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REFLECTION SEISMOLOGY SYSTEMS FOR PLANETARY GEOLOGY: A FEASIBILITY STUDY

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ABSTRACT

A feasibility study is conducted to determine whether reflection seismology systems can be used for planetary geology research. The focus is on systems with up to 20,000 seismic detectors, such as used today in Earth geological research and energy companies. The study follows a top-down systems engineering end-user approach starting with the identification of possible applications of a seismic system. These applications (scenarios) have been determined with the help of geologists. These scenarios are transformed into system requirements using geophysicists’ methods. Among these methods are simulations where the seismic image was simulated of subsurface structures based on models. Concepts are created based on current reflection seismology technologies and key areas, which require improvements for a space application. To keep the end result as broadly applicable as possible, no specific mission or scenario was used as reference. Instead, a set of possible missions was drafted. Suitable concepts will be selected for each mission type. At the time of writing (September 2009), the system requirements are determined and various concepts are created.

INTRODUCTION

Reflection seismology is the branch of seismology that uses the reflection of elastodynamic waves for the determination of subsurface structures. Unlike regular and refraction seismology, reflection seismology enables to create an image of the subsurface structure. Refraction and standard seismology can only provide averaged values for the depths of the present layers or global structure. Reflection seismology is therefore a preferable method to determine the subsurface structure. The method provides detailed information which is useful for the interpretation of the subsurface structure and the processes that created them. Reflection seismology is also accountable for mapping most of the subsurface structure of the Earth. Furthermore, it is the primary method used in the oil and gas industry to map oil and gas fields.

Reflection seismology systems are more complex than refraction and regular seismology systems. While the latter two usually consist of a couple of seismic detectors (seismographs), a reflection seismology system consists of a few tens to tens of thousands seismic detectors.

Reflection seismology systems (seismic systems in short) can be a valuable method for scientific research on planetary bodies. With a seismic system, it would be possible to map the subsurface structure of geological features which cannot be (completely) explained from surface imagery and other research methods. The obtained data can, for instance, help to explain how the geological processes resulted in the geological features.

Seismology systems have already been deployed on the Moon during the Apollo Moon landing missions.2, Besides the seismographs, the Apollo Lunar Surface Experiment Packages (ALSEPs) of Apollo 14, 16 and 17 contained active seismic systems which, operationally, resemble a seismic system. However, the experiment only contained four seismic detectors (geophones) and was therefore only capable to approximately determine the local thickness of the regolith and underlying layers.

The goal of the study is to determine whether seismic systems can be used in space applications with the same amount of seismic detectors as the Earth applications. If so, the second goal is to determine what changes need to be made to such an
existing system and which technologies can and should be implemented. Based on the end user requirements, the results are used to create various concepts for reflection seismology systems for space applications.

The study was initiated as a side study of ESA’s ExoGeoLab project. A seismic system is one of the instruments investigated in the ExoGeoLab project with the goal, among others, to create an instrument package for lunar or Martian exploration.

**PROJECT DESCRIPTION**

The feasibility study is performed with an end-user requirement approach. The primary reason for this approach is to maximize the usability of the end result by accounting for the end user wishes from the beginning. The study was split up into three parts:

1. Requirements determination,
2. Reflection seismology technology study and concept generation,
3. Missions and constraints determination.

The results of these parts are the requirements, the design and technology options and mission constraints of a seismic system respectively.

The study was initiated with an extensive exploration study to familiarize with the various aspects of reflection seismology and finding all the required information. The requirements found in the requirements discovery study have been channelled into sets of system (parameter) requirements. The technology options are used to generate concepts. The missions and constraints are combined into a list of missions with corresponding constraints.

When the requirements, missions and constraints are determined, the requirements and constraints will be used in the trade-off study to select suitable concepts. Figure 1 shows a simplified work flow diagram for the study. Parts one to three are described in more detail in the next three sections.

