilateral domain onto a rectangular one is a homography defined by a  $3 \times 3$  matrix  $H = [h_{ji}]$  (see Fig. 1). The transformation is given by:

$$\forall (x, y) \in \Omega, \begin{bmatrix} \mathcal{F}_{\xi}(x, y) \\ \mathcal{F}_{\eta}(x, y) \end{bmatrix} = \begin{bmatrix} \frac{h_{11}x + h_{12}y + h_{13}}{h_{31}x + h_{32}y + h_{33}} \\ \frac{h_{21}x + h_{22}y + h_{23}}{h_{31}x + h_{32}y + h_{33}} \end{bmatrix}. \quad (17)$$

The four terms of the Jacobian are then:

$$\begin{aligned} \frac{\partial \xi}{\partial x}(x, y) &= \frac{(h_{11}h_{22} - h_{31}h_{12})y + h_{11}h_{23} - h_{31}h_{13}}{(h_{31}x + h_{32}y + h_{33})^2} \\ \frac{\partial \eta}{\partial x}(x, y) &= \frac{(h_{21}h_{22} - h_{31}h_{22})y + h_{21}h_{23} - h_{32}h_{23}}{(h_{31}x + h_{32}y + h_{33})^2} \\ \frac{\partial \xi}{\partial y}(x, y) &= \frac{(h_{12}h_{21} - h_{31}h_{11})x + h_{21}h_{23} - h_{31}h_{23}}{(h_{31}x + h_{32}y + h_{33})^2} \\ \frac{\partial \eta}{\partial y}(x, y) &= \frac{(h_{22}h_{21} - h_{32}h_{21})x + h_{22}h_{23} - h_{32}h_{23}}{(h_{31}x + h_{32}y + h_{33})^2} \end{aligned} \quad (18)$$

**IV. PART BY PART RECONSTRUCTION**

Given a set of input points and a rectangular domain  $\Gamma$ , our part by part horizon reconstruction method consists of three steps:

- 1) Subdivision of  $\Gamma$  in quadrilateral domains  $\Omega$  by considering the input points as corners of the domains.
- 2) For each domain  $\Omega$ :
  - a) Choice of the size of the rectangular computational domain  $\Omega'$  and estimation of the transformation  $\mathcal{F}$ .
  - b) Reconstruction of the horizon part along the boundary  $\partial\Omega$ .
  - c) Reconstruction of the horizon part on  $\Omega$ .
- 3) Reconstruction of the entire horizon on  $\Gamma$  by juxtaposition of all reconstructed horizon parts.

An input point has firstly to be picked on each corner of  $\Gamma$ . A Delaunay triangulation can secondly be performed for the input points [15]. Then, the triangles can be combined two by two in order to form quadrangles or each triangle can be subdivided in several quadrilateral elements (see Fig. 2). As the method is clearly under optimal, the choice of the computational domain size is a crucial step:  $\Omega'$  must be large enough to avoid losing data accuracy, but not too large to keep a low computational cost. The four segments constituting the boundary  $\partial\Omega$  are reconstructed in

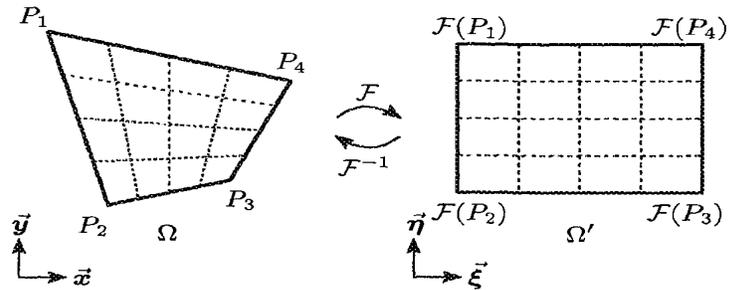


Fig. 1. Quadrilateral domain  $\Omega$  and rectangular domain  $\Omega'$  obtained by a homography  $\mathcal{F}$ .

a 2-D space by the one-dimensional version of the horizon reconstruction algorithm even though the two-dimensional transformation defined by (13) is applied to the local dip tangent. These segments are then used as Dirichlet conditions in the algorithm to obtain the 2-D horizon part on  $\Omega$ .

Part by part and Lomask's global optimization methods [7] are evaluated and compared on real seismic data (1,750 ms  $\times$  4,000 m  $\times$  1,600 m, see Fig. 3). Complex geometries and convergent structures of the treated data result in an extremely noisy estimated dip, so a set of 27 input points are sequentially picked in critical regions (peaks, bassins, etc.) of the horizon to be reconstructed, starting from an initial set of 13 points (see Fig. 2). The number  $K$  of iterations is empirically fixed to 30 to reach convergence of both methods. For the part by part method, each triangle is subdivided in three quadrilateral elements as described in [9]. The 27 input points then lead to 126 quadrangles. For the global optimization method, each update term computation through a direction descent approach requires 300 iterations and the algorithm has to be initialized with a function  $\tau_0$  close to the solution. The function  $\tau_0$  proposed in [7] is obtained from a horizon reconstructed over the entire domain by assuming that only one particular input point is known. Figure 4 compares the part by part and the global optimization horizons on a data cross-section for 27 input points. In spite of some differences (in particular on the right edge), the visible horizon and the reconstructed ones are almost superimposed, which proves precision and noise robustness of both methods. The cross-sections presented Fig. 5 depict the part by part horizon around the middle basin. They show that the reconstructed horizon and the visible horizon are more and more closer by increasing the number of input points.

For a given number of inputs points, the non-fixed part of the part by part method computational cost mainly depends on the cost of the Fourier transform, determined by the size of the rectangular domain  $\Omega'$ . The width and the length of  $\Omega'$  are two independant sizes linked to the sizes of the two pairs of opposite sides of  $\Omega$ . They can be taken as the shortest (Min) or the longest (Max) size as well as the arithmetic mean ( $\Sigma$ ) or the geometric mean ( $\Pi$ ) of each pair. The geometric mean is used for the considered horizon in Fig.

TABLE I  
COMPUTATIONAL TIMES IN SECONDS VERSUS RECTANGULAR DOMAINS SIZES FOR 27 INPUTS POINTS. TIMES IN BRACKETS ARE THE TIMES DEDICATED TO THE FOURIER TRANSFORM COMPUTATIONS.

Size of $\Omega'$	Part by part method		Global optimization
	Normal size	Optimal size	
Min	3.3 (1.41)	2.7 (0.561)	79.1
Max	9.98 (5.47)	6.43 (2.41)	
$\Sigma$	5.82 (2.9)	4.26 (1.56)	
$\Pi$	5.4 (2.54)	3.78 (1.4)	

4 and 5 and TABLE II. The corresponding computational costs for 27 input points are grouped in the second column of TABLE I. These costs can be strongly reduced by replacing each considered size by the closest size which is optimal for a fast Fourier transform algorithm. For instance, the optimal sizes for the FFTW library [16] are sizes of the form  $2^a 3^b 5^c 7^d 11^e 13^f$ , where  $e + f$  is either 0 or 1, and the other exponents are arbitrary (see the third column of TABLE I). In all cases, the cost of the part by part method is lower than the cost of the global optimization method, up to 30 times for the optimal shortest side size. This can principally be explained by two reasons. Firstly, the cost of the initialization step proposed in [7] is higher than the cost of the entire part by part horizon reconstruction without considering the local dip transformation step. Secondly, the update term is computed in one step in the part by part method whereas a large number of iterations is required in Lomask's one.

Adding or displacing vertically one input point causes a reestimation of the entire horizon with the global optimisation method. On the contrary, a partial (or incremental) reestimation of the horizon can be carried out with the part by part method: only the quadrangles connected to the added or the displaced point need to be recalculated. While the computational cost of the global optimization method does not depend on the number of input points, the costs of the entire and the incremental part by part reconstruction methods versus the number of points are presented in TABLE II. As expected, the incremental part by part reconstruction is extremely fast compared to the entire reconstruction and its time decreases when the number of points increases. Incremental part by part method can consequently be considered as a real-time method which allows an interactive reconstruction of a seismic horizon.

## V. CONCLUSION

We have developed a fast method to reconstruct a seismic horizon with respect to a set of input points. Our approach consists in a part by part reconstruction on quadrilateral subdomains. The key point is the transformation of the estimated local dip instead of the derivatives to solve a Poisson equation with a direct Fourier method, which guarantees a low computational cost. The horizons obtained for real seismic

TABLE II  
COMPUTATIONAL TIMES IN SECONDS OF THE PART BY PART RECONSTRUCTION VERSUS NUMBER OF INPUT POINTS. TIMES IN BRACKETS ARE THE TIMES DEDICATED TO THE FOURIER TRANSFORM COMPUTATIONS.

Number of input points	Entire reconstruction	Incremental reconstruction
13	3.8 (1.4)	-
18	3.73 (1.4)	0.627 (0.219)
23	3.72 (1.38)	0.603 (0.233)
27	3.78 (1.4)	0.5 (0.184)

data prove accuracy and noise robustness of the method. They are close to the visible ones and to those reconstructed by a more time-consuming global optimization method. The method moreover allows a real-time interactive reconstruction.

## ACKNOWLEDGMENT

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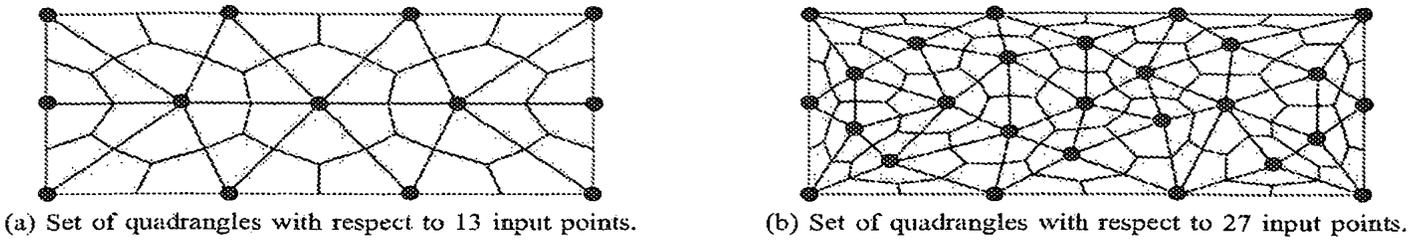


Fig. 2. Subdivision of domain  $\Gamma$  in a set of quadrangles with respect to input points (black disks). Each triangle is subdivided in three quadrilateral elements as described in [9].

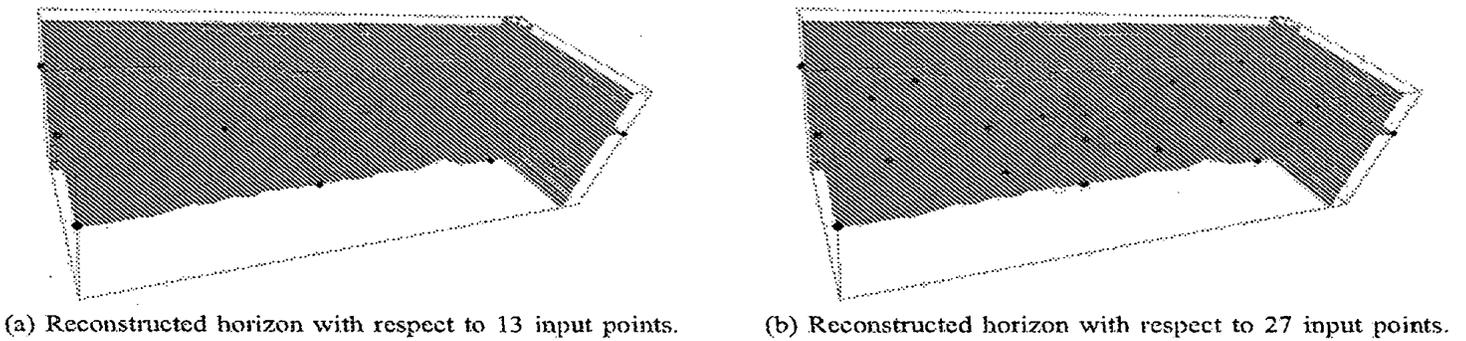


Fig. 3. Part by part horizon reconstruction with respect to input points (black spheres).

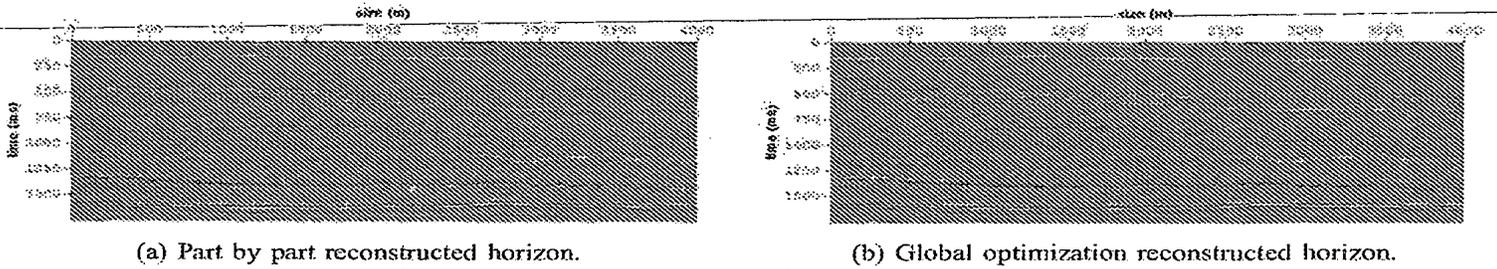


Fig. 4. Cross-section of the part by part and the global optimization reconstructed horizons with respect to 27 input points.

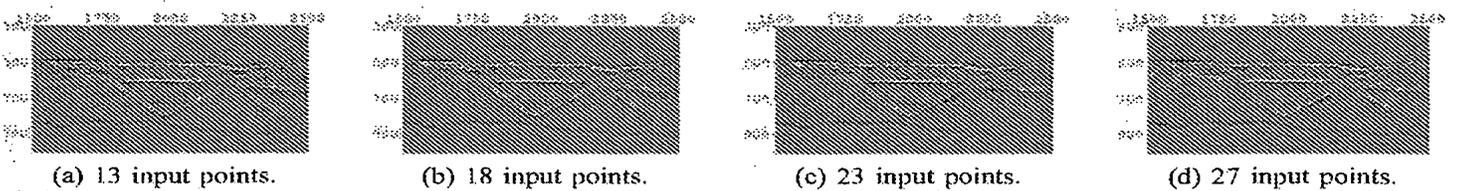


Fig. 5. Part by part reconstructed horizon versus number of input points.

Claims

1. A fast seismic horizon reconstruction system as described herein.
2. A method for fast seismic horizon reconstruction based on local dip transformation.

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Please Select One:	<input checked="" type="radio"/> Customer Number	<input type="radio"/> US Patent Practitioner	<input type="radio"/> Limited Recognition (37 CFR 11.9)
Customer Number	24113		

**Domestic Benefit/National Stage Information:**

This section allows for the applicant to either claim benefit under 35 U.S.C. 119(e), 120, 121, or 365(c) or indicate National Stage entry from a PCT application. Providing this information in the application data sheet constitutes the specific reference required by 35 U.S.C. 119(e) or 120, and 37 CFR 1.78(a)(2) or CFR 1.78(a)(4), and need not otherwise be made part of the specification.			
Prior Application Status			<input type="button" value="Remove"/>
Application Number	Continuity Type	Prior Application Number	Filing Date (YYYY-MM-DD)
Additional Domestic Benefit/National Stage Data may be generated within this form by selecting the Add button.			<input type="button" value="Add"/>

**Foreign Priority Information:**

Under the Paperwork Reduction Act of 1995, no persons are required to respond to a collection of information unless it contains a valid OMB control number.

<b>Application Data Sheet 37 CFR 1.76</b>	Attorney Docket Number	4229.30US01P1
	Application Number	
Title of Invention	FAST SEISMIC HORIZON RECONSTRUCTION BASED ON LOCAL DIP TRANSFORMATION	

This section allows for the applicant to claim benefit of foreign priority and to identify any prior foreign application for which priority is not claimed. Providing this information in the application data sheet constitutes the claim for priority as required by 35 U.S.C. 119(b) and 37 CFR 1.55(a).

<input type="button" value="Remove"/>			
Application Number	Country <sup>i</sup>	Parent Filing Date (YYYY-MM-DD)	Priority Claimed
			<input type="radio"/> Yes <input checked="" type="radio"/> No
Additional Foreign Priority Data may be generated within this form by selecting the Add button.			<input type="button" value="Add"/>

**Assignee Information:**

Providing this information in the application data sheet does not substitute for compliance with any requirement of part 3 of Title 37 of the CFR to have an assignment recorded in the Office.

<b>Assignee 1</b>					<input type="button" value="Remove"/>
If the Assignee is an Organization check here. <input type="checkbox"/>					
Prefix	Given Name	Middle Name	Family Name	Suffix	
<b>Mailing Address Information:</b>					
Address 1					
Address 2					
City		State/Province			
Country <sup>i</sup>	Postal Code				
Phone Number		Fax Number			
Email Address					
Additional Assignee Data may be generated within this form by selecting the Add button.					<input type="button" value="Add"/>

**Signature:**

A signature of the applicant or representative is required in accordance with 37 CFR 1.33 and 10.18. Please see 37 CFR 1.4(d) for the form of the signature.

