Carbon Capture Storage Monitoring ("CCSM")

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Kurzfassung

Es ist eine Tatsache, dass die vom Menschen verursachten CO_2-Emissionen zur globalen Erwärmung beitragen. In der öffentlichen Diskussion scheint der CO_2-Ausstoß vor allem auf die Energieerzeugung zurückzuführen zu sein. Dies ist jedoch nur partiell richtig, denn die Emissionen aus anderen industriellen Aktivitäten tragen ganz wesentlich auch zur CO_2-Emission bei.
Es ist auch eine Tatsache, dass der einzige Weg – nach dem derzeitigen Stand der Entwicklung –, um diese Emissionen zu reduzieren, die Trennung von CO_2 aus den Abgasen und deren Speicherung im Untergrund ist. Es gibt keine andere Lösung – und diese Lösung ist technisch möglich. Zumindest in Europa erscheint im öffentlichen Bewusstsein die CO_2-Speicherung als »Endlagerung« ähnlich der Endlagerung von nuklearem Abfall gesehen zu werden.
Das wichtigste technische Anliegen bei solchen unterirdischen Speichern ist, dass bisher keine angemessene Überwachungsmethode zur Verfügung steht, um das Verhalten von Flüssigkeiten (das injizierte CO_2, ev. Wasser) in solchen unterirdischen Speichern permanent zu überwachen.
Dieser Artikel beschreibt eine Methode zur permanenten Überwachung des Speichers und des dynamischen Verhaltens der Fluide im Speicher. Diese Methode nutzt das allgegenwärtige seismische Hintergrundrauschen als Werkzeug zur Überwachung der unterirdischen Speicherung.
Die vorgeschlagene Methode beruht auf dem Aufbau eines »Forensic Event Space«, der die nahe Zukunft des Systems berechnet – auf dessen Grundlage die Entropie des Systems berechnet werden kann, und damit können Aussagen über die zukünftige Entwicklung des Systems gemacht werden.
Das Verfahren kann als Überwachungs- und Frühwarnsystem beim Betrieb von CO_2-Lagerstätten eingesetzt werden und bildet das letzte Glied in der CO_2-Prozesskette der langfristigen Speicherung.

Abstract

It is a fact that the man-made CO_2 emission contributes to global warming. In the public discussion the CO_2 emission seems to be attributed mostly to energy generation – this is only partially true because emissions from other industrial activities make significant contributions.
In the light of current knowledge and technical developments the only way to reduce these emissions is to separate CO_2 and store it underground. There is no other solution - and this solution is technically possible.
At least in Europe public awareness is considering CO_2 storage as "Final Waste Material Deposit" similar to a deposit of "Nuclear Waste".
The main technical concern for such an underground storage is that no adequate monitoring method is available to permanently monitor the fluid behavior in the underground storage.
This article describes a method to monitor the storage environment and the dynamic behavior of the fluids in storage. This method uses the omnipresent seismic background noise as a tool for monitoring the underground storage, regarded as a Technical Dynamic System.
The proposed method is based on the buildup of a "Forensic Event Space" calculating the near future of the system. The method can be used as an early warning system for storage operations.

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1 Introduction

One of the key problems of our industrialized civilization and social economic systems is the destabilization of the biosphere by man-made emissions, which can no longer be controlled and absorbed by natural processes.
Increasing emission of carbon dioxide (CO_2) has a major impact on global warming.
Significantly large quantities of CO_2 are created as exhaust gases from the global industrial production – such as cement and steel industries, but mainly from fossil fuel driven electric power plants – but also as associated gas from oil and gas production. CO_2 has not only a negative impact on the environment as the so called "Green House Gas" – CO_2 at higher concentrations is also directly "lethal" for the human body.
The increase of energy consumption goes hand in hand with the increase of CO_2 emissions and especially the decision to build more and more coal power plants is in contradiction to the overall demand to reduce CO_2 emissions.
Therefore – to reduce the emission of CO_2 into the atmosphere – industry is aiming for a method to extract CO_2 from the exhaust gases (Alstom) and capture it in large quantities in artificial storages in subsurface geological formations. Such underground storages are already geologically very well known and sometimes applied as storages for natural gas in subsurface underground formations, e. g. saline aquifers. The problem with such natural storages even for temporary deposition of waste and toxic gases is to take sufficient measures to secure the stability of such storages and to avoid uncontrolled "escapes" of the captured media. The "sealing conditions" of such natural/artificial formations have to be properly investigated and determined but the most important tool to secure uncontrolled events is to install a powerful technical control and monitoring system which can help to identify hazardous and unpredicted events and predict deviations from normal operating conditions – in advance: An "Early Warning System" for hazardous waste disposals.
The problem with these storages is the uncertainty of the cap rocks and the uncertainty of the geological and lithological sealing boundaries of the storage as well as the uncertainty of the interreactivity of different CO_2 phases with boundary spaces (Fig. 1).
To minimize the risk of unpredictable events it is mandatory to develop methods which are able to monitor the flow and behavior of fluids inside the Carbon Capture Storage as well as lithological changes and induced boundary changes.
In the public awareness an artificial Carbon Capture Storage in subsurface geological formations is considered as "Waste Disposal of hazardous material" and consequently there is a very high degree of resistance against such underground carbon capture storages – especially "not in my backyard".
To achieve public acceptance it is at least necessary to apply transparent monitoring technologies to reduce the uncertainty about the behavior of the technical storage conditions and the dynamics of the stored media.
Such a method must be able to monitor any kind of "change of conditions" over the entire storage space and its boundaries continuously and permanently during the whole lifetime of the storage.
There is a fundamental difference – philosophically – in monitoring the fluid behavior in a tank or even in an oil reservoir – where operating parameters are monitored and