**APPLICATION REQUIREMENTS DETERMINATION**

The goal of the requirements determination was to set up two or three sets of seismic system requirements and design parameters. These requirements are used for the selection of suitable concepts and should be considered as the requirements imposed on the system design.

The determination of these system requirements consisted of two steps, which involved geologists and the geophysicists, the two disciplines that are involved in the use of a seismic system. Their relation to the seismic system and their use of the obtained data was used to determine the requirements.

Emphasis should be placed on the fact that sets of requirements have been determined instead of a single set. In the early beginning of the study, it became clear that a single set of requirements would be unfeasible and too general for the concept selection. It was therefore decided to work towards two to three sets of requirements and system design parameters to provide more conclusive requirements while keeping them as broad as possible.

**Geologists’ requirements discovery**

The end-user approach used in the study is mostly visible in the requirements discovery. In the case of a seismic system, the end users are the geologists that use the obtained data for structural interpretation. However, before the seismic data is of use to the geologists, the raw measured data has to be processed into a seismic image, a task performed by the geophysicist. The system requirements have therefore been based on the wishes of the geologists through the requirements of the geophysicists.

The system requirements (these include the system parameters) depend on the requirements on the seismic image that has to be obtained with the seismic system. The latter are called the seismic requirements. These seismic requirements in turn depend on what the geologist wants to investigate.

The seismic requirements have been determined in consolidation with planetary geologists and literature research. The geological questions were translated into scenarios with corresponding seismic requirements:

1. Scenario depth [m],
2. Scenario size (horizontal dimensions [m²]),
3. Required resolution [m].
Furthermore, the materials that are expected to be present were logged as constraints since they impose limitations to the measurement frequency domain.

The result of this investigation was a list of 30 scenarios, each with its own seismic requirements and material list. The locations of the scenarios range from Mercury to Kuiper Belt objects. Table 1 provides a list with the locations of the 30 scenarios. Besides the scenarios for scientific research, scenarios have been determined for utilization application such as the detection of water ice layers. The Moon and Mars have been given preference in the search for scenarios because of their relative close proximity and better known geology. This preference resulted in more scenarios for the Moon or Mars.

Table 1: List of scenarios’ locations, the number indicates the amount of scenarios of the 30 on the location.

<table>
<thead>
<tr>
<th>Location</th>
<th># of scenarios</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Scientific research</strong></td>
<td>22</td>
</tr>
<tr>
<td>Moon</td>
<td>6</td>
</tr>
<tr>
<td>Mars</td>
<td>6</td>
</tr>
<tr>
<td>Mercury</td>
<td>3</td>
</tr>
<tr>
<td>Venus</td>
<td>2</td>
</tr>
<tr>
<td>Volcanic moons</td>
<td>1</td>
</tr>
<tr>
<td>Ice moons</td>
<td>1</td>
</tr>
<tr>
<td>Asteroids</td>
<td>1</td>
</tr>
<tr>
<td>Comets</td>
<td>1</td>
</tr>
<tr>
<td>Kuiper Belt Object</td>
<td>1</td>
</tr>
<tr>
<td><strong>Utilization applications</strong></td>
<td>8</td>
</tr>
<tr>
<td>Moon</td>
<td>3</td>
</tr>
<tr>
<td>Mars</td>
<td>2</td>
</tr>
<tr>
<td>Secondary applications</td>
<td>3</td>
</tr>
</tbody>
</table>

Among the determined scenarios are Mars’ chaotic terrains which are believed to be inverted terrains due to surface water ice melt (Figure 2), and Hebes Chasma, an enclosed canyon with no outflow channels, with in its centre a mountain which origin cannot be (completely) determined (Figure 3). Lunar scenarios include the mascons and the possibility of water ice in permanent shaded polar craters. The primary reason to include all the 30 scenarios in the proceeding requirement determination is that the results cover a wide variety of applications.