<b>Signature</b>	/Thomas G. Dickson/		<b>Date (YYYY-MM-DD)</b>	2012-08-08	
<b>First Name</b>	Thomas G.	<b>Last Name</b>	Dickson	<b>Registration Number</b>	51616

This collection of information is required by 37 CFR 1.76. The information is required to obtain or retain a benefit by the public which is to file (and by the USPTO to process) an application. Confidentiality is governed by 35 U.S.C. 122 and 37 CFR 1.14. This collection is estimated to take 23 minutes to complete, including gathering, preparing, and submitting the completed application data sheet form to the USPTO. Time will vary depending upon the individual case. Any comments on the amount of time you require to complete this form and/or suggestions for reducing this burden, should be sent to the Chief Information Officer, U.S. Patent and Trademark Office, U.S. Department of Commerce, P.O. Box 1450, Alexandria, VA 22313-1450. DO NOT SEND FEES OR COMPLETED FORMS TO THIS ADDRESS. **SEND TO: Commissioner for Patents, P.O. Box 1450, Alexandria, VA 22313-1450.**

## Privacy Act Statement

The Privacy Act of 1974 (P.L. 93-579) requires that you be given certain information in connection with your submission of the attached form related to a patent application or patent. Accordingly, pursuant to the requirements of the Act, please be advised that: (1) the general authority for the collection of this information is 35 U.S.C. 2(b)(2); (2) furnishing of the information solicited is voluntary; and (3) the principal purpose for which the information is used by the U.S. Patent and Trademark Office is to process and/or examine your submission related to a patent application or patent. If you do not furnish the requested information, the U.S. Patent and Trademark Office may not be able to process and/or examine your submission, which may result in termination of proceedings or abandonment of the application or expiration of the patent.

The information provided by you in this form will be subject to the following routine uses:

1. The information on this form will be treated confidentially to the extent allowed under the Freedom of Information Act (5 U.S.C. 552) and the Privacy Act (5 U.S.C. 552a). Records from this system of records may be disclosed to the Department of Justice to determine whether the Freedom of Information Act requires disclosure of these records.
2. A record from this system of records may be disclosed, as a routine use, in the course of presenting evidence to a court, magistrate, or administrative tribunal, including disclosures to opposing counsel in the course of settlement negotiations.
3. A record in this system of records may be disclosed, as a routine use, to a Member of Congress submitting a request involving an individual, to whom the record pertains, when the individual has requested assistance from the Member with respect to the subject matter of the record.
4. A record in this system of records may be disclosed, as a routine use, to a contractor of the Agency having need for the information in order to perform a contract. Recipients of information shall be required to comply with the requirements of the Privacy Act of 1974, as amended, pursuant to 5 U.S.C. 552a(m).
5. A record related to an International Application filed under the Patent Cooperation Treaty in this system of records may be disclosed, as a routine use, to the International Bureau of the World Intellectual Property Organization, pursuant to the Patent Cooperation Treaty.
6. A record in this system of records may be disclosed, as a routine use, to another federal agency for purposes of National Security review (35 U.S.C. 181) and for review pursuant to the Atomic Energy Act (42 U.S.C. 218(c)).
7. A record from this system of records may be disclosed, as a routine use, to the Administrator, General Services, or his/her designee, during an inspection of records conducted by GSA as part of that agency's responsibility to recommend improvements in records management practices and programs, under authority of 44 U.S.C. 2904 and 2906. Such disclosure shall be made in accordance with the GSA regulations governing inspection of records for this purpose, and any other relevant (i.e., GSA or Commerce) directive. Such disclosure shall not be used to make determinations about individuals.
8. A record from this system of records may be disclosed, as a routine use, to the public after either publication of the application pursuant to 35 U.S.C. 122(b) or issuance of a patent pursuant to 35 U.S.C. 151. Further, a record may be disclosed, subject to the limitations of 37 CFR 1.14, as a routine use, to the public if the record was filed in an application which became abandoned or in which the proceedings were terminated and which application is referenced by either a published application, an application open to public inspections or an issued patent.
9. A record from this system of records may be disclosed, as a routine use, to a Federal, State, or local law enforcement agency, if the USPTO becomes aware of a violation or potential violation of law or regulation.

## **DOCUMENT MADE AVAILABLE UNDER THE PATENT COOPERATION TREATY (PCT)**

International application number:	<b>PCT/EP2013/066492</b>
International filing date:	<b>06 August 2013 (06.08.2013)</b>
Document type:	<b>Certified copy of priority document</b>
Document details:	Country/Office: <b>US</b>
	Number: <b>61/681 005</b>
	Filing date: <b>08 August 2012 (08.08.2012)</b>
Date of receipt at the International Bureau:	<b>24 September 2013 (24.09.2013)</b>

Remark: Priority document submitted or transmitted to the International Bureau in compliance with Rule 17.1(a),(b) or (b-bis)

**PCT REQUEST**

Print Out (Original in Electronic Form)

<b>0</b>	<b>For receiving Office use only</b>	
<b>0-1</b>	International Application No.	<b>PCT/EP2013/066492</b>
<b>0-2</b>	International Filing Date	<b>06 AUG 2013 (06.08.2013)</b>
<b>0-3</b>	Name of receiving Office and "PCT International Application"	<b>RO/EP</b>
<b>0-4</b>	<b>Form PCT/RO/101 PCT Request</b>	
0-4-1	Prepared Using	<b>PCT Online Filing Version 3.5.000.235 MT/FOP 20020701/0.20.5.20</b>
<b>0-5</b>	<b>Petition</b> The undersigned requests that the present international application be processed according to the Patent Cooperation Treaty	
<b>0-6</b>	<b>Receiving Office (specified by the applicant)</b>	<b>European Patent Office (EPO) (RO/EP)</b>
<b>0-7</b>	<b>Applicant's or agent's file reference</b>	<b>BCT130177OD</b>
<b>I</b>	<b>Title of Invention</b>	<b>METHOD FOR ENHANCING THE DETERMINATION OF A SEISMIC HORIZON</b>
<b>II</b>	<b>Applicant</b>	
II-1	This person is	<b>Applicant only</b>
II-2	Applicant for	<b>All designated States</b>
II-4	Name	<b>TOTAL SA</b>
II-5	Address	<b>2 place Jean Millier La Défense 6 92400 COURBEVOIE France</b>
II-6	State of nationality	<b>FR</b>
II-7	State of residence	<b>FR</b>
<b>III-1</b>	<b>Applicant and/or inventor</b>	
III-1-1	This person is	<b>Applicant only</b>
III-1-2	Applicant for	<b>All designated States</b>
III-1-4	Name	<b>CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE - CNRS -</b>
III-1-5	Address	<b>3, rue Michel Ange 75794 PARIS CEDEX 16</b>
III-1-6	State of nationality	<b>FR</b>
III-1-7	State of residence	

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<b>III-2</b>	<b>Applicant and/or inventor</b>	
III-2-1	This person is	<b>Applicant only</b>
III-2-2	Applicant for	<b>All designated States</b>
III-2-4	Name	<b>UNIVERSITE de BORDEAUX I</b>
III-2-5	Address	<b>351, cours de la Libération 33400 TALENCE</b>
III-2-6	State of nationality	<b>FR</b>
III-2-7	State of residence	<b>FR</b>
<b>III-3</b>	<b>Applicant and/or inventor</b>	
III-3-1	This person is	<b>Applicant only</b>
III-3-2	Applicant for	<b>All designated States</b>
III-3-4	Name	<b>École Nationale Supérieure des Sciences Agronomiques de Bordeaux-Aquitaine</b>
III-3-5	Address	<b>1 Cours du Général de Gaulle 33170 GRADIGNAN France</b>
III-3-6	State of nationality	<b>FR</b>
III-3-7	State of residence	<b>FR</b>
<b>III-4</b>	<b>Applicant and/or inventor</b>	
III-4-1	This person is	<b>Applicant only</b>
III-4-2	Applicant for	<b>All designated States</b>
III-4-4	Name	<b>INSTITUT POLYTECHNIQUE DE BORDEAUX</b>
III-4-5	Address	<b>1 avenue du Docteur Albert Schweitzer 33400 TALENCE France</b>
III-4-6	State of nationality	<b>FR</b>
III-4-7	State of residence	<b>FR</b>
<b>III-5</b>	<b>Applicant and/or inventor</b>	
III-5-1	This person is	<b>Inventor only</b>
III-5-3	Inventor for	
III-5-4	Name (LAST, First)	<b>ZINCK, Guillaume</b>
III-5-5	Address	<b>351 Cours de la Libération 33405 TALENCE France</b>
<b>III-6</b>	<b>Applicant and/or inventor</b>	
III-6-1	This person is	<b>Inventor only</b>
III-6-3	Inventor for	
III-6-4	Name (LAST, First)	<b>DONIAS, Marc</b>
III-6-5	Address	<b>351 Cours de la Libération 33405 TALENCE France</b>

**PCT REQUEST**

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<b>III-7</b> III-7-1 III-7-3 III-7-4 III-7-5	<b>Applicant and/or inventor</b> This person is Inventor for Name (LAST, First) Address	<b>Inventor only</b>  <b>DANIEL, Jacques</b> <b>351 Cours de la Libération</b> <b>33405 TALENCE</b> <b>France</b>
<b>III-8</b> III-8-1 III-8-3 III-8-4 III-8-5	<b>Applicant and/or inventor</b> This person is Inventor for Name (LAST, First) Address	<b>Inventor only</b>  <b>LAVIALLE, Olivier</b> <b>351 Cours de la Libération</b> <b>33405 TALENCE</b> <b>France</b>
<b>III-9</b> III-9-1 III-9-3 III-9-4 III-9-5	<b>Applicant and/or inventor</b> This person is Inventor for Name (LAST, First) Address	<b>Inventor only</b>  <b>GUILLON, Sébastien</b> <b>C/O TOTAL SA CSTJF-EB 279 Avenue</b> <b>Larribau</b> <b>64000 PAU</b> <b>France</b>
<b>IV-1</b>  IV-1-1 IV-1-2  IV-1-3 IV-1-4 IV-1-5	<b>Agent or common representative; or address for correspondence</b> The person identified below is hereby/ has been appointed to act on behalf of the applicant(s) before the competent International Authorities as: Name (LAST, First) Address  Telephone No. Facsimile No. e-mail	<b>Agent</b>  <b>AMELINE, Jean-Paul</b> <b>Cabinet PLASSERAUD</b> <b>52 rue de la Victoire</b> <b>75440 PARIS CEDEX 09</b> <b>France</b>  <b>00 33 1 40 16 70 00</b> <b>00 33 1 42 80 01 59</b> <b>info@plass.com</b>
<b>IV-2</b> IV-2-1	<b>Additional agent(s)</b> Name(s)	<b>additional agent(s) with same address as first named agent</b> <b>BEROGIN, Francis; KOENIG, Christine;</b> <b>BOIRE, Philippe; BURBAUD, Eric; CHATEAU,</b> <b>Marielle; COUSIN, Geoffroy; HASSINE,</b> <b>Albert; LE FALHER, Guy; LOISEL,</b> <b>Bertrand; LOUBAT, Patrice; PRIEUR,</b> <b>Patrick; VERDURE, Stéphane; WLODARCZYK,</b> <b>Lukasz; LOUVEL, Philippe; MOORE,</b> <b>Nicholas</b>

**PCT REQUEST**

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<b>V</b>	<b>DESIGNATIONS</b>		
<b>V-1</b>	<b>The filing of this request constitutes under Rule 4.9(a), the designation of all Contracting States bound by the PCT on the international filing date, for the grant of every kind of protection available and, where applicable, for the grant of both regional and national patents.</b>		
<b>VI-1</b>	<b>Priority claim of earlier national application</b>		
VI-1-1	Filing date	<b>08 August 2012 (08.08.2012)</b>	
VI-1-2	Number	<b>61/681 005</b>	
VI-1-3	Country	<b>US</b>	
<b>VI-2</b>	<b>Incorporation by reference :</b> where an element of the international application referred to in Article 11(1)(iii)(d) or (e) or a part of the description, claims or drawings referred to in Rule 20.5(a) is not otherwise contained in this international application but is completely contained in an earlier application whose priority is claimed on the date on which one or more elements referred to in Article 11(1)(iii) were first received by the receiving Office, that element or part is, subject to confirmation under Rule 20.6, incorporated by reference in this international application for the purposes of Rule 20.6.		
<b>VII-1</b>	<b>International Searching Authority Chosen</b>	<b>European Patent Office (EPO) (ISA/EP)</b>	
<b>VIII</b>	<b>Declarations</b>	Number of declarations	
VIII-1	Declaration as to the identity of the inventor	—	
VIII-2	Declaration as to the applicant's entitlement, as at the international filing date, to apply for and be granted a patent	—	
VIII-3	Declaration as to the applicant's entitlement, as at the international filing date, to claim the priority of the earlier application	—	
VIII-4	Declaration of inventorship (only for the purposes of the designation of the United States of America)	—	
VIII-5	Declaration as to non-prejudicial disclosures or exceptions to lack of novelty	—	
<b>IX</b>	<b>Check list</b>	Number of sheets	Electronic file(s) attached
IX-1	Request (including declaration sheets)	<b>5</b>	✓
IX-2	Description	<b>32</b>	✓
IX-3	Claims	<b>8</b>	✓
IX-4	Abstract	<b>1</b>	✓
IX-5	Drawings	<b>8</b>	✓
IX-7	TOTAL	<b>54</b>	

**PCT REQUEST**

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	<b>Accompanying Items</b>	Paper document(s) attached	Electronic file(s) attached
IX-8	Fee calculation sheet	—	✓
IX-18	PCT-SAFE physical media	—	—
<b>IX-20</b>	<b>Figure of the drawings which should accompany the abstract</b>	<b>12</b>	
<b>IX-21</b>	<b>Language of filing of the international application</b>	<b>English</b>	
<b>X-1</b>	<b>Signature of applicant, agent or common representative</b>	<b>(PKCS7 Digital Signature)</b>	
<b>X-1-1</b>	Name (LAST, First)	<b>AMELINE, Jean-Paul</b>	
<b>X-1-2</b>	Name of signatory	<b>, Jean-Paul Ameline 33528</b>	
<b>X-1-3</b>	Capacity (if such capacity is not obvious from reading the request)	<b>(Representative)</b>	

**FOR RECEIVING OFFICE USE ONLY**

<b>10-1</b>	<b>Date of actual receipt of the purported international application</b>	<b>06 AUG 2013 (06.08.2013)</b>
<b>10-2</b>	<b>Drawings:</b>	<b>X</b>
10-2-1	Received	
10-2-2	Not received	
<b>10-3</b>	<b>Corrected date of actual receipt due to later but timely received papers or drawings completing the purported international application</b>	
<b>10-4</b>	<b>Date of timely receipt of the required corrections under PCT Article 11(2)</b>	
<b>10-5</b>	<b>International Searching Authority</b>	<b>ISA/EP</b>
<b>10-6</b>	<b>Transmittal of search copy delayed until search fee is paid</b>	

**FOR INTERNATIONAL BUREAU USE ONLY**

<b>11-1</b>	<b>Date of receipt of the record copy by the International Bureau</b>	
-------------	---	--

From the INTERNATIONAL BUREAU

**PCT**NOTIFICATION OF THE RECORDING  
OF A CHANGE(PCT Rule 92bis.1 and  
Administrative Instructions, Section 422)

To:

AMELINE, Jean-Paul  
Cabinet PLASSERAUD  
52 rue de la Victoire  
F-75440 Paris Cedex 09  
FRANCE

Date of mailing ( <i>day/month/year</i> ) 28 January 2015 (28.01.2015)	<b>IMPORTANT NOTIFICATION</b>
Applicant's or agent's file reference BCT130177OD	
International application No. PCT/EP2013/066492	International filing date ( <i>day/month/year</i> ) 06 August 2013 (06.08.2013)

1. The following indications appeared on record concerning:

the applicant                       the inventor                       the agent                       the common representative

Name and Address UNIVERSITE DE BORDEAUX I 351, cours de la Libération Talence, 33400 France	State of Nationality FR	State of Residence
	Telephone No.	
	Facsimile No.	
	E-mail address	

2. The International Bureau hereby notifies the applicant that the following change has been recorded concerning:

the person                       the name                       the address                       the nationality                       the residence

Name and Address UNIVERSITE DE BORDEAUX 35 Place Pey Berland 33000 Bordeaux France	State of Nationality FR	State of Residence FR
	Telephone No.	
	Facsimile No.	
	E-mail address <input type="checkbox"/> Notifications by e-mail authorized	

3. Further observations, if necessary:

4. A copy of this notification has been sent to:

the receiving Office                       the International Preliminary Examining Authority  
 the International Searching Authority                       the designated Offices concerned  
 the Authority(ies) specified for supplementary search                       the elected Offices concerned  
 other:

The International Bureau of WIPO 34, chemin des Colombettes 1211 Geneva 20, Switzerland	Authorized officer <b>Hoeltker Christoph</b> e-mail pt06.pct@wipo.int Telephone No. +41 22 338 74 06
Facsimile No. +41 22 338 89 70	

INTERNATIONAL SEARCH REPORT

International application No  
PCT/EP2013/066492

A. CLASSIFICATION OF SUBJECT MATTER  
INV. G01V1/30  
ADD.  
  
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED  
Minimum documentation searched (classification system followed by classification symbols)  
G01V  
  
Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)  
EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	LOMASK J ET AL: "FLATTENING WITHOUT PICKING", GEOPHYSICS, SOCIETY OF EXPLORATION GEOPHYSICISTS, US, vol. 71, no. 4, 1 July 2006 (2006-07-01), pages P13-P20, XP001245370, ISSN: 0016-8033, DOI: 10.1190/1.2210848 the whole document -----	1-14
A	JESSE LOMASK ET AL: "Flattening with geological constraints", SEG TECHNICAL PROGRAM EXPANDED ABSTRACTS 2006, 1 January 2006 (2006-01-01), pages 1053-1057, XP055103785, DOI: 10.1190/1.2369693 cited in the application the whole document ----- -/--	1-14

Further documents are listed in the continuation of Box C.