Figure 2: Aram Choas, one of the many chaotic terrains found around the Martian equator east of Valles Marineris. © ESA, DLR, FU Berlin

Figure 3: Hebes chasma, a completely enclosed canyon (chasma) with a mountain of unknown origin. © ESA, DLR, FU Berlin

**Requirements transformation**

Once the seismic requirements from the geologists have been determined, they were transformed into the system requirements. The goal was to obtain two to three sets of systems requirements, as explained before. The thirty sets of seismic requirements, each for a specific scenario, therefore had to be narrowed down to two to three sets of requirements containing the larger part of the scenarios. This process was called scenario generalisation, since the goal was to obtain sets of general requirements.

The system requirements (system parameters) that were to be obtained are:
1. Total amount of sensors,
2. (Maximum) Interval distance between the sensors,
3. Frequency range which the sensors should measure,
4. Seismic source requirements.

Figure 4 shows the relations between the seismic requirements and system requirements, expressed in a
Figure 4: Workflow diagram of the requirement transformation. Left is the column with the seismic requirements. Right is the column with the system requirements that had to be obtained.

The transformation was performed in a systematic way along the following steps:
1. Insertion of the following data in a data sheet,
   a. seismic requirements of each scenario,
   b. seismic system measurement line length and measurement area dimensions for each scenario, based on scenario sizes and survey guidelines,
2. Calculation of the desired frequency, frequency limitations and selection of the target frequency,
3. Weighting of the scenarios for the scientific value and utilization value,
4. Plotting of the weights versus the seismic system’s measurement line length and measurement area size,
5. Selection of measurement line and area domains. Combined, these domains had to contain over 95% of the total amount of weight points rewarded, both for a measurement line and a measurement area,
6. Per domain selected in step 5 the determination of:
   a. frequency range of the target frequencies,
   b. maximum interval range between the seismic detectors,
   c. materials present,
   d. total amount of detectors based on interval distance and line length or area size,
7. Testing whether the desired seismic images could be obtained by simulating seismic images of scenarios models. These simulation activities are described in the next paragraph.

The final results of the requirement transformation will be used in the concept selection. It should be noted that the generalisation and transformation process used in this study applies a simplified method. Typically performed by geophysicists, this process involves a more complex analysis to determine if and how a seismic measurement could provide the data that the geologists require from a specific scenario. However, since this study did not involve a specific scenario and is intentionally kept broad, a detailed analysis would not have been possible nor would it provide more conclusive results. The steps taken in the scenario generalization and requirements transformation of this are based on experiences of geophysicists and empirical data. Figure 5 provides an illustration of the intermediate results; one of the plots described in step 4.

Figure 5: The plot of the scenarios’ weights versus the seismic system’s measurement line length. The indicated domains contain 96% of the total amount of awarding weight points.

**Simulation activities**
Step 7 of the scenario generalization and requirements transformation consists of a simulation of the seismic image that could be obtained with a seismic system. The primary goal of the simulation is to verify whether the determined system parameters (measurement frequencies and interval range) could provide the required seismic image.

In an actual situation, the recorded data is processed by computer algorithms, where the principal processing step is known as migration. At this stage, a seismic depth image of the subsurface is obtained.
Structural information can be obtained from the migration image. Seismic interpretation is not a trivial task, because of the relatively low resolution of the migration image. To simulate a migrated image, a novel strategy is used where a migration image is simulated by filtering a geological model with a spatial resolution filter \(^{12,13}\). The spatial resolution filter (SRF) is the migrated impulse response of a point scatterer. The filter can also be applied as deconvolution filter, as was first done to enhance the resolution of the images of the Hubble space telescope after it was found that it had an imperfect lens \(^{14}\).

The major advantage of this method is the significant reduction in simulation time which would normally require a Finite Elements Model (FEM) simulation of a subsurface model and the processing of the obtained data into a seismic image.

The code is considered a suitable simulation method for this study. This seismic image is considered detailed enough to prefer this faster simulation method above the time consuming FEM simulation and processing.

One adaptation has been made to the code. The original codes were developed for simulations with a single SRF which was sufficient for its intended applications. For the deeper planetary scenarios with dust layers with low seismic wave velocities, this assumption would no longer hold. The original codes were therefore adapted to vary the SRFs with the depth and, in doing so, create a more accurate simulation of the seismic image.

The codes have been adapted for varying SRFs and tested. The simulations of seismic images will be initiated after the scenario generalization has been performed and the basic models, based on the obtained general requirements, have been created. Figure 6 illustrates what type of simulated seismic images will be obtained with the simulation. Figure 7 shows the corresponding velocity model.

**TECHNOLOGY STUDY AND CONCEPT GENERATION**

The goals of the second part of the study were to:
- Summarize reflection seismology technology and methods,
- Determine the (technological) option for space applications and the developments in Earth’s systems,
- Determine the additional technology options, such as power supply, for space applications,
- Create, based on the found information, concepts for seismic detectors and concepts for the deployment of the detectors,
- Determine the workable combinations of the detector concepts and deployment concepts.

The first three goals are part of the technology study while the latter two are part of the concept generation (see Figure 1).

![Figure 6: The result of a test simulation of a simple horizontal layered basalt basin model based on the lunar maria. The colour code indicates the measured vibrations normalized to the maximum amplitude [-].](image1)

![Figure 7: The velocity model used for the simulation of the seismic image shown in figure 6. The colour bar indicates the seismic wave velocities [m/s]](image2)

**Technology study**

The reflection seismology technology was studied to determine its operation principles and to find possible or required areas of improvement for space applications. This paragraph presents the important findings of this study.

The study focused on the seismic detectors. The technologies and design of the other parts, the seismic source and the central station, are likely to be integrated parts of the spacecraft and were therefore not studied in as much detail as the seismic detectors.

Magnetic coil geophones are the most common type of seismic detectors used in land based surveys. An
alternative are Micro Electro Mechanical System (MEMS) geophones, which share in land surveys is increasing. For space applications, the MEMS geophones are a preferable choice to decrease the mass of the detectors. The MEMS geophones are in particular attractive for measurement applications with lower frequencies which require higher masses of the magnetic coil geophone.

Seismic systems for Earth applications are primarily designed to withstand rough handling and severe weather conditions. As a result, the cables and casings are heavy and robust. This type of design however results in such high system masses that often several trucks are required for transport. The design of a seismic system for the space applications can be much lighter when designed for a low mass instead of robustness.

Probably the most significant design choice to reduce the system’s mass is to use wireless communication instead of cables. The mass of the cables can run up to 90% of the entire system for large interval distances between the seismic detectors. Wireless Geophone Systems (WGSs) are currently already developed for Earth applications since the increasing system sizes impose high requirements on transport and deployment\[15,16]. The use of a WGS would, furthermore, significantly reduce the deployment effort (further discussed in the next chapter). Disadvantages of wireless geophones are that they require their own power supply and onboard processing capabilities.

An investigation, performed by Savazzi and Spagnolini (2008), shows a range of wireless communication protocols and architectures for WGSs\[16]. Some of these protocols (IR-UWB and MB-OFDM) allow position determination among the transmitters. This additional function allows random deployment of the seismic detectors and position determination afterwards.

Earth applications of seismic systems often include seismic sources like airguns (for sea applications), dynamite and vibroseises (trucks with shaker tables). For a space application, the latter seismic source has a too high mass; a typical vibroseis has a mass of twenty tonnes and often multiple vibroseises are required. Dynamite also has its limitations and increased risks. Space applications could however use the impacts of artificial or natural objects as a seismic source.

Seismic systems using artificial seismic sources are known as active seismic systems. An alternative is a passive seismic system. This type of systems measures continuously and specific seismic events are traced afterwards and used for obtaining the seismic image. Passive seismic systems are developed within the Low Frequency Array (LOFAR) project run by several Dutch institutes\[17].