See patent family annex.

\* Special categories of cited documents :

- "A" document defining the general state of the art which is not considered to be of particular relevance
- "E" earlier application or patent but published on or after the international filing date
- "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
- "O" document referring to an oral disclosure, use, exhibition or other means
- "P" document published prior to the international filing date but later than the priority date claimed

- "T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
- "X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
- "Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
- "&" document member of the same patent family

Date of the actual completion of the international search

24 February 2014

Date of mailing of the international search report

03/03/2014

Name and mailing address of the ISA/  
European Patent Office, P.B. 5818 Patentlaan 2  
NL - 2280 HV Rijswijk  
Tel. (+31-70) 340-2040,  
Fax: (+31-70) 340-3016

Authorized officer

Scappazzoni, E

## INTERNATIONAL SEARCH REPORT

International application No  
PCT/EP2013/066492

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	ZINCK G ET AL: "Discontinuous seismic horizon tracking based on a poisson equation with incremental dirichlet boundary conditions", IMAGE PROCESSING (ICIP), 2011 18TH IEEE INTERNATIONAL CONFERENCE ON, IEEE, 11 September 2011 (2011-09-11), pages 3385-3388, XP032080418, DOI: 10.1109/ICIP.2011.6116436 ISBN: 978-1-4577-1304-0 the whole document	1-14
A	----- HONGZHI ZHONG ET AL: "Solution of Poisson and Laplace equations by quadrilateral quadrature element", INTERNATIONAL JOURNAL OF SOLIDS AND STRUCTURES, vol. 35, no. 21, 1 January 1998 (1998-01-01), pages 2805-2819, XP055103787, the whole document	1-14
A	----- JACK HOYES ET AL: "A review of "global" interpretation methods for automated 3D horizon picking", THE LEADING EDGE, 1 January 2011 (2011-01-01), pages 39-47, XP055103790, the whole document	1-14
A,P	----- GUILLAUME ZINCK ET AL: "Fast seismic horizon reconstruction based on local dip transformation", JOURNAL OF APPLIED GEOPHYSICS, vol. 96, 1 September 2013 (2013-09-01), pages 11-18, XP055103792, ISSN: 0926-9851, DOI: 10.1016/j.jappgeo.2013.06.010 the whole document	1-14
A,P	----- Guillaume Zinck: "Reconstruction d'hypersurfaces de champs de normales sous contraintes - Application à l'analyse stratigraphique des images sismiques",  18 December 2012 (2012-12-18), XP055103793, Retrieved from the Internet: URL:http://ori-oai.u-bordeaux1.fr/pdf/2012/ZINCK_GUILLAUME_2012.pdf [retrieved on 2014-02-21] section 1.2.4; chapter 3; section 3.3 -----	1-14



- (51) International Patent Classification:  
*G01V 1/30* (2006.01)
- (21) International Application Number:  
PCT/EP2013/066492
- (22) International Filing Date:  
6 August 2013 (06.08.2013)
- (25) Filing Language:  
English
- (26) Publication Language:  
English
- (30) Priority Data:  
61/681 005 8 August 2012 (08.08.2012) US

33405 Talence (FR). **GUILLOIN, Sébastien**; C/O TOTAL SA CSTJF-EB 279 Avenue Larribau, F-64000 Pau (FR).

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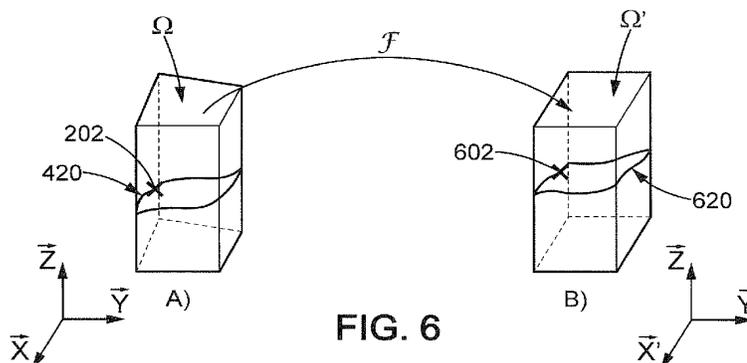
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(54) Title: METHOD FOR ENHANCING THE DETERMINATION OF A SEISMIC HORIZON



(57) Abstract: The invention pertains to a method for enhancing the determination, from a seismic image, of at least a portion of a seismic horizon in a three-dimensional domain, wherein said method comprises: - receiving the seismic image; - receiving a plurality of related control points; - defining pseudo-rectangles; - for each pseudo-rectangle: - applying a diffeomorphic transformation  $F$ : - defining a new domain; - transforming points of the seismic image; - transforming said pseudo-rectangle into a corresponding rectangle; - applying a horizon reconstruction algorithm to the transformed points, to determine a part of a transformed horizon, the reconstruction comprising solving a Poisson equation; - computing a part of the horizon, said computing comprising applying an inverse diffeomorphic transformation  $F^{-1}$  to the determined part of a transformed horizon.

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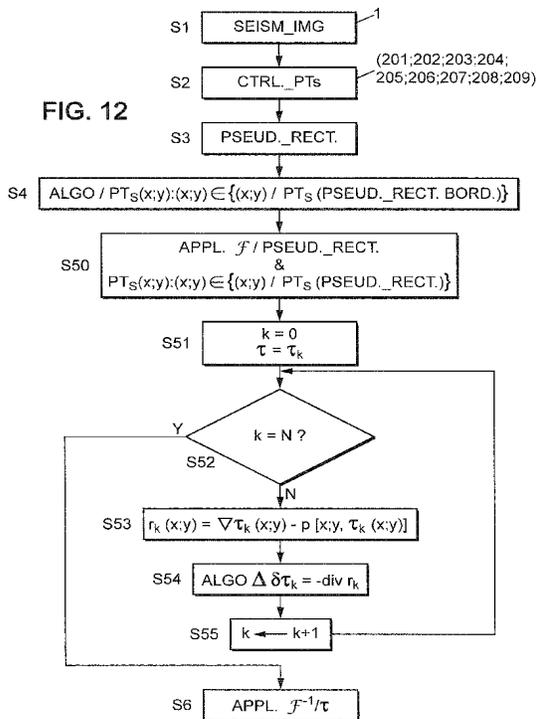
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(54) Title: METHOD FOR ENHANCING THE DETERMINATION OF A SEISMIC HORIZON



(57) Abstract: The invention pertains to a method for enhancing the determination, from a seismic image, of at least a portion of a seismic horizon in a three-dimensional domain, wherein said method comprises: - receiving the seismic image; - receiving a plurality of related control points; - defining pseudo-rectangles; - for each pseudo-rectangle: - applying a diffeomorphic transformation F : - defining a new domain; - transforming points of the seismic image; - transforming said pseudo-rectangle into a corresponding rectangle; - applying a horizon reconstruction algorithm to the transformed points, to determine a part of a transformed horizon, the reconstruction comprising solving a Poisson equation; - computing a part of the horizon, said computing comprising applying an inverse diffeomorphic transformation F<sup>-1</sup> to the determined part of a transformed horizon.



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**METHOD FOR ENHANCING THE DETERMINATION OF A SEISMIC HORIZON**

The invention pertains to the field of methods implemented in order to determine seismic horizons.

5

The invention more specifically relates to a method that enhances the determination of a seismic horizon without suffering from some of the drawbacks of the prior art.

10 Geological surveys involving generators of seismic waves and detectors of their reflections in the ground are often conducted to determine the position of oil reservoirs and/or to get to know the composition and thickness of the many layers that form the underground. Seismic reflection techniques consist in generating a seismic wave that propagates through the ground and reflects at the interfaces  
15 thereof. A precise measurement of these echoes and more specifically of their arrival times enables a determination of the shape, depth and composition of the layers that the seismic waves went through.

In a first phase following the measurement of these data signals, image generation algorithms, well-known in the art, are used to reconstruct a raw picture  
20 of the underground in the form of seismic images, sometimes also referred to as echographic images. These images can be either two-dimensional in shape or three-dimensional. Such seismic images comprise pixels the intensity of which is correlated to a seismic wave amplitude, dependent on the local impedance variation.

25 Geophysicists are used to manipulating such seismic images displaying information relating to amplitude. By merely looking at such seismic images, a geophysicist is capable of identifying areas of the underground having distinct characteristics, and use these to determine the corresponding structure of the underground.

Automatic techniques for extracting structural information from seismic images are known. These generally involve seismic horizon reconstruction algorithms that analyze amplitude gradients in a seismic image and extract the tangent of the local dip in a direction that is transverse to that gradient. Examples of techniques used for reconstructing a seismic horizon using a seismic image are for example described in the French patent FR 2 869 693 and US application US 20130083973.

Sometimes the exact depth of a layer can be known due to other data inputs or because of reliable geological information. Therefore, it is sometimes useful to define fixed related control points on a seismic image which are known to belong to a seismic horizon. It is then useful to compute a seismic horizon by implementing a seismic reconstruction algorithm with imposed conditions on a certain limited number of related control points.

One method for reconstructing a seismic horizon with imposed conditions on a number of related control points is described in the article "Flattening with geological constraints" in *Annual Meeting Expanded Abstracts*, Society of Exploration Geophysicists (SEG), 2006, pp. 1053-1056 by J. Lomask and A. Guitton.

The method disclosed in this article considers a global approach by solving a two-dimensional nonlinear partial derivative equation relied on local dip. The partial derivative equation is solved using a Gauss-Newton approach by an iterative algorithm whose crucial step is the resolution of a Poisson equation. The approach is global in that it systematically computes a seismic horizon on the entire domain of the seismic image, no matter the number of related control points received as input.

Even if it provides realistic seismic horizons, the method proposed by Lomask *et al.* suffers from two major drawbacks: its computational cost is often prohibitive for large data volumes, and it requires solving an iterative algorithm on the entire domain of the seismic image every time a change occurs in the number and/or position of the related control points received as input.

The high computational cost of the horizon reconstruction algorithm implemented by Lomask is further increased by the computational means for solving the Poisson equation that forms the core step of the iterative algorithm. In general, another iterative algorithm may be used to solve the Poisson equation.

5 The method disclosed by Lomask therefore comprises an iterative algorithm within another iterative algorithm.

To overcome these drawbacks, an enhancement of the determination of a seismic horizon that optimizes the computational speed of the horizon reconstruction algorithm is sought.

10 To achieve such an optimization and thereby overcome the drawbacks of the prior art, the invention provides a method for enhancing the determination, from a seismic image, of at least a portion of a seismic horizon in a three-dimensional domain comprising axes  $\vec{X}$ ,  $\vec{Y}$ ,  $\vec{Z}$ . In this three-dimensional domain, the seismic horizon is a function of coordinates along axes  $\vec{X}$ ,  $\vec{Y}$ . The method  
15 comprises:

- receiving the seismic image, the seismic image having points associated with coordinates along axes  $\vec{X}$ ,  $\vec{Y}$ ,  $\vec{Z}$ ;
- receiving a plurality of related control points associated with coordinates on axes  $\vec{X}$ ,  $\vec{Y}$ ,  $\vec{Z}$ ;
- 20 - in a reference plane defined by axes  $\vec{X}$  and  $\vec{Y}$ , defining, for at least one related control point among the plurality of related control points, an associated reference point with coordinates along axes  $\vec{X}$ ,  $\vec{Y}$ , among a plurality of reference points, the reference point having coordinates on axes  $\vec{X}$  and  $\vec{Y}$  identical to coordinates on axes  $\vec{X}$  and  $\vec{Y}$  of the related  
25 control point,
- defining pseudo-rectangles in said reference plane, each pseudo-rectangle comprising a reference point among a plurality of reference points.

30 In a subsequent step, the invention consists in, for each current pseudo-rectangle among the defined pseudo-rectangles:

- applying a diffeomorphic transformation  $F$ , the diffeomorphic transformation  $F$ :
  - being a function of coordinates along  $\vec{X}$ ,  $\vec{Y}$  and defining a new domain comprising axes  $\vec{X}'$ ,  $\vec{Y}'$ ,  $\vec{Z}$ ;
  - 5 - transforming points of the seismic image having coordinates along axes  $\vec{X}$ ,  $\vec{Y}$  identical to coordinates along axes  $\vec{X}$ ,  $\vec{Y}$  of points in the current pseudo-rectangle, the points of the seismic image including the related control point associated with the current pseudo-rectangle;
  - 10 - transforming the current pseudo-rectangle into a corresponding rectangle;
- applying a horizon reconstruction algorithm to the transformed points, to determine a part of a transformed horizon, the part of a transformed horizon comprising the transformed related control point, the reconstruction of the seismic horizon comprising solving the Poisson equation  $\Delta(\delta\tau) = -\text{div}(r)$ , where  $\delta\tau$  is an unknown function of coordinates along axes  $\vec{X}'$ ,  $\vec{Y}'$ ,  $\Delta$  denotes the Laplace operator in the new domain,  $\text{div}$  denotes the divergence vector operator in the new domain and  $r$  is a fixed function of coordinates along axes  $\vec{X}'$ ,  $\vec{Y}'$ ;
- 15 - computing a part of the horizon, the computing of a part of the horizon comprising applying an inverse diffeomorphic transformation  $F^{-1}$  to the determined part of a transformed horizon.

25

The term pseudo-rectangle is used to refer to any quadrangle or quadrilateral that has a convex shape, that is to say that each of its inner angles is smaller than  $180^\circ$ . Simple diffeomorphic transformations can be used to transform a convex quadrangle into a rectangle.

30

Axes  $\vec{X}$ ,  $\vec{Y}$ ,  $\vec{Z}$  are used to define corresponding coordinates  $x$ ,  $y$  and  $z$  for each point in the three-dimensional domain.

For the sake of clarity, any point belonging to the reference plane will be referred to using the adjective reference, e.g. a reference center, and the corresponding points on the seismic horizon having the same  $x$  and  $y$  coordinates will be referred to using the adjective related, e.g. a related central point.

One advantageous feature of the invention resides in the definition of pseudo-rectangles that delimit portions of the three-dimensional domain. Each of these portions has a pseudo-rectangular section and comprises points in the vicinity of a related control point. A horizon reconstruction algorithm is applied to the points of these portions of the three-dimensional domain. The combined volume of these portions, corresponding to the sum of all the volumes of the portions defined by pseudo-rectangles, may be smaller than the volume of the domain corresponding to the entire seismic image. This reduction in volume provides a first enhancement of the computational speed of the horizon reconstruction algorithm.

A second advantageous feature of the invention is that it provides fast means for solving the Poisson equation, the latter generally implementing an iterative algorithm within the horizon reconstruction algorithm. To do so, the invention introduces for each previously defined pseudo-rectangle, a corresponding diffeomorphic transformation  $F$  which transforms each pseudo-rectangle into a corresponding rectangle in a transformed reference plane defined by axes  $\vec{X}'$  and  $\vec{Y}'$ . The same diffeomorphic transformation  $F$  also transforms the points of the corresponding portion of the three-dimensional domain into transformed points which are within a transformed portion of the three-dimensional domain delimited by the corresponding rectangle. The purpose of this transformation is to meet some conditions in which the Poisson equation can be solved in one step, i.e. using direct calculation techniques that do not rely on an iterative algorithm. It is known, by a man skilled in the art of solving Poisson equations on discrete systems, that at least two conditions can be met to enable such a fast computation:

- the portion of the three-dimensional domain on which the equation is solved advantageously has a rectangular or circular section and,
- either

5

- at least one related control point belongs to the latter portion of the three-dimensional domain, this being also associated with specific conditions on the boundaries called Neumann condition, or
- the boundary conditions along the edges of the portion of the three-dimensional domain are known, the latter condition being also referred to as Dirichlet boundary condition.

10

In the invention, the diffeomorphic transformation of pseudo-rectangles into rectangles ensures that the first condition is met. The diffeomorphic transformation associated with a pseudo-rectangle is applied to all the points of the seismic image whose coordinates along axes  $\vec{X}$  and  $\vec{Y}$  match those of points in the pseudo-rectangle. The coordinates along axis  $\vec{Z}$  are not affected by that transformation.

15

The second condition is met by defining pseudo-rectangles that comprise reference points associated with related control points received as input and the coordinates of which are known.

20

Another original feature of the invention resides in the fact that each diffeomorphic transformation is applied to the portion of the seismic image comprising points having the same x and y coordinates as points in the pseudo-rectangles. Therefore, it may not be necessary to replace the Laplace operator of the Poisson equation by a differential operator with variable coefficients, which would render the resolution of the Poisson equation complex. In the invention, the divergence operator and the fixed function r are the ones that are transformed, thereby enabling the implementation of fast solvers and not necessarily matrix methods.

25

30

Finally, another original feature of this invention is the possibility of choosing pseudo-rectangles delimiting portions of the three-dimensional domain having any section suitable for encompassing the received related control points. This is particularly interesting in situations where the related control points are inhomogeneously scattered in the three-dimensional domain, with areas locally

having higher concentrations of related control points. In such situations, defining a portion of the three-dimensional domain with a rectangular section may prove difficult insofar as it may require defining rectangles with small dimensions, sometimes referred to as degenerated rectangles. Horizon reconstruction algorithms might suffer from an insufficient number of data points in portions delimited by such degenerated rectangles and provide less accurate results. The use of pseudo-rectangles gives more freedom in choosing shapes adapted to the local distribution of related control points without suffering from the disadvantages that arise when defining portions of the three-dimensional domain delimited by rectangles.