Passive systems can be used for space applications as well. Natural sources as quakes or impacts can then be used as a seismic source. The deployment of a passive seismic system should only be considered if the planetary body is known to experience seismic activities.

Developments over the last few years, several of them performed at the TU Delft, allow the development of intelligent geophones. A recent study performed by Haddadi et al. (2008) showed that a parallel processing system can even be more intelligent than a single processing unit with the same processing capability combined.

Parallel processing could make a WGS less dependent on the central station. The central station’s tasks could then be performed by the geophones together. This would decrease the risk of failure of a mission. If several geophones do not function, the system can still operate, which is not the case if the central station fails. The geophones of a parallel processing WGS could be equipped with several (relatively simple) commands which would make the system adaptive and intelligent as a total system like ants in an ant colony.

As a final remark, it should be noted that the improvements that can or have to be made for a space application of a seismic system will be beneficial for Earth applications as well.

**Concept generation**

The concept generation has been split up into two parts; seismic detector concepts and deployment concepts. A seismic detector design and a deployment design are of course not uncoupled but the two sets are generated separately for a reason.

Separate concept generation makes it possible to combine detector designs with deployment methods afterwards in a compliance matrix. This approach provides a clear view of the possible concept combinations and the combinations’ strengths, indicated with grades of --, --, 0, + and ++.

Creating a single set of concepts, with detectors design and deployment methods combined, makes it difficult and time consuming to generate all the possible combinations as concepts. Certain concepts are bound to be forgotten and a single long list is less clear in indicating the strengths of the combinations. The concept generation is in its initial phase at the moment of writing, so no definite results can be shown.
MISSION AND CONSTRAINTS DETERMINATION

Since the study is a feasibility study for space seismic systems in general, there were no specific mission(s) or other constraints in which the system had to function. This allowed the possibility to keep the results of the study as broad as possible for potential applications. It was however well realised that no constraints at all would lead to false and useless concepts and results.

In order to prevent the latter, it was decided to include a missions and constraints study in the feasibility study as well. The goal was to determine on what type of missions a seismic system could be flown and what the top level constraints on the system would be.

The mission options have been based on previous and coming landing missions. The missions' specifications such as mass, range (in case of rovers) and mission duration have been used to determine the ranges of these specifications for these respective mission types.

This approach in the determination of missions and their constraints has an attractive advantage. While the constraints, although only top level, allow the elimination of unsuitable concepts, it does not exclude workable concept/mission combinations since all the suitable mission types have been included. The result is that proper selection of suitable concepts can be performed without losing a broad end product and conclusion.

Deployment constraints

Within the determination of the mission types and their corresponding constraints, special emphasis was placed on the deployment of a seismic system. A typical deployment of a seismic system on Earth involves several teams of up to hundreds of team members which each have the advantage of the manoeuvrability of a human body.

If a seismic system were to be deployed on a planetary body, an experienced deployment team is a luxury that is not feasible or affordable. Even if astronauts were to deploy the system, they still would experience trouble due to the limited manoeuvrability of their space suit and they are likely limited to only a few team members.

A space application thus requires assistance of robotic equipment in the deployment. Robotic equipment however has its limitations in manoeuvrability, flexibility and innovate thinking to tackle different deployment situations.

An alternative to complex robotic equipment and deployment procedures is to loosen the deployment strategies. Typical Earth deployment strategies require the seismic detectors (geophones) to be placed straight up and on the correct predetermined grid position. In particular, the latter requirement poses implications since it requires that the detector can be deployed on any type of surface present.

For the space applications, this would imply that the deployment equipment is fitted with drills for soft soil and hard rock, plaster tools and means to press a geophone into the soil. By increasing the flexibility of the location of a seismic detector, the deployment could be limited to only specific circumstances. The deployment would then only require one or two methods for deployment, preferably the easiest and least risky methods.