More specifically, it may be advantageous that a pseudo-rectangle is defined so that the reference point comprised in a pseudo-rectangle belongs to a current reference edge of said pseudo-rectangle.

In this embodiment, the portion of a seismic horizon is determined by first determining the boundaries of the portion of the domain delimited by the current pseudo-rectangle. Having a reference point on a current reference edge may increase the efficiency of the algorithm by providing means for calculating these boundaries of the seismic horizon. Indeed, when a reference point belongs to a current reference edge of a pseudo-rectangle, the associated related control point belongs to a related edge of the seismic horizon. It may then be possible to implement a calculation of the boundaries on the sought seismic horizon.

A further improvement of the method of the invention may consist in choosing advantageous methods for finding boundary conditions in the portion of the three-dimensional domain delimited by a pseudo-rectangle comprising reference points on a current reference edge.

To this end, prior to applying a diffeomorphic transformation  $F$ , the method may comprise applying, for each current pseudo-rectangle comprising a reference point belonging to a current reference edge of said pseudo-rectangle among the defined pseudo-rectangles, for each current reference edge of said current pseudo-rectangle, a horizon reconstruction algorithm to edge points having

coordinates along axes  $\vec{X}$ ,  $\vec{Y}$  identical to the coordinates along axes  $\vec{X}$ ,  $\vec{Y}$  of reference edge points of said current reference edge.

The horizon reconstruction algorithm implemented to compute these boundary conditions may be a simplified algorithm insofar as its solutions are functions that can be graphically represented in two dimensions as lines. A first current reference edge may advantageously be chosen as being the one comprising the reference point associated with the related control point. A first horizon line comprising said related control point and forming a first related edge associated with reference edge points of the first current reference edge may be determined. The extremities of this first related edge may be used to determine, respectively, a second and third related edge, by implementing horizon reconstruction algorithms in a similar fashion on points of faces of the portion of the three-dimensional domain delimited by the current pseudo-rectangle associated with reference edge points of a second and third current reference edge. Two extremities of the second and third related edge may correspond to extremities of a fourth related edge. Therefore the fourth related edge may be determined by implementing a horizon reconstruction algorithm on edge points of a face associated with a fourth current reference edge, with the condition that the horizon line passes through both extremities of the fourth related edge.

It may be advantageous to perform the calculation of the boundaries prior to applying a diffeomorphic transformation to each pseudo-rectangle, insofar as some pseudo-rectangles and therefore, the portions of the three-dimensional domain that is delimited by these pseudo-rectangles, may share at least a portion of an edge. In this way, it may be possible to reduce the number of calculations that are performed to determine the boundary conditions by using the already calculated boundaries of portions of the three-dimensional domain delimited by adjacent pseudo-rectangles. It may however also be possible to perform these calculations individually for each pseudo-rectangle in the transformed domain after applying a diffeomorphic transformation  $F$ . In this alternative embodiment of the invention, it may be possible to use the corresponding inverse diffeomorphic transformation  $F^{-1}$  to reuse the portions of boundaries that are identical for the portions of the three-dimensional domain delimited by two adjacent pseudo-rectangles.

Some techniques for defining pseudo-rectangles may be particularly advantageous, may further reduce the computation time of the algorithm, and may be easy to implement.

5 For instance, it may be possible to define pseudo-rectangles such that at least one reference corner of each pseudo-rectangle among the defined pseudo-rectangles may have coordinates along axes  $\vec{X}$ ,  $\vec{Y}$  identical to the coordinates along axes  $\vec{X}$ ,  $\vec{Y}$  of a related control point among the plurality of related control points.

10 In such an embodiment, each pseudo-rectangle among the defined pseudo-rectangles may have a reference corner associated with a related control point, thus enabling an easy calculation of the boundary conditions, for example by applying successive horizon reconstruction algorithms to points of faces of the portion of the three-dimensional domain comprising a reference edge comprising  
15 said corner and axis  $\vec{Z}$ .

In a particularly advantageous configuration, the received plurality of related control points may comprise at least three related control points, and defining pseudo-rectangles comprises:

- 20
- identifying reference points in the reference plane;
  - identifying triangles having a first reference corner, a second reference corner and a third reference corner among the identified reference points using a triangulation, and
  - in each of the identified triangles:  
25
    - identifying a reference centroid of said triangle,
    - identifying a first reference center of the segment defined by the first reference corner and the second reference corner;
    - identifying a second reference center of the segment defined by the first reference corner and the third reference corner;

30 wherein a pseudo-rectangle is defined by segments connecting the first reference corner with the first reference center, the first reference center with the reference

centroid, the reference centroid with the second reference center and the second reference center with the first reference corner.

Such a method of defining pseudo-rectangles may provide several advantages. First of all, it can be easily implemented by a computer program, no matter the distribution of the related control points. Secondly, this method may optimize the size distribution of the pseudo-rectangles, since the area of the pseudo-rectangles that are part of a given triangle is substantially the same. Thirdly, this way of defining pseudo-rectangles may greatly facilitate the determination of boundary conditions, since a reference corner of each pseudo-rectangle is associated with a related control point, and the triangles define lines joining reference points. These lines enable an easy calculation of the corresponding horizon line by applying a horizon reconstruction algorithm to points of a plane comprising axis  $\vec{Z}$  and two of the related control points.

15

More specifically, when pseudo-rectangles are defined in this way, the method of the invention may advantageously comprise, for an identified triangle, and prior to applying a diffeomorphic transformation F :

- identifying a first, second and third related control point among the plurality of related control points associated with corresponding first , second and third reference corners of said identified triangle;
- applying a horizon reconstruction algorithm to points of a plane comprising axis  $\vec{Z}$  and comprising the first and second related control points to determine a first portion of a first local horizon;
- identifying a first related central point on the first portion of the first local horizon having coordinates along axes  $\vec{X}$  and  $\vec{Y}$  identical to coordinates along axes  $\vec{X}$  and  $\vec{Y}$  of the first reference center;
- applying a horizon reconstruction algorithm to points of a plane comprising axis  $\vec{Z}$  and comprising the first and third related control points to determine a second portion of a second local horizon;

30

- identifying a second related central point on the second portion of the second local horizon having coordinates along axes  $\vec{X}$  and  $\vec{Y}$  identical to coordinates along axes  $\vec{X}$  and  $\vec{Y}$  of the second reference center;
- computing a coordinate along axis  $\vec{Z}$  of a related middle point having  
5 coordinates along axes  $\vec{X}$  and  $\vec{Y}$  identical to coordinates along axes  $\vec{X}$  and  $\vec{Y}$  of the reference centroid of said identified triangle, the computation of said coordinate along axis  $\vec{Z}$  being a function of the coordinates of a point on said determined first or second local horizons.

More specifically, the computation of the z coordinate of the related middle  
10 point can be a function of any point belonging to the first or second local horizon. For example, it could advantageously be a function of one of the extremities of the first or second local horizons, or either related central point.

The method described above may benefit from one major advantage: it may be particularly efficient from a computational point of view because many steps are  
15 implemented once for a first identified triangle, but can be skipped when applying the method to points associated with adjacent triangles. This more specifically concerns the portions of local horizons joining two related control points associated with two reference corners of a triangle. These portions of local horizons may be shared by two adjacent portions of the three-dimensional domain  
20 delimited by two adjacent triangles.

It may be possible to compute the coordinates along axis  $\vec{Z}$  of the related middle point of the identified triangle by applying a horizon reconstruction  
25 algorithm to points of a plane comprising axis  $\vec{Z}$ , and comprising the segment connecting the first reference center with the reference centroid or the segment connecting the second reference center with the reference centroid.

Doing so may increase the precision of the above mentioned method.

Alternatively, computing a coordinate along axis  $\vec{Z}$  of the related middle  
30 point can also be achieved by calculating the mean value of the coordinates along axis  $\vec{Z}$  of at least the first and second related central points.

This technique may be very quick and provide a good accuracy especially if the size of the triangle is small.

5 Several techniques may be foreseen to solve the Poisson equation that is computed in the horizon reconstruction algorithm. Once the conditions required for a one-step direct resolution of the equation are met, it may be advantageous to solve the Poisson equation using a Fourier transform algorithm.

10 The latter algorithms are well-known and easy to implement in a computer program for instance, due to the multitude of existing libraries for performing Fourier transforms on discrete data. Furthermore, Fourier transform algorithms are excellent alternatives to matrix methods, the latter being a lot more complex to compute.

15 The method described above can be implemented on portions of the three-dimensional domain comprising points having the same x and y coordinates as individualized pseudo-rectangles.

However it is possible to define pseudo-rectangles that map a continuous portion of the reference plane.

20 This may increase the computational speed of the method due to the fact that some of the computed data, for example the boundaries, can be reused on portions of the three-dimensional domain delimited by neighboring pseudo-rectangles.

25 In a final step, once two-dimensional portions of a horizon have been calculated for each of the defined pseudo-rectangles, the method may further comprise assembling all these portions of horizons to define a finalized portion of a reconstructed horizon.

30 To do so, the method may comprise computing a portion of a seismic horizon from at least the computed part of the horizon of each current pseudo-rectangle among the defined pseudo-rectangles.

When pseudo-rectangles were defined using a triangulation as described above, the method may further comprise computing a portion of a seismic horizon from at least the computed part of the horizon of each current pseudo-rectangle

among the defined pseudo-rectangles, and after computing a portion of a seismic horizon, the method may comprise:

- receiving modification information relating to the related control points;
- identifying pseudo-rectangles affected by the received modification information relating to the related control points;
- 5 - defining a new set of pseudo-rectangles in a local area corresponding to the area occupied by the pseudo-rectangles affected by said received modification information relating to the related control points;
- for each current pseudo-rectangle among the new set of pseudo rectangles:
- 10 - applying a diffeomorphic transformation  $F$ , said diffeomorphic transformation  $F$ :
  - being a function of coordinates along  $\vec{X}$ ,  $\vec{Y}$  and defining a new domain comprising axes  $\vec{X}'$ ,  $\vec{Y}'$ ,  $\vec{Z}$ ;
  - 15 - transforming points of the seismic image having coordinates along axes  $\vec{X}$ ,  $\vec{Y}$  identical to coordinates along axes  $\vec{X}$ ,  $\vec{Y}$  of points in said current pseudo-rectangle, said points of the seismic image including the related control point associated with the current pseudo-rectangle;
  - 20 - transforming said current pseudo-rectangle into a corresponding rectangle;
- applying a horizon reconstruction algorithm to the transformed points, to determine a part of a transformed horizon, said part of a transformed horizon comprising the transformed related control point, the reconstruction of the seismic horizon comprising solving the Poisson equation  $\Delta(\delta\tau) = -\text{div}(r)$ , where  $\delta\tau$  is an unknown function of coordinates along axes  $\vec{X}'$ ,  $\vec{Y}'$ ,  $\Delta$  denotes the Laplace operator in the new domain,  $\text{div}$  denotes the divergence vector operator in the new domain and  $r$  is a fixed function of coordinates along axes  $\vec{X}'$ ,  $\vec{Y}'$ ;
- 25
- 30

- computing a part of the horizon, said computing of a part of the horizon comprising applying an inverse diffeomorphic transformation  $F^{-1}$  to the determined part of a transformed horizon.

Therefore, whenever new related control points are added, or former related control points are removed, the method can efficiently limit the portion of the three-dimensional domain on which new calculations are performed to the portion of the three-dimensional domain concerned by the modifications that were performed.

The invention also pertains to a device for enhancing the determination, from a seismic image, of at least a portion of a seismic horizon in a three-dimensional domain comprising axes  $\vec{X}$ ,  $\vec{Y}$ ,  $\vec{Z}$ , said seismic horizon being a function of coordinates along axes  $\vec{X}$ ,  $\vec{Y}$  in said three-dimensional domain, wherein said device comprises:

- an input interface for receiving the seismic image, the seismic image having points associated with coordinates along axes  $\vec{X}$ ,  $\vec{Y}$ ,  $\vec{Z}$ ; and for receiving a plurality of related control points associated with coordinates on axes  $\vec{X}$ ,  $\vec{Y}$ ,  $\vec{Z}$ ;
- a circuit for defining, in a reference plane defined by axes  $\vec{X}$  and  $\vec{Y}$ , for at least one related control point among the plurality of related control points, an associated reference point with coordinates along axes  $\vec{X}$ ,  $\vec{Y}$ , among a plurality of reference points, the reference point having coordinates on axes  $\vec{X}$  and  $\vec{Y}$  identical to coordinates on axes  $\vec{X}$  and  $\vec{Y}$  of the related control point,
- a circuit for defining pseudo-rectangles in the reference plane, each pseudo-rectangle comprising a reference point among a plurality of reference points;
- a circuit being adapted for, for each current pseudo-rectangle among the defined pseudo-rectangles:
  - applying a diffeomorphic transformation  $F$ , said diffeomorphic transformation  $F$ :

- being a function of coordinates along  $\vec{X}$ ,  $\vec{Y}$  and defining a new domain comprising axes  $\vec{X}'$ ,  $\vec{Y}'$ ,  $\vec{Z}$ ;
- transforming points of the seismic image having coordinates along axes  $\vec{X}$ ,  $\vec{Y}$  identical to coordinates along axes  $\vec{X}$ ,  $\vec{Y}$  of points in said current pseudo-rectangle, said points of the seismic image including the related control point associated with the current pseudo-rectangle;
- transforming said current pseudo-rectangle into a corresponding rectangle;
- applying a horizon reconstruction algorithm to the transformed points, to determine a part of a transformed horizon, said part of a transformed horizon comprising the transformed related control point, the reconstruction of the seismic horizon comprising solving the Poisson equation  $\Delta(\delta\tau) = -\text{div}(r)$ , where  $\delta\tau$  is an unknown function of coordinates along axes  $\vec{X}'$ ,  $\vec{Y}'$ ,  $\Delta$  denotes the Laplace operator in the new domain,  $\text{div}$  denotes the divergence vector operator in the new domain and  $r$  is a fixed function of coordinates along axes  $\vec{X}'$ ,  $\vec{Y}'$ ;
- computing a part of the horizon, said computing of a part of the horizon comprising applying an inverse diffeomorphic transformation  $F^{-1}$  to the determined part of a transformed horizon.

The invention also pertains to a non-transitory computer readable storage medium, having stored thereon a computer program comprising program instructions, the computer program being loadable into a data-processing unit and adapted to cause the data-processing unit to carry out the sequence of operations of the method described above when the computer program is run by the data-processing device.

The method of the invention will be better understood by reading the detailed description of exemplary embodiments presented below. These embodiments are illustrative and by no means limitative. They are provided with the appended figures and drawings on which:

- 5           - figure 1 is a schematic representation of a seismic image in a three-dimensional domain; and
- figure 2 is a schematic representation of the three-dimensional domain of figure 1 comprising related control points and their associated reference points in the reference plane; and
- 10           - figure 3 is a schematic representation of the reference plane of figure 2; and
- figure 4 is a schematic representation of a plane pointed at on figure 3 and comprising axis  $\vec{Z}$ , a portion of seismic image, a current reference edge of a pseudo-rectangle and a related control point associated with a reference point on the current reference edge; and
- 15           - figure 5 is a schematic representation of the three-dimensional domain of figure 1 comprising one related control point the associated current pseudo-rectangle and the boundaries of the sought seismic horizon delimited by the current pseudo-rectangle; and
- figure 6 presents schematic representations (A and B) of the transformation operated by the diffeomorphic transformation  $F$  associated with the pseudo-rectangle of figure 5; and
- 20           - figure 7 presents schematic representations (A and B) of the transformation operated by the inverse diffeomorphic transformation  $F^{-1}$  associated with the pseudo-rectangle of figures 5, 6 element A and 6 element B; and
- 25           - figure 8 is a schematic representation of the three-dimensional domain of figure 1 comprising related control points and their associated portions of a reconstructed seismic horizon; and

- figure 9 is a schematic representation of the reference plane of figure 2 according to a second embodiment; and

- figure 10 is a schematic representation of the reference plane of figure 9 with three pseudo-rectangles defined in accordance with the second embodiment;  
5 and

- figure 11 is a schematic representation of the reference plane of figure 9 illustrating the pseudo-rectangles affected by the addition of a related control point; and

- figure 12 is a flow chart illustrating the main steps implemented by the  
10 horizon reconstruction method; and

- figure 13 is a possible embodiment for a device that enables the present invention.

For the sake of clarity, the dimensions of features represented on these figures may not necessarily correspond to the real-size proportions of the  
15 corresponding elements. Like reference numerals on the figures correspond to similar elements or items.

Figure 1 represents an exemplary seismic image in a three-dimensional domain **1** associated with axes  $\vec{X}$ ,  $\vec{Y}$ ,  $\vec{Z}$ . Such an image comprises dark regions **101**, **102**, **103** alternating with brighter regions **110**, **120**, **130**. From the  
20 data contained in the seismic image of figure 1, geophysicists may extract the tangent of the local dip  $p$  associated with every data point of the seismic image. The tangent of the local dip is expressed as a function of class  $C^1$  of  $x$ ,  $y$ ,  $z$  coordinates. The aim of a horizon reconstruction method is to find a two-dimensional surface in the three-dimensional domain **1**, that can be numerically  
25 represented as a function of class  $C^2$ :

$$\tau: (x;y) \rightarrow \tau (x,y)$$

of  $x$ ,  $y$  coordinates and verifying the condition :

$$\tau = \arg \min_{f \in C^2} \int_{\Omega} \|\nabla f(x; y) - p[x; y; f(x; y)]\|^2 d\Omega$$

where  $\| \cdot \|$  denotes a norm, for example the absolute value,  $\nabla$  denotes the gradient operator and  $\Omega$  the portion of the three-dimensional domain **1** on which the seismic horizon is calculated. Iterative horizon reconstruction algorithms to solve the above equation are well-known from the existing prior art, such as for example from the  
 5 above-cited article by Lomask *et al.*

In the process of implementing a horizon reconstruction algorithm, one constraint resides in the fact that any calculated horizon must pass through all the related control points received as input.

10 Several key steps are implemented in such an algorithm. Generally, a first horizon corresponding to a function  $\tau = \tau_0$  is initialized. Then, a residual term  $r$  is calculated. This term  $r$  is another function of coordinates  $x, y$ , verifying the condition  $r(x; y) = \nabla \tau(x; y) - p[x; y; \tau(x; y)]$ , which corresponds to the difference between the tangent of the local dip of the seismic image and the gradient of the  
 15 horizon.

While implementing the iterative horizon reconstruction algorithm, the main challenge resides in minimizing this residual term  $r$ . This is done by progressively correcting function  $\tau$ , so that after each step  $k$  of the horizon reconstruction algorithm,  $\tau_{k+1} = \tau_k + \delta\tau_k$ . At each step, an update term  $\delta\tau$  is computed, the latter  
 20 verifying:

$$\delta\tau = \arg \min_{f \in C^2} \int_{\Omega} \|\nabla f(x; y) + r(x; y)\|^2 d\Omega$$

This update term, later added to function  $\tau$ , is numerically obtained by solving the Poisson equation:

$$\Delta(\delta\tau) = -\text{div}(r)$$

As mentioned above, the invention resides in the way this Poisson equation is calculated.

As illustrated on figure 2, the method comprises receiving related control points **201, 202, 203, 204, 205, 206, 207, 208** in the three-dimensional domain **1**.

5 These related control points **201, 202, 203, 204, 205, 206, 207, 208** may for example be points that are known to belong to a given horizon because of drills realized in the ground or because of reliable geological data. The horizon reconstruction algorithm relies on using the x and y coordinates of the points of the three-dimensional domain **1** as input, and calculating a corresponding coordinate

10 along axis  $\vec{Z}$  to determine a reconstructed horizon. The method of the invention involves transformations on these points, that only affect their x and y coordinates, but do not change their z coordinate. To simplify the process of defining pseudo-rectangles and diffeomorphic transformations that are part of this invention, reference points **210, 220, 230, 240, 250, 260, 270, 280** associated with said

15 related control points are defined in a reference plane **10**, this reference plane being defined by axes  $\vec{X}$  and  $\vec{Y}$ . The reference points **210, 220, 230, 240, 250, 260, 270, 280** have the same x and y coordinates along axes  $\vec{X}$  and  $\vec{Y}$  as the related control points **201, 202, 203, 204, 205, 206, 207, 208** i.e. the point **210** (respectively **220, 230, 240, 250, 260, 270, 280**) is a projection of the related

20 control point **201** (respectively **202, 203, 204, 205, 206, 207, 208**) on a plane surface  $(\vec{X}, \vec{Y})$ .

As illustrated on figure 3, the invention then consists in defining pseudo-rectangles in the reference plane **10** comprising the reference points **210, 220, 230, 240, 250, 260, 270, 280** associated with related control points. This may be

25 done in many different ways, some of which are illustrated on figures 3, 9 and 10. On figure 3, pseudo-rectangles with random shapes map a portion of the reference plane **10**. Each of these pseudo-rectangles contains one of the reference points **210, 220, 230, 240, 250, 260, 270, 280**. The latter points can be located anywhere on a current pseudo-rectangle. For example, reference point

30 **280** belongs to a reference corner of a current pseudo-rectangle, and reference point **220** belongs to a current reference edge of a current pseudo-rectangle **3220**.

The pseudo-rectangles comprising reference points **210**, **220**, **230**, **240**, **250**, **260**, **270**, **280** verify the boundary conditions called Neumann conditions, which state that for a unique point of fixed coordinates on the horizon, the derivative of the update term along the exterior normal  $\vec{\omega}$  to the boundary is assumed to be equal to zero and its mean value fixed to zero. In other words, for any value of coordinates  $x$  and  $y$  along the edges of the horizon in the portion  $\Omega$  of the three-dimensional domain **1** delimited by the current pseudo-rectangle, the following scalar product is equal to zero:  $\nabla\delta\tau(x;y).\vec{\omega}(x;y)=0$ . In such pseudo-rectangles, it is advantageous to avoid calculating the boundary conditions since these boundaries are not required to rapidly solve the horizon reconstruction algorithm. It may also be advantageous to verify that adjacent calculated portions of a seismic horizon form a continuous surface, and implement corrections to ensure that there is no discontinuity at their shared boundary.

In another embodiment, it may be advantageous to compute the boundary conditions on the edges of the horizon in the portion  $\Omega$  of the three-dimensional domain **1** delimited by the current pseudo-rectangle, to verify the Dirichlet conditions and in order to be sure that the different determined horizons for each pseudo-rectangle are continuous. On figure 3, a plane **20** defined by axis  $\vec{Z}$  and containing reference point **220** and reference corners **2220**, **2210** is represented. This plane **20** comprises the current reference edge **320** of the current pseudo-rectangle **3220**. On figure 3, this plane **20** appears as a line.

On figure 4, the same plane **20** is represented with the points from the seismic image having the same coordinates in the three-dimensional domain **1** as points from the plane **20**, reference point **220**, the related control point **202**, and the reference corners **2220**, **2210**. To find the related edge **302** comprising related control point **202** and belonging to the seismic horizon, a horizon reconstruction algorithm can be applied to points of plane **20**. This horizon reconstruction algorithm is easier to implement since it resolves the Poisson equation in two-dimensions, that is to say, it computes a function  $\tau$  which can be expressed as a function of one variable and which can be graphically represented in a plane. As can be seen on figure 4, the reconstructed horizon line **302** tends to follow the tangent of the dip of the points from the seismic image.

The boundaries of the sought horizon are represented on figure 5. Figure 5 represents the portion of the three-dimensional domain **1** delimited by pseudo-rectangle **3220**. This portion comprises four faces: face **501** appears on the left side, face **504** on the right side, face **502** at the back and face **503** at the front of the illustration on figure 5. Knowing a related edge **302**, corresponding to a horizon line of the sought horizon, comprised in face **501**, it is possible to compute the boundaries **420**. The horizon line **302** can be used to compute the other horizon lines along the adjacent faces **502**, **503** of the current portion of the three-dimensional domain **1** delimited by the current pseudo-rectangle **3220**. To do so, the extremities **2201** and **2202** of the horizon line are used in two horizon reconstruction algorithms to determine a second and third horizon lines. The second horizon line passes through extremity **2202**, comprises another extremity **2203** and is comprised in face **502**. The third horizon line passes through extremity **2201**, comprises another extremity **2204** and is comprised in face **503**. The horizon line comprised in the remaining face **504** is determined by applying a horizon reconstruction algorithm to points of the remaining face **504**, so that the horizon line passes through extremities **2203** of the second and **2204** third horizon line.

This step by step approach leads to the determination of the boundary conditions in the portion  $\Omega$  of the three-dimensional domain **1** delimited by the current pseudo-rectangle, thereby fulfilling the Dirichlet boundary conditions. Figure 5 illustrates the determined boundaries **420** in the current portion  $\Omega$  of the three-dimensional domain **1** delimited by the current pseudo-rectangle associated with related control point **202**.

It is to be noted that although the above description and illustrations describe a way of determining the boundary conditions in the current portion  $\Omega$ , it is possible to skip this step and proceed with the method described below. Indeed, the method of this invention is also efficient in the case where a single related control point is contained in the current portion  $\Omega$ . Alternatives such as the configuration in which a related control point has the same x and y coordinates as a reference corner of the current pseudo-rectangle, as is the case for related control point **208**, is also compatible with the invention. As long as any one of the boundary conditions is met, the method of the invention further proceeds by

identifying, for a current pseudo-rectangle, a diffeomorphic transformation  $F$  which transforms the current pseudo-rectangle into a corresponding rectangle. For a current pseudo-rectangle, such a diffeomorphic transformation  $F$  is a function which transforms coordinates  $(x;y)$  into corresponding coordinates  $(x',y')$  so that:

$$5 \quad \begin{bmatrix} x' \\ y' \end{bmatrix} = F(x;y) = \begin{bmatrix} F_x(x;y) \\ F_y(x;y) \end{bmatrix}$$

Figure 6 (element A) illustrates a current portion  $\Omega$  of the three-dimensional domain **1** delimited by the current pseudo-rectangle associated with related control point **202**, for which the Dirichlet conditions, represented by boundaries **420**, have been computed. All the points of this current portion  $\Omega$  are transformed using  
 10 diffeomorphic transformation  $F$  to obtain the corresponding rectangle and the new domain  $\Omega'$  delimited by the corresponding rectangle illustrated on figure 6 element B. The boundary conditions **620** in the new domain as well the transformed related control point **602** are also represented. The new domain is associated with the transformed axes  $\vec{X}'$ ,  $\vec{Y}'$ ,  $\vec{Z}'$ . In addition to transforming the current portion  $\Omega$  into  
 15 the new domain  $\Omega'$ , the method of the invention also transforms the corresponding portion of the seismic image, to obtain a set of transformed points in the new domain. The gradient field of the function  $\tau$  is therefore relied on a vector field by a partial differential equation:

$$\nabla \tau(x'; y') = p' [x'; y'; \tau(x'; y')]$$

20 where  $p'$  is the tangent of the transformed local dip  $p$ . It can be expressed as:

$$p' = J_F^{-1} p$$

where  $J_F^{-1}$  is the inverse of the transformation Jacobian matrix  $J_F$  defined by:

$$J_F = \begin{bmatrix} \frac{\partial x'}{\partial x} & \frac{\partial y'}{\partial x} \\ \frac{\partial x'}{\partial y} & \frac{\partial y'}{\partial y} \end{bmatrix}$$

The diffeomorphic transformation F transforming a current pseudo-rectangle into a corresponding rectangle is a homography defined by a 3x3 matrix  $H = [h_{ij}]$ .

This transformation is given, for any x, y coordinates in the current portion  $\Omega$  by:

$$\begin{bmatrix} x' \\ y' \end{bmatrix} = \begin{bmatrix} \frac{h_{11}x + h_{12}y + h_{13}}{h_{31}x + h_{32}y + h_{33}} \\ \frac{h_{21}x + h_{22}y + h_{23}}{h_{31}x + h_{32}y + h_{33}} \end{bmatrix}$$

5 The four terms of the Jacobian are then defined by:

$$\frac{\partial x'}{\partial x}(x; y) = \frac{(h_{11}h_{32} - h_{31}h_{12})y + h_{11}h_{33} - h_{31}h_{13}}{(h_{31}x + h_{32}y + h_{33})^2}$$

$$\frac{\partial y'}{\partial x}(x; y) = \frac{(h_{21}h_{32} - h_{31}h_{22})y + h_{21}h_{33} - h_{31}h_{23}}{(h_{31}x + h_{32}y + h_{33})^2}$$

$$\frac{\partial x'}{\partial y}(x; y) = \frac{(h_{12}h_{31} - h_{31}h_{121})x + h_{21}h_{33} - h_{31}h_{23}}{(h_{31}x + h_{32}y + h_{33})^2}$$

$$\frac{\partial y'}{\partial y}(x; y) = \frac{(h_{22}h_{31} - h_{32}h_{21})x + h_{22}h_{33} - h_{31}h_{23}}{(h_{31}x + h_{32}y + h_{33})^2}$$

10 It is therefore possible to compute, for each point of the new domain, a transformed residual term r and solve the Poisson equation in the transformed domain.

15 With the elements obtained so far, two conditions are met to allow a direct and one-step resolution of the Poisson equation: the domain on which a solution is searched corresponds to points having x and y coordinates identical to those of a rectangle, and either at least one related control point is within this new domain, or the boundary conditions of the solution are known.

20 The determination of the update term, the solution of the Poisson equation, can be calculated using fast Fourier transform algorithms, for example by solving the equation:

$$\delta\tau = FT^{-1} \left[ \frac{FT[-\text{div}(r)]}{FT[\Delta]} \right]$$

where FT denotes a Fourier transform and  $FT^{-1}$  denotes an inverse Fourier transform.

Advantageously, the Fourier transform is a discrete Fourier transform, and even more advantageously a fast Fourier transform. If the size of the new domain  
5 can be expressed as a number verifying  $2^a 3^b 5^c 7^d 11^e 13^f$ , where a, b, c, d, e and f are positive integers and e+f is smaller than 1, then a particularly efficient fast Fourier transform can be implemented to further reduce the computation time of the method of the invention.

As represented on figure 7 element A, once the transformed part of a  
10 reconstructed horizon **7020** is obtained, the method comprises applying the inverse diffeomorphic transformation  $F^{-1}$  to the transformed part of a reconstructed horizon to obtain a part of a reconstructed horizon **720**, as represented on figure 7 element B.

Finally, the invention advantageously comprises assembling all the parts of  
15 a reconstructed horizon to obtain a reconstructed horizon on a portion of the three-dimensional domain **1** as represented on figure 8.

Besides the general method described above, the invention may  
20 advantageously benefit from substantial optimizations that allow it to be performed faster and be easily programmed to be executed with minimal input from the user.

To this end, figure 9 represents a method for defining pseudo-rectangles that have a substantially similar shape and which allows a fast and reliable calculation of the boundary conditions in each pseudo-rectangle.

On figure 9 reference points **210, 220, 230, 240, 250, 260, 270, 280**  
25 associated with related control points **201, 202, 203, 204, 205, 206, 207, 208** are represented in the reference plane **10**. A triangulation, advantageously a Delaunay triangulation, connecting all these reference points to form triangles is implemented. Then, as represented on figure 10, the center of each side of an identified triangle is selected. Figure 10 represents the triangle identified by  
30 corners corresponding to reference points **210, 220** and **230**. The reference

centers **223**, **212** and **213** of the sides of this triangle are also used to determine the centroid **2123** of this triangle, the centroid being the point where the median lines of the triangle cross. In this manner, the obtained three pseudo-rectangles have substantially the same area in each triangle, and the method can  
5 systematically be implemented by a computer program.

Other advantages arise from the method of defining pseudo-rectangles represented on figures 9 and 10. The sides of each triangle are lines joining two reference points having the same x and y coordinates as related control points, and boundary conditions can be easily computed in the plane comprising axis  $\vec{Z}$   
10 and comprising two related control points by using a horizon reconstruction algorithm to obtain a horizon line. Since it may occur, as seen on figure 9, that several triangles share a common side, the calculation of boundary conditions may not have to be computed for each triangle in the portion of the three-dimensional domain **1** delimited by a triangle. Indeed the results obtained in the portion of the  
15 three-dimensional domain **1** delimited by a previously identified triangle may be reused in the portion of the three-dimensional domain **1** delimited by subsequent triangles.

The centroid of each triangle, called reference centroid **2123**, shares the same x and y coordinates as a related middle point of the horizon. This related  
20 middle point is shared by three portions of horizon in three adjacent portions of the three-dimensional domain **1**. There are several options for determining the z coordinate of that middle point of the horizon.

It is for example possible to make realistic approximations that are likely to be valid for triangles having a small area compared to the size of the three-  
25 dimensional domain **1**. One of these consists in calculating the mean value of the z coordinate of related central points of the horizon, associated with reference centers **212**, **223**, **213** of at least two of the three sides of a current triangle. Another consists in assuming the z coordinate of that related middle point is equal to the z coordinate of any related point of the horizon associated with a reference  
30 point of the triangle, for example a reference corner **220**, **230**, **210** or a reference center **212**, **223**, **213** of a side of the triangle. Another method consists in applying a horizon reconstruction algorithm to points of the plane comprising axis  $\vec{Z}$  and

comprising one of the segments connecting a reference center **212**, **223**, **213** of a side of the triangle, and the reference centroid **2123**, to obtain a horizon line.

In an alternative embodiment, it is possible to define pseudo-rectangles by combining the identified triangles two by two. Two adjacent triangles are combined  
5 by removing the segment they have in common. This embodiment is advantageous in that it makes it even easier to determine the boundary conditions of the portion  $\Omega$  of the three-dimensional domain **1** delimited by a pseudo-rectangle, since every reference corner of each pseudo-rectangle is associated with a related control point. In this embodiment, horizon lines passing through the  
10 related control points define the boundary conditions of each pseudo-rectangle.

The method of the invention nonetheless also offers another major advantage over the existing prior art. Indeed, it is very efficient for computing portions of a seismic horizon when a related control point is added to or removed from a set of related control points.