An extreme in flexible deployment would be random spreading by simply tossing in the approximate desired direction. This method of deployment is considered favourable for future Earth systems to significantly reduce the deployment effort. For space applications, this method would be even more desirable and even critical for large scale (>10,000 sensors) system.

Such a random spreading deployment method is not suitable with a typical Earth geophone. Its design has to be altered in order to function properly after random spreading deployment. This design should include:

- The ability to locate the sensor,
- The ability to determine its orientation and have the movement detection in the correct direction,
- Preferably a wireless communication system and, if so, has its own power supply,
- A rigid design to withstand the loads during deployment.

Fortunately, the technologies discussed in the previous chapter, make this type of sensors possible.

Another important constraint for a seismic system is the limitations to the data rates for sending data back to Earth. For larger seismic systems, the amount of data can rapidly increase to several hundreds of Mb/s or even to several Gb/s. These high data rates are in particular hard to obtain for the distant applications.

Several solutions are possible to reduce the data rate. The data rate is determined by the bit size of a measurement and the interval time between the measurements. The latter is determined by the Nyquist criterion that requires a minimum of two measurements per wavelength to prevent aliasing. The data rates can therefore be reduced by filtering the higher frequencies to allow longer measurement intervals. Lower frequencies however reduce the accuracy of the measurement. The filtering should therefore be limited to the frequencies that can still provide the required accuracy.

Other option to reduce the data rate is to send the data over a longer time span than the measurement
time span. This method is easy applicable for active systems which only measure for relatively short time lengths. For passive systems, it would mean that continuous measurements are not possible and the measurements have to be split up into periods. The disadvantage is that the system might not be measuring during interesting seismic events.

If the data rate is still too high, it would be possible to equip the central station of the seismic system with processing programmes. The obtained data could be filtered and processed into a seismic image which has a significant lower memory size. A profound disadvantage is the loss of raw data. Different processing methods or adaptations cannot be performed unless commanded to the central station.

**CONCEPT SELECTION**
The results of the three parts of the study are used in the final step of the study: the concept selection. As described in the beginning of the previous chapter, it is the intention to determine what applications can be flown on the determined mission types and select the appropriate detector and deployment concepts. Several system engineering tools are used to make this process clear and systematic such as trade-off tables and the Quality Function Deployment.

The latter will be used to transform system requirements and technology options into product requirements which are used in the concept trade-off. Once the concept(s) for each set of system requirements have been selected, a compliance matrix is used to determine in which type of missions the solution could be flown.

As there are several sets of system requirements and mission constraints and none with conclusive quantitative values, the trade-off studies will be of qualitative nature. The lack of conclusive and detailed requirements and constraints furthermore limits the concept selection to a top level analysis. The limitation to top level and qualitative analysis does however keep the results for a broad range of applications as they are intended to be according to the study goals.

**CONCLUSIONS AND OUTLOOK**
A systematic approach has been developed to derive seismic system requirements from scientific end user requirements. To this end, various customer interviews have been conducted and the requirement definition is under way.

Reflection seismology has been proven possible during the Apollo programme. However, for space applications at the scale of Earth applications, the system mass has to be reduced. Several technologies and different design philosophies allow this mass reduction. Some of the most significant improvements are:

- Wireless communication instead of cables to eliminate the cables mass,
- MEMS geophones instead of magnetic coil geophones,
- Passive monitoring systems instead of active systems with high mass or dangerous seismic sources,
- Parallel processing would make a seismic system intelligent and adaptive. These capabilities can be used for power reduction and other applications.

Besides the required technology improvements such as the mass reduction, the deployment of the seismic system is a point of concern. Developments are required to reduce the deployment effort.

Finally, the conventional seismic sources need to be adapted as well for a space application due to their high mass or risky nature. Alternatives are artificial impacts or the use of a passive monitoring system which awaits natural seismic events as a seismic source.

Future work will be the completion of the requirements determination, concept generation and the missions and constraints determination. After completion, the concept selection will be performed.

**REFERENCES**