15 Figure 11 represents reference plane **10** containing reference points **210**, **220**, **230**, **240**, **250**, **260**, **270**, **280** associated with related control points **201**, **202**, **203**, **204**, **205**, **206**, **207**, **208**. First, modification information relating to the related control points is received, for example the addition of a related control point. Then, the reference point **1100** in the reference plane **10** associated with the added  
20 related control point requires locally redefining pseudo-rectangles. Nevertheless, the effect is only local as shown on figure 11, on which the darkest pseudo-rectangles correspond to the affected area that is chosen for a recalculation of the local horizon. In general, adding a related control point only affects the pseudo-rectangle or pseudo-rectangles to which the added reference point associated with  
25 the added related control point belongs. Nevertheless, it is advantageous to identify an affected area by identifying the triangle or triangles to which the reference point belongs. This may enable defining new pseudo-rectangles having substantially the same size as already defined surrounding pseudo-rectangles. Since the pseudo-rectangles comprising the added reference point may share  
30 boundaries with neighboring pseudo-rectangles, two of which may belong to neighboring triangles, it is advantageous to include these neighboring triangles into the affected area and triangulate a new set of pseudo-rectangles on this

affected area. On figure 11, the area affected by the addition of reference point **1100** implies a new triangulation giving rise to twelve new pseudo-rectangles. Similar conclusions arise when a related control point is removed.

For the above reason, the invention is very efficient in terms of computation  
5 time required to determine a horizon, for example when a user decides to add several related control points in a portion of the three-dimensional domain **1** which requires a finer resolution in the reconstructed horizon.

Figure 12 is a flow-chart schematically illustrating the different steps that are implemented by the method of this invention.

10 In a first step S1, a seismic image SEISM\_IMG **1** is received. The seismic image **1** can for example be received from a raw seismic data treatment program that outputs the data points in the three-dimensional domain **1**.

In a second step S2, related control points CTRL.\_PTs **201, 202, 203, 204, 205, 206, 207, 208** are received. The x, y, z coordinates of these points are fixed  
15 and they all belong to the same horizon.

In a subsequent step S3, pseudo-rectangles PSEUD.\_RECT. are defined, in such a way that each pseudo-rectangle is in a reference plane and comprises at least one reference point **210, 220, 230, 240, 250, 260, 270, 280**.

In step S4, it is possible to apply, for each pseudo-rectangle  
20 PSEUD.\_RECT. one or several horizon reconstruction algorithms to points of an edge of a portion of the three-dimensional domain **1** delimited by the current pseudo-rectangle, in order to find the boundaries **420**.

In step S50, a diffeomorphic transformation F is identified for each pseudo-rectangle. An identified diffeomorphic transformation F is applied to a current  
25 pseudo-rectangle to transform it into a corresponding rectangle. By doing so, the method generates conditions in which solving the Poisson equation can be greatly simplified.

Step S50 also comprises applying said transformation to the points of the seismic image having the same x and y coordinates as points of the pseudo-  
30 rectangle.

The invention further comprises the horizon reconstruction algorithm per se. It starts with step S51 which comprises identifying a horizon corresponding to an initialization function  $\tau_k$  at  $k=0$  and proceeding iteratively as follows:

5 - comparing the number of iterations to a preset value  $N$ . It is assumed that the calculated horizon converges to a reliable solution typically after a few tens of iterations. In case the number of iterations is smaller than the preset value  $N$ , the method proceeds by;

- computing a residual term  $r_k$  using the horizon  $\tau_k$  and the tangent of the transformed local dip  $p$  at step S54;

10 - applying a horizon reconstruction algorithm using Fourier transforms to solve the Poisson equation in the new domain  $\Omega'$  at step S54;

- incrementing  $k$  by one digit at step S55 and returning to step S52.

15 When the number  $k$  of iterations reaches the target value  $N$ , the method proceeds with step S6 by applying the inverse diffeomorphic transformation  $F^{-1}$  that can transform the corresponding rectangle into the current pseudo-rectangle, to the computed horizon  $\tau_k$ .

Finally, all the portions of a reconstructed horizon obtained for each pseudo-rectangle can be assembled to form the portion of a reconstructed horizon represented on figure 8.

20 A comparison of the method of the invention and the global optimization method disclosed by Lomask *et al.* was performed on real seismic data defining a volume of 1750m by 4000m by 1600m. Complex geometries and convergent structures of the treated data resulted in an extremely noisy estimated dip, so a set of twenty seven related control points were sequentially received in critical regions  
25 corresponding for example to peaks or basins of the horizon to be reconstructed, starting from an initial set of thirteen related control points.

30 The number of iterations in the horizon reconstruction algorithm to reach convergence of both methods was set to thirty. For the method of the invention, each identified triangle is subdivided in three pseudo-rectangles as described above. The twenty seven related control points then lead to one hundred and

twenty six pseudo-rectangles. For the global optimization method disclosed by Lomask *et al.* each update term  $\delta\tau$  computation through a direction descent approach required three hundred iterations and the algorithm had to be initialized with a function  $\tau_0$  close to the solution. This function  $\tau_0$  was obtained from a horizon reconstructed over the entire domain by assuming that only one particular related control point was known.

Table 1 resumes the computation time in seconds that was measured using both methods. The time in parentheses corresponds to the time measured for the calculations dedicated to the Fourier transforms.

Size of rectangular domain (new domain)	Method of the invention		Method disclosed by Lomask <i>et al.</i>
	Normal size	Optimal size	
smallest	3.3 s (1.41 s)	2.7 s (0.561 s)	79.1 s
largest	9.98 s (5.47 s)	6.43 s (2.41 s)	
arithmetic mean	5.82 s (2.9 s)	4.26 s (1.56 s)	
geometric mean	5.4 s (2.54 s)	3.78 s (1.4 s)	

10 Table 1

Table 1 shows the time required to do calculations on the portions of the three-dimensional domain **1** based on the size of the domain. The column labeled normal size gives the measured time that elapsed during the implementation of the method of the invention on portions of a domain that did not have a size optimized for fast Fourier transforms. The column labeled optimal size gives the same data but measured on portions of a domain that had a size suitable for implementing a fast Fourier transform algorithm. The line labeled smallest corresponds to the smallest defined portions of domains, the line labeled largest corresponds to the largest defined portions of domains, and the arithmetic and geometric means give times calculated based on a mean value of the size of the rectangular domains. It arises from the data of table 1 that the method of the invention enables reducing

the computation time by as much as thirty times when compared to global approaches like the one disclosed by Lomask *et al.* .

Another test was conducted to determine the time that can be saved using the method of the invention when modification instructions regarding the related control points are received. Table 2 summarizes the times in seconds measured for implementing the method of the invention when increasing the number of related control points from thirteen to twenty-seven. The time in parentheses corresponds to the time measured for the calculations dedicated to the Fourier transforms. In the column labeled entire reconstruction, the measured times are substantially the same, since the volume on which the computation is implemented is the entire three-dimensional domain **1**. In the column labeled incremental reconstruction, the method is only applied to the portion of the three-dimensional domain **1** which is affected by the addition of new related control points.

Number of related control points	Entire reconstruction	Incremental reconstruction
13	3.8 s (1.4 s)	
18	3.73 s (1.4 s)	0.627 s (0.219 s)
23	3.72 s (1.38 s)	0.603 s (0.233 s)
27	3.78 s (1.4 s)	0.5 s (0.184 s)

Table 2

It appears from table 2 that the selective computation of portions of a horizon on only those parts that are affected by the addition or removal of related control points further enhances the computational speed of the method.

Figure 13 is a possible embodiment for a device that enables the present invention.

In this embodiment, the device **1300** comprises a computer, this computer comprising a memory **1305** to store program instructions loadable into a circuit and adapted to cause circuit **1304** to carry out the steps of the present invention when the program instructions are run by the circuit **1304**.

5           The memory **1305** may also store data and useful information for carrying the steps of the present invention as described above.

The circuit **1304** may be for instance:

- 10           - a processor or a processing unit adapted to interpret instructions in a computer language, the processor or the processing unit may comprise, may be associated with or be attached to a memory comprising the instructions, or
- the association of a processor / processing unit and a memory, the processor or the processing unit adapted to interpret instructions in a computer language, the memory comprising said instructions, or
- 15           - an electronic card wherein the steps of the invention are described within silicon, or
- a programmable electronic chip such as a FPGA chip (for « Field-Programmable Gate Array »).

20           This computer comprises an input interface **1303** for the reception of data used for the above method according to the invention and an output interface **1306** for providing a stacked model.

To ease the interaction with the computer, a screen **1301** and a keyboard **1302** may be provided and connected to the computer circuit **1304**.

25

The invention is not limited to the embodiments described above and may encompass equivalent embodiments.

For example, it is possible to define non quadrangular surfaces in the reference plane. Instead of defining pseudo-rectangles, it may for example be possible to define surfaces for which diffeomorphic transformations, transforming

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these surfaces into circles, can be obtained. Indeed, a rapid resolution of the Poisson equation in a domain having a circular section, instead of a rectangular section, is possible.

5 It is possible to apply the diffeomorphic transformation  $F$  to a current pseudo-rectangle before calculating boundary conditions associated with the current pseudo-rectangle.

10 It is also possible to define some pseudo-rectangles which are not associated with any related control point. Although doing so might seem less advantageous from a computational point of view, it may be interesting in the case in which large gaps exist between local concentrations of related control points. Defining pseudo-rectangles that are not associated with any related control point may allow mapping a continuous portion of the three-dimensional domain **1** without having a high dispersion in the size of the pseudo-rectangles. It is also possible to have pseudo-rectangles that are not associated with any related  
15 control point, but which are adjacent to other pseudo-rectangles which are. Thereby, it is possible to use the boundary conditions of the neighboring pseudo-rectangles to meet the conditions enabling a direct resolution of the Poisson equation.

20 The method described above may also be implemented in a domain comprising more than three dimensions.

One may also define quadrangles that are not pseudo-rectangles, although this may render the calculation of the diffeomorphic transformations more complicated.

## Claims

1. Method for enhancing the determination, from a seismic image, of at least a  
5 portion of a seismic horizon in a three-dimensional domain (1) comprising axes  $\vec{X}$ ,  
 $\vec{Y}$ ,  $\vec{Z}$ , said seismic horizon being a function of coordinates along axes  $\vec{X}$ ,  $\vec{Y}$  in  
said three-dimensional domain (1),  
wherein said method comprises:
- 10 - receiving (S1) the seismic image, the seismic image having points  
associated with coordinates along axes  $\vec{X}$ ,  $\vec{Y}$ ,  $\vec{Z}$ ;
  - receiving (S2) a plurality of related control points (201, 202, 203, 204,  
205, 206, 207, 208) associated with coordinates on axes  $\vec{X}$ ,  $\vec{Y}$ ,  $\vec{Z}$ ;
  - in a reference plane (10) defined by axes  $\vec{X}$  and  $\vec{Y}$ , defining, for at least  
15 one related control point among the plurality of related control points  
(201, 202, 203, 204, 205, 206, 207, 208), an associated reference point  
with coordinates along axes  $\vec{X}$ ,  $\vec{Y}$ , among a plurality of reference points  
(210, 220, 230, 240, 250, 260, 270, 280), the reference point having  
coordinates on axes  $\vec{X}$  and  $\vec{Y}$  identical to coordinates on axes  $\vec{X}$  and  $\vec{Y}$   
of the related control point,
  - 20 - defining (S3) pseudo-rectangles in said reference plane (10), each  
pseudo-rectangle comprising a reference point among a plurality of  
reference points (210, 220, 230, 240, 250, 260, 270, 280);
  - for each current pseudo-rectangle among the defined pseudo-rectangles:
    - 25 - applying a diffeomorphic transformation F (S50), said diffeomorphic  
transformation F :
      - being a function of coordinates along  $\vec{X}$ ,  $\vec{Y}$  and defining a  
new domain comprising axes  $\vec{X}'$ ,  $\vec{Y}'$ ,  $\vec{Z}$ ;
      - transforming points of the seismic image having  
coordinates along axes  $\vec{X}$ ,  $\vec{Y}$  identical to coordinates

along axes  $\vec{X}$ ,  $\vec{Y}$  of points in said current pseudo-rectangle, said points of the seismic image including the related control point associated with the current pseudo-rectangle;

5 - transforming said current pseudo-rectangle into a corresponding rectangle;

10 - applying (S52, S53, S54, S55) a horizon reconstruction algorithm to the transformed points, to determine a part of a transformed horizon (7020), said part of a transformed horizon (7020) comprising the transformed related control point (602), the reconstruction of the seismic horizon comprising solving (S54) the Poisson equation  $\Delta(\delta\tau) = -\text{div}(r)$ , where  $\delta\tau$  is an unknown function of coordinates along axes  $\vec{X}'$ ,  $\vec{Y}'$ ,  $\Delta$  denotes the Laplace operator in the new domain,  $\text{div}$  denotes the divergence vector operator in the new domain and  $r$  is a fixed function of coordinates along axes  $\vec{X}'$ ,  $\vec{Y}'$ ;

15 - computing a part of the horizon (720), said computing of a part of the horizon (720) comprising applying (S6) an inverse diffeomorphic transformation  $F^{-1}$  to the determined part of a transformed horizon (7020).

20

**2.** Method according to claim 1 wherein, a pseudo-rectangle is defined so that the reference point (220) comprised in a pseudo-rectangle (3220) belongs to a current reference edge (320) of said pseudo-rectangle (3220).

25 **3.** Method according to claim 2, wherein prior to applying a diffeomorphic transformation  $F$  (S50), said method comprises applying, for each current pseudo-rectangle (3220) comprising a reference point (220) belonging to a current reference edge (320) of said pseudo-rectangle (3220) among the defined pseudo-rectangles, for each current reference edge of said current pseudo-rectangle  
 30 (3220), a horizon reconstruction algorithm to edge points having coordinates along axes  $\vec{X}$ ,  $\vec{Y}$  identical to the coordinates along axes  $\vec{X}$ ,  $\vec{Y}$  of reference edge points of said current reference edge.

4. Method according any one of the preceding claims wherein at least one reference corner of each pseudo-rectangle among the defined pseudo-rectangles has coordinates along axes  $\vec{X}$ ,  $\vec{Y}$  identical to the coordinates along axes  $\vec{X}$ ,  $\vec{Y}$  of a related control point among the plurality of related control points (201, 202, 203, 204, 205, 206, 207, 208).

5. Method according to any one of the preceding claims, wherein the received plurality of related control points (201, 202, 203, 204, 205, 206, 207, 208) comprises at least three related control points (201, 202, 203), and wherein defining pseudo-rectangles comprises:

- identifying reference points in a reference plane (10);
- identifying triangles having a first reference corner (210), a second reference corner (220) and a third reference corner (230) among the identified reference points (210, 220, 230, 240, 250, 260, 270, 280) using a triangulation, and
- in each of the identified triangles:
  - identifying a reference centroid (2123) of said triangle,
  - identifying a first reference center (212) of the segment defined by the first reference corner (210) and the second reference corner (220);
  - identifying a second reference center (213) of the segment defined by the first reference corner (210) and the third reference corner (230);

wherein a pseudo rectangle is defined by segments connecting the first reference corner (210) with the first reference center (212), the first reference center (212) with the reference centroid (2123), the reference centroid (2123) with the second reference center (213) and the second reference center (213) with the first reference corner (210).

6. Method according to claim 5, wherein prior to applying a diffeomorphic transformation F (S50), the method comprises, for an identified triangle:

- identifying a first (201), second (202) and third (203) related control point among the plurality of related control points associated with

corresponding first (210), second (220) and third (230) reference corners of said identified triangle;

- applying a horizon reconstruction algorithm to points of a plane comprising axis  $\vec{Z}$  and comprising the first (201) and second (202) related control points to determine a first portion of a first local horizon;
- identifying a first related central point on the first portion of the first local horizon having coordinates along axes  $\vec{X}$  and  $\vec{Y}$  identical to coordinates along axes  $\vec{X}$  and  $\vec{Y}$  of the first reference center (212);
- applying a horizon reconstruction algorithm to points of a plane comprising axis  $\vec{Z}$  and comprising the first (201) and third (203) related control points to determine a second portion of a second local horizon;
- identifying a second related central point on the second portion of the second local horizon having coordinates along axes  $\vec{X}$  and  $\vec{Y}$  identical to coordinates along axes  $\vec{X}$  and  $\vec{Y}$  of the second reference center (213);
- computing a coordinate along axis  $\vec{Z}$  of a related middle point having coordinates along axes  $\vec{X}$  and  $\vec{Y}$  identical to coordinates along axes  $\vec{X}$  and  $\vec{Y}$  of the reference centroid (2123) of said identified triangle, the computation of said coordinate along axis  $\vec{Z}$  being a function of the coordinates of a point on said determined first or second local horizons.

20

7. Method according to claim 6, wherein computing a coordinate along axis  $\vec{Z}$  of the related middle point of said identified triangle is achieved by applying a horizon reconstruction algorithm to points of a plane comprising axis  $\vec{Z}$  and comprising the segment connecting the first (212) reference center with the reference centroid or the segment connecting the second (213) reference center with the reference centroid (2123).

25

8. Method according to claim 6, wherein computing a coordinate along axis  $\vec{Z}$  of the related middle point is achieved by calculating the mean value of the

coordinates along axis  $\vec{Z}$  of at least the first (212) and second (213) related central points.

5 **9.** Method according to any one of the preceding claims, wherein the Poisson equation is solved (S54) using a Fourier transform algorithm.

**10.** Method according to any one of the preceding claims, wherein the defined pseudo-rectangles map a continuous portion of the reference plane (10).

10 **11.** Method according to any one of the preceding claims, wherein the method further comprises computing a portion of a seismic horizon (800) from at least the computed part of the horizon (720) of each current pseudo-rectangle among the defined pseudo-rectangles.

15 **12.** Method according to any one of claims 5 to 8 and any of claims 9 to 10, wherein the method further comprises computing a portion of a seismic horizon (800) from at least the computed part of the horizon (720) of each current pseudo-rectangle among the defined pseudo-rectangles, and after computing a portion of a seismic horizon (800), the method comprises:

20 - receiving modification information relating to the related control points;  
- identifying pseudo-rectangles affected by said received modification information relating to the related control points;  
- defining a new set of pseudo-rectangles in a local area corresponding to the area occupied by said pseudo-rectangles affected by said  
25 received modification information relating to the related control points ;  
- for each current pseudo-rectangle among the new set of pseudo-rectangles:

- applying a diffeomorphic transformation F (S50), said diffeomorphic transformation F :

30 - being a function of coordinates along  $\vec{X}$ ,  $\vec{Y}$  and defining a new domain comprising axes  $\vec{X}'$ ,  $\vec{Y}'$ ,  $\vec{Z}$ ;

- 5
- transforming points of the seismic image having coordinates along axes  $\vec{X}$ ,  $\vec{Y}$  identical to coordinates along axes  $\vec{X}$ ,  $\vec{Y}$  of points in said current pseudo-rectangle, said points of the seismic image including the related control point associated with the current pseudo-rectangle;
  - transforming said current pseudo-rectangle into a corresponding rectangle;
- 10
- applying (S52, S53, S54, S55) a horizon reconstruction algorithm to the transformed points, to determine a part of a transformed horizon (7020), said part of a transformed horizon (7020) comprising the transformed related control point (602), the reconstruction of the seismic horizon comprising solving (S54) the Poisson equation  $\Delta(\delta\tau) = -\text{div}(r)$ , where  $\delta\tau$  is an unknown function of coordinates
- 15
- along axes  $\vec{X}'$ ,  $\vec{Y}'$ ,  $\Delta$  denotes the Laplace operator in the new domain,  $\text{div}$  denotes the divergence vector operator in the new domain and  $r$  is a fixed function of coordinates along axes  $\vec{X}'$ ,  $\vec{Y}'$ ;
  - computing a part of the horizon (720), said computing of a part of the horizon (720) comprising applying (S6) an inverse diffeomorphic
- 20
- transformation  $F^{-1}$  to the determined part of a transformed horizon (7020).

**13.** Device (1300) for enhancing the determination, from a seismic image, of at least a portion of a seismic horizon in a three-dimensional domain (1) comprising

25 axes  $\vec{X}$ ,  $\vec{Y}$ ,  $\vec{Z}$ , said seismic horizon being a function of coordinates along axes  $\vec{X}$ ,  $\vec{Y}$  in said three-dimensional domain (1), wherein said device (1300) comprises:

- an input interface (1303) for receiving (S1) the seismic image, the seismic image having points associated with coordinates along axes  $\vec{X}$ ,
- 30  $\vec{Y}$ ,  $\vec{Z}$ ; and for receiving (S2) a plurality of related control points (201,

202, 203, 204, 205, 206, 207, 208) associated with coordinates on axes  $\vec{X}$ ,  $\vec{Y}$ ,  $\vec{Z}$ ;

- 5 - a circuit (1304) for defining, in a reference plane (10) defined by axes  $\vec{X}$  and  $\vec{Y}$ , for at least one related control point among the plurality of related control points (201, 202, 203, 204, 205, 206, 207, 208), an associated reference point with coordinates along axes  $\vec{X}$ ,  $\vec{Y}$ , among a plurality of reference points (210, 220, 230, 240, 250, 260, 270, 280), the reference point having coordinates on axes  $\vec{X}$  and  $\vec{Y}$  identical to coordinates on axes  $\vec{X}$  and  $\vec{Y}$  of the related control point,
- 10 - a circuit (1304) for defining pseudo-rectangles in the reference plane (10), each pseudo-rectangle comprising a reference point among a plurality of reference points (210, 220, 230, 240, 250, 260, 270, 280);
- a circuit (1304) being adapted for, for each current pseudo-rectangle among the defined pseudo-rectangles:
  - 15 - applying a diffeomorphic transformation F (S50), said diffeomorphic transformation F :
    - being a function of coordinates along  $\vec{X}$ ,  $\vec{Y}$  and defining a new domain comprising axes  $\vec{X}'$ ,  $\vec{Y}'$ ,  $\vec{Z}$ ;
    - transforming points of the seismic image having
    - 20 coordinates along axes  $\vec{X}$ ,  $\vec{Y}$  identical to coordinates along axes  $\vec{X}$ ,  $\vec{Y}$  of points in said current pseudo-rectangle, said points of the seismic image including the related control point associated with the current pseudo-rectangle;
    - 25 - transforming said current pseudo-rectangle into a corresponding rectangle;
  - applying (S52, S53, S54, S55) a horizon reconstruction algorithm to the transformed points, to determine a part of a transformed horizon (7020), said part of a transformed horizon (7020) comprising the
  - 30 transformed related control point (602), the reconstruction of the

seismic horizon comprising solving (S54) the Poisson equation  $\Delta(\delta\tau) = -\text{div}(r)$ , where  $\delta\tau$  is an unknown function of coordinates along axes  $\vec{X}'$ ,  $\vec{Y}'$ ,  $\Delta$  denotes the Laplace operator in the new domain,  $\text{div}$  denotes the divergence vector operator in the new domain and  $r$  is a fixed function of coordinates along axes  $\vec{X}'$ ,  $\vec{Y}'$ ;

5

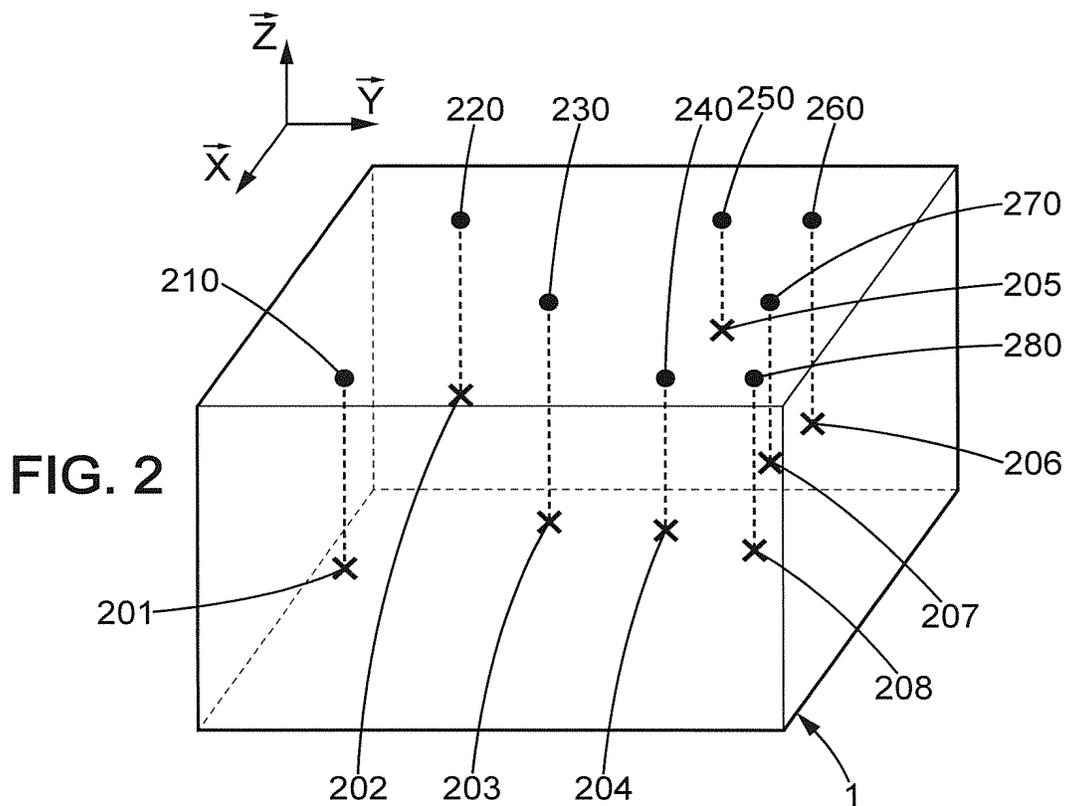
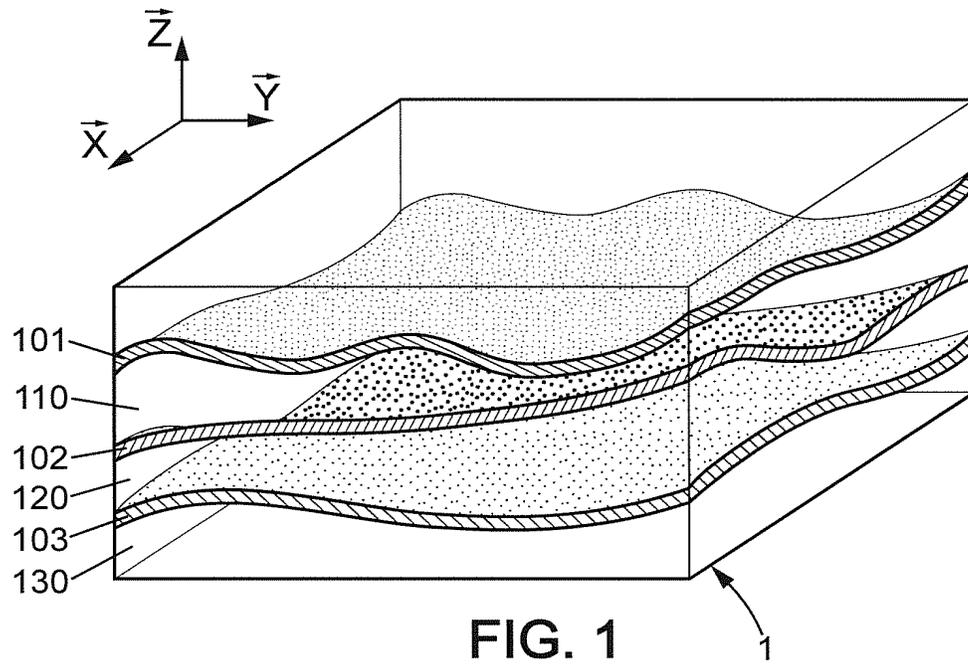
- computing a part of the horizon (720), said computing of a part of the horizon (720) comprising applying (S6) an inverse diffeomorphic transformation  $F^{-1}$  to the determined part of a transformed horizon (7020).

10

**14.** A non-transitory computer readable storage medium, having stored thereon a computer program comprising program instructions, the computer program being loadable into a data-processing unit and adapted to cause the data-processing unit to carry out the steps of any of claims 1 to 12 when the computer program is

15

run by the data-processing device.



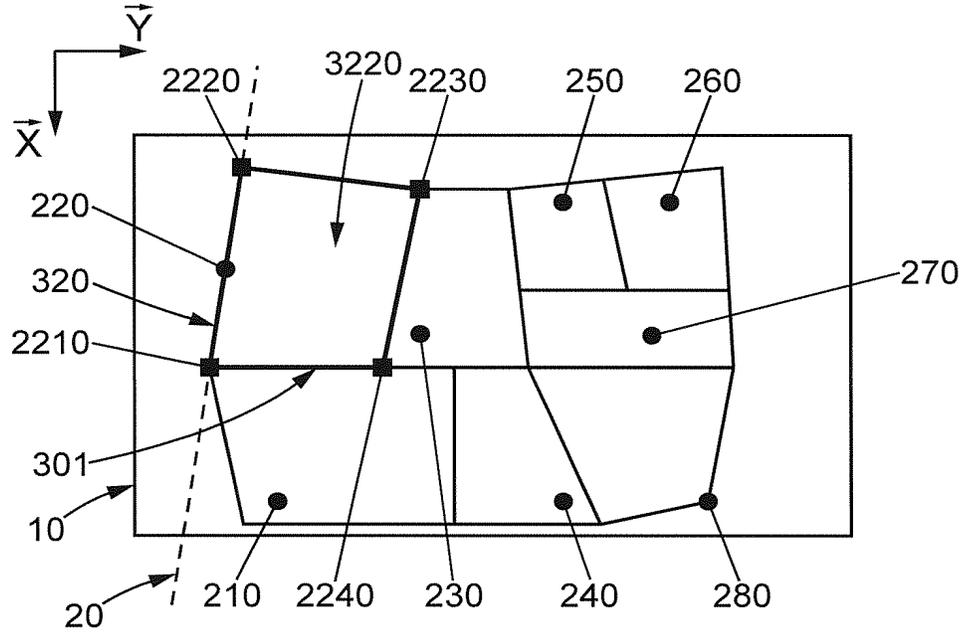


FIG. 3

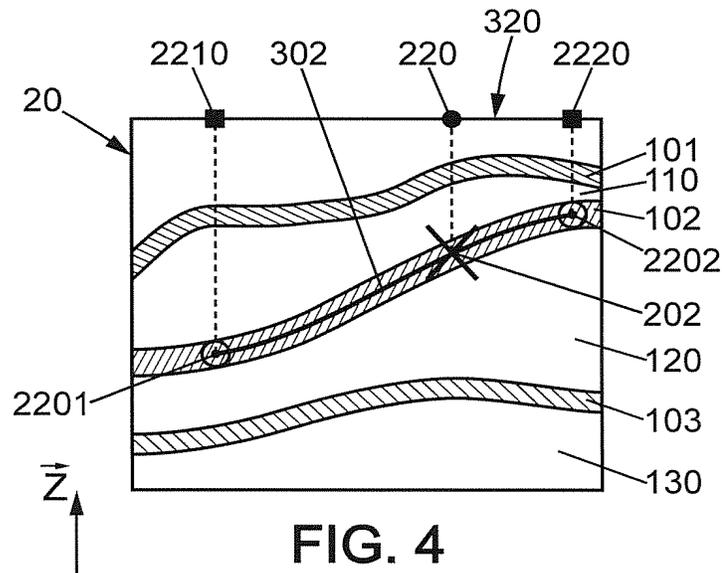


FIG. 4

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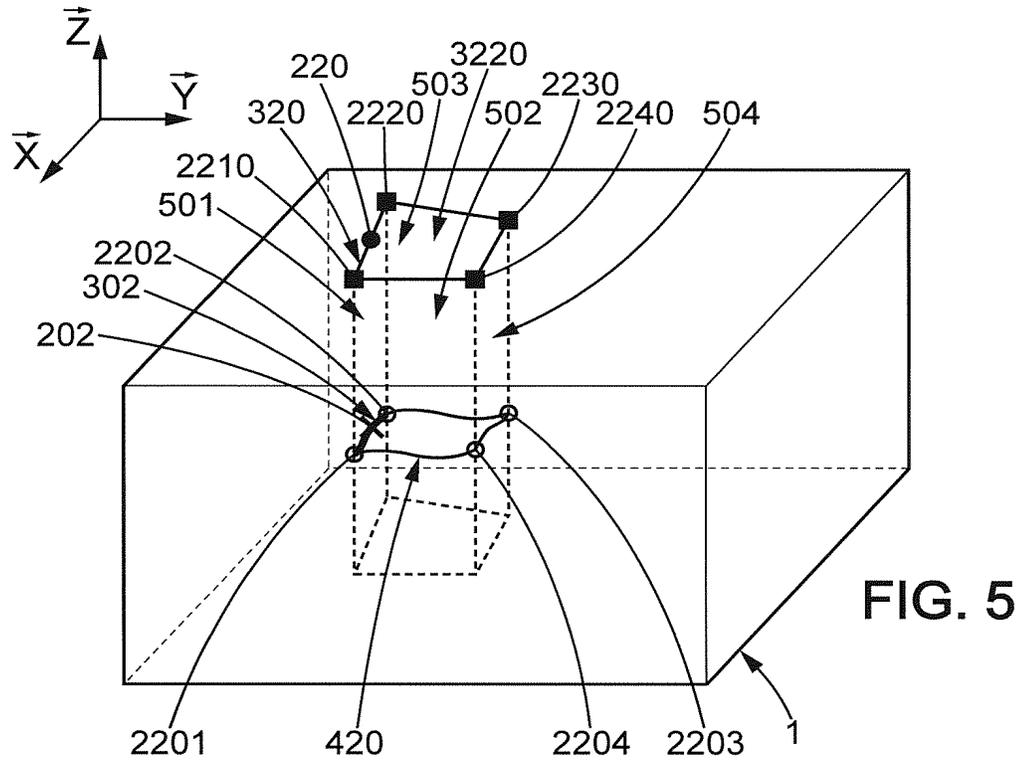


FIG. 5

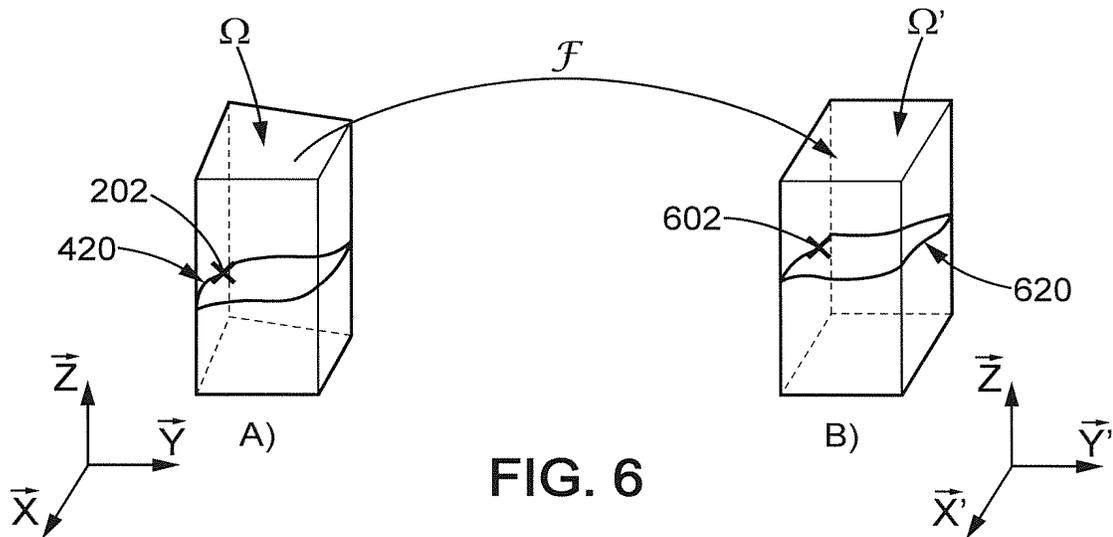


FIG. 6

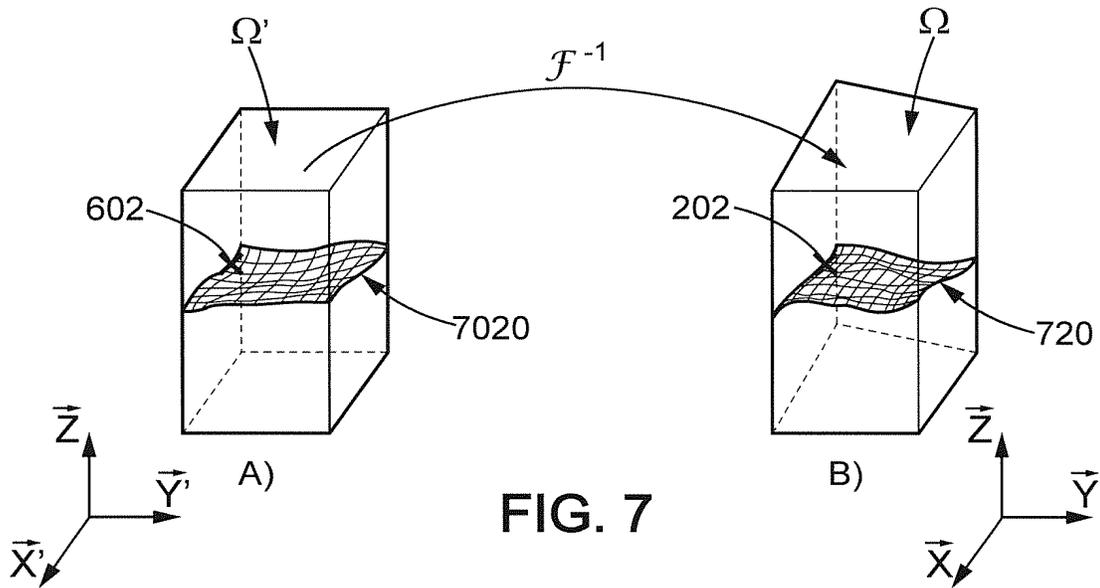


FIG. 7

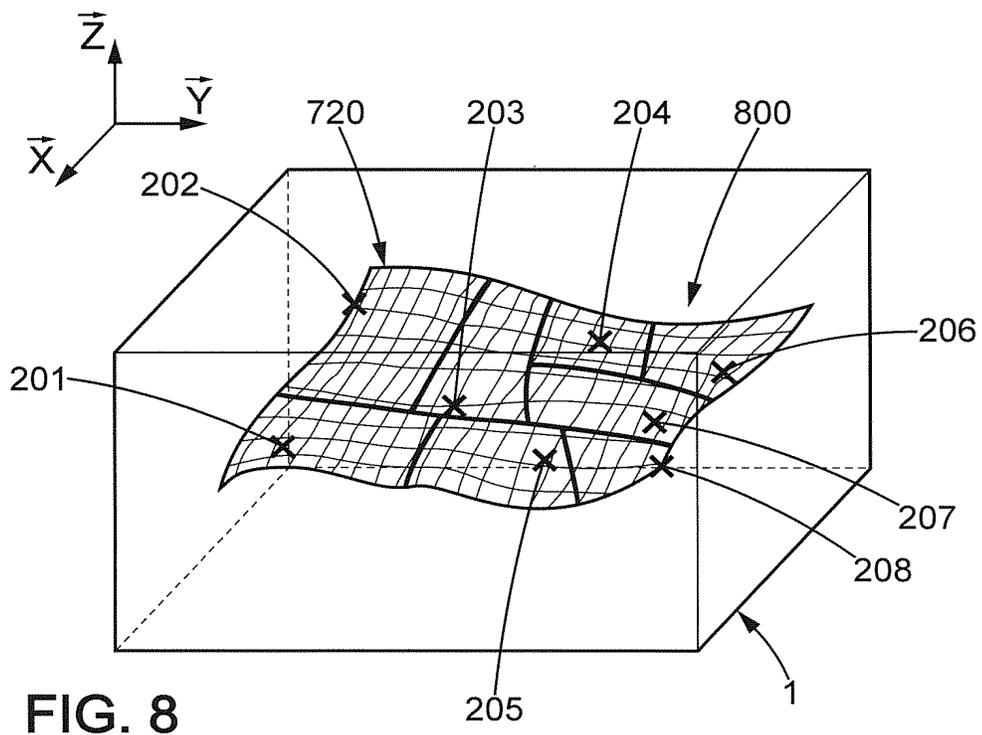


FIG. 8

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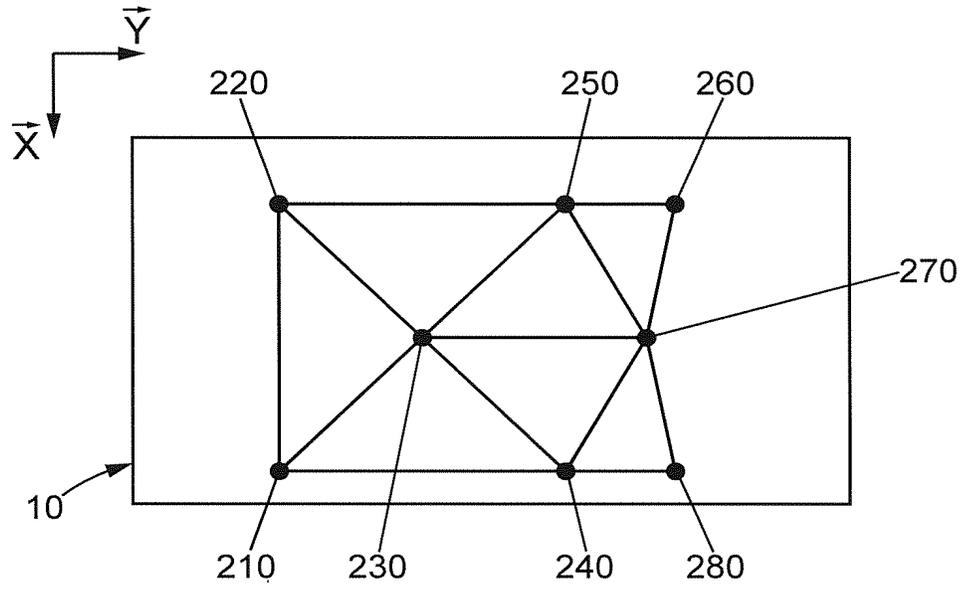


FIG. 9

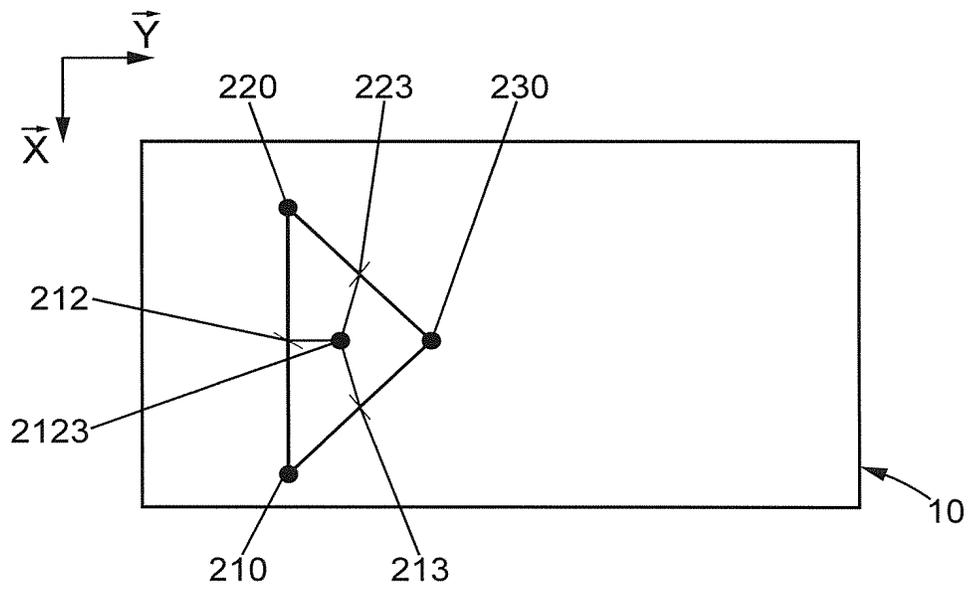


FIG. 10

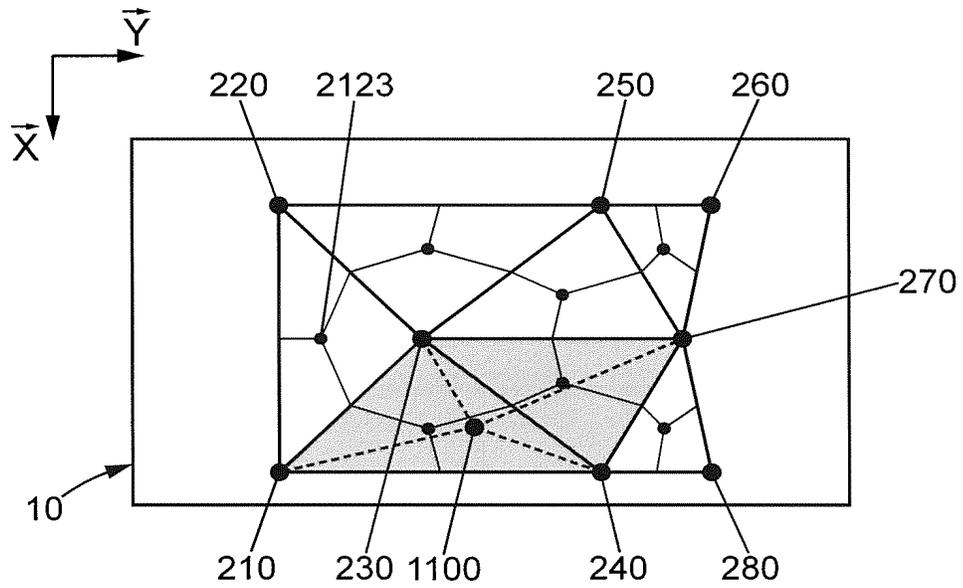
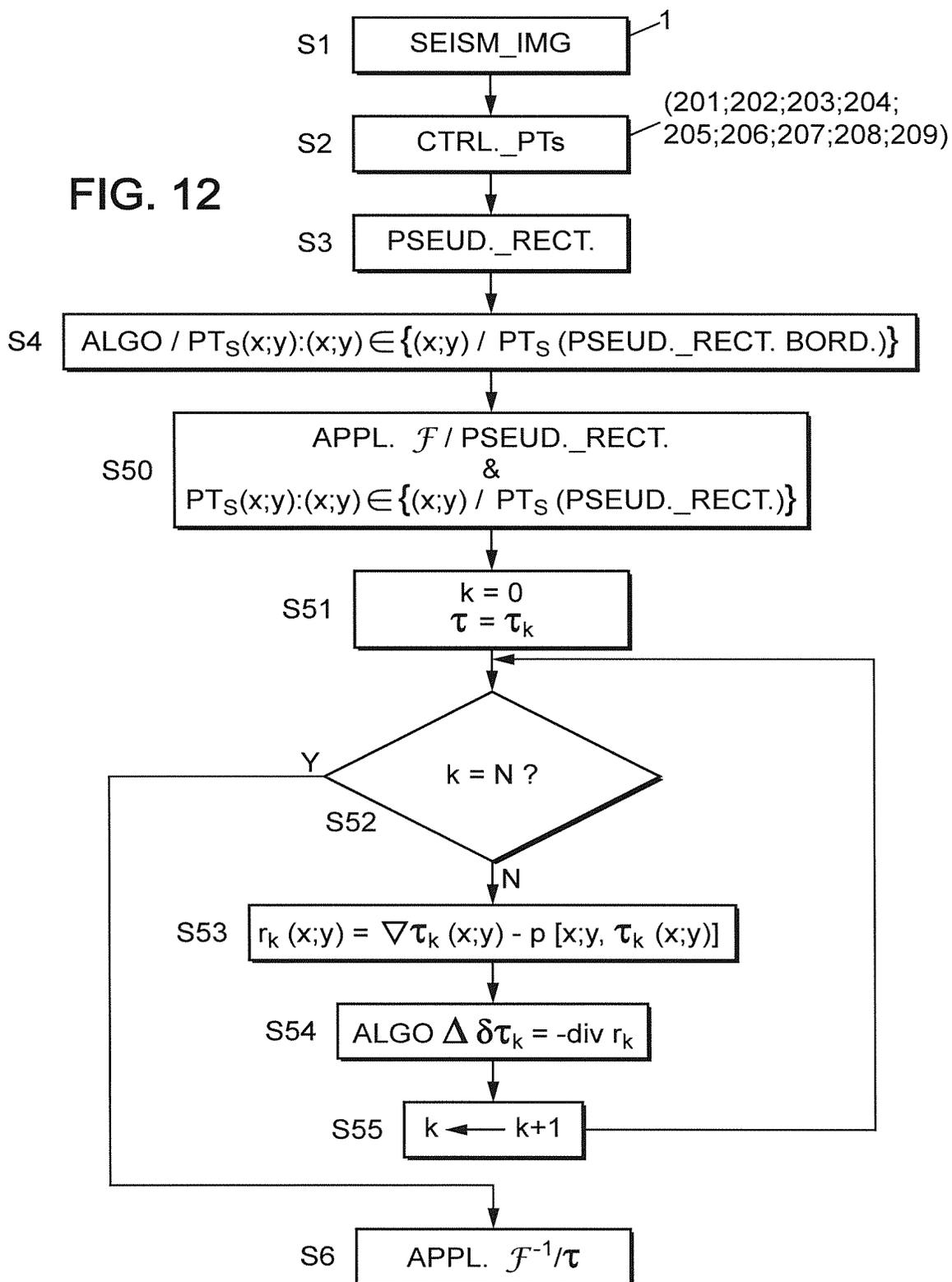


FIG. 11

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FIG. 12



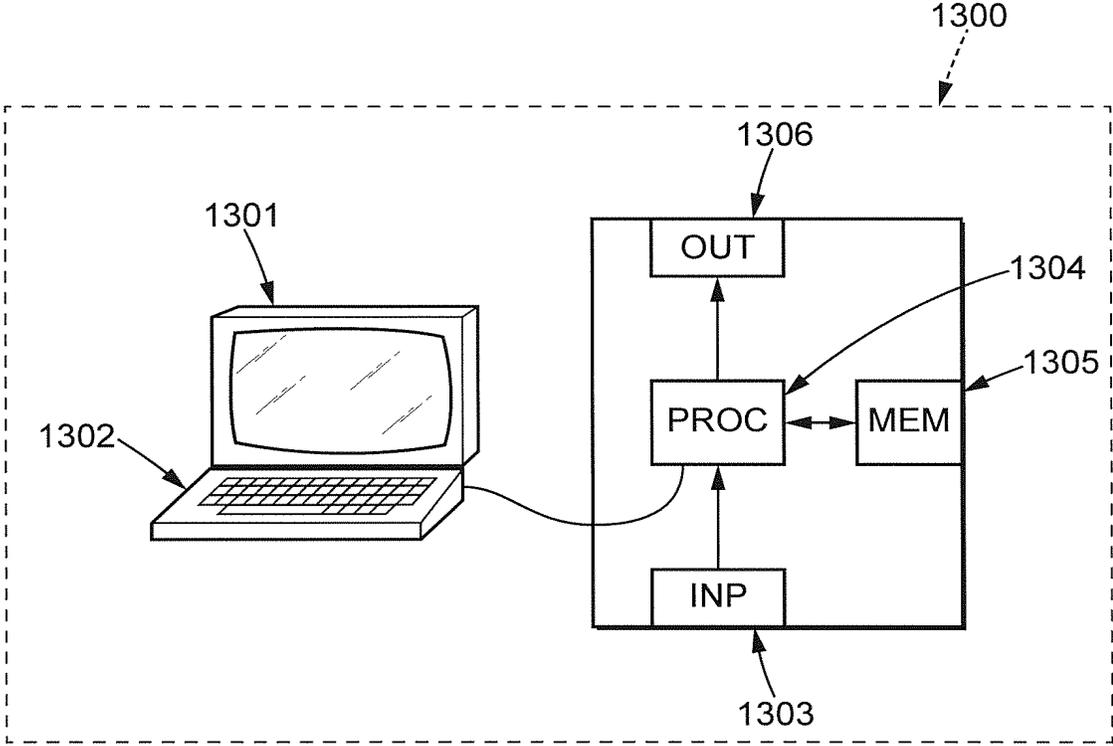


FIG. 13