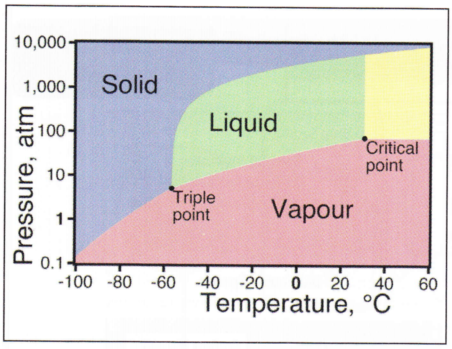

Fig. 1 **Phase diagram CO_2**
(Source: www.chemistry-blog.com)

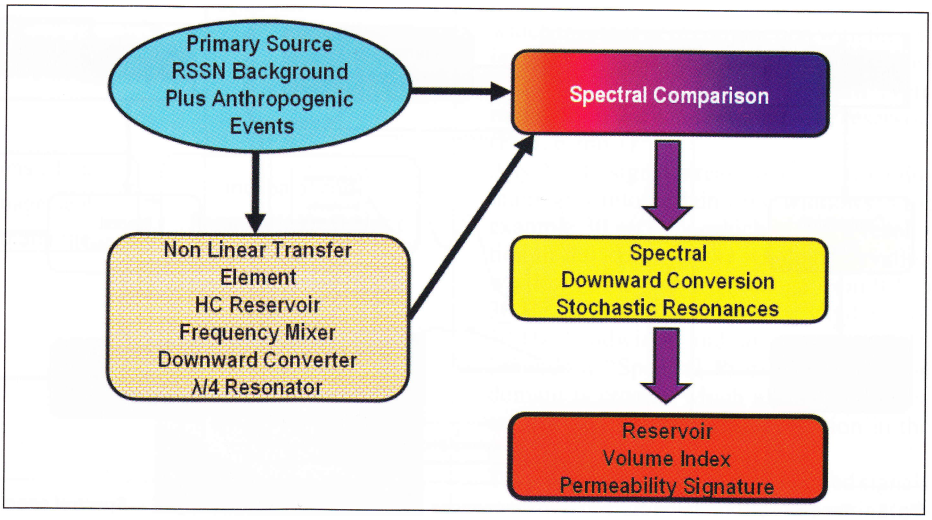

Fig. 2 **Principle of the ULF-PSSM analysis**

measured – and monitoring the fluid behavior in an artificial storage of hazardous waste material where it is not enough to monitor the prevailing operating parameters because what actually has to be monitored is the "unpredictable" since it is assumed that something might happen beyond the operating parameters; something neither expected nor predicted. Nobody knows what will happen, or how/when/where, but everybody expects that something could happen.

2 State of the Art Practice

Currently in Carbon Capture Storages observation wells are drilled mainly for permanent observation purposes and they are equipped with downhole sensors to measure pressure, temperature and other physical, chemical and electrical properties of the media surrounding the borehole.
From the total data and gradients relating to all these parameters models of the behavior of the stored media inside the storage are derived – and of course such models do not cater for the "unpredictable", which after all was the reason for monitoring and modeling. These methods in connection with modeling techniques are very well known and very useful in application as long as the storage is a known system with stable physical and chemical properties and well-defined stable boundary conditions.
A Carbon Capture Storage however represents a spatial distributed "dynamic system" with uncertain boundary conditions and the "test well monitoring concept" alone does not meet the given requirements.
The results of such monitoring methods are only reliable as long as the storage mechanism in the entire corpus behave "as modeled" but they are not able to detect phenomena beyond the models. For this reason the classical parametric methods satisfy the control of "storage tank" working conditions but they are not suited to measure or predict the "unpredicted". Also the number of test wells is limited and so is the spatial resolution.
Another class of methods can be seen in ground penetrating radar or sonar systems but unfortunately the penetration depth and spectral properties of such methods are not suited to such applications.

A further method to identify structural and impedance changes could be seen in the application of time lapse reflection seismic (4D) – however the penetration features and also the limited range of information as well as the requisite controlled source do not allow this method as a permanent and continuous monitoring tool for Carbon Capture Storages – not to mention the operation costs of such method.

3 Marmot's CCSM Technology

As a solution for a permanent Carbon Capture Storage Monitoring system Marmot's CCSM [9] provides a technical method which allows monitoring the fluid behavior inside the storage as well as structural changes using "non-invasive" technical means from the surface without penetrating mechanically into the storage space itself.
Two conditions are fundamental for such a monitoring system:

- The surveillance of the storage must be permanent and continuous and for any kind of measurement this needs a permanently and continuously operating signal source which should have no additional impact on the environment.
- The source signal must have adequate energetic and spectral "properties" to allow the signal to reach any "element" of the storage system in space and time – including the boundaries and sealing spaces.

The technical conclusion from these conditions is to use a broadband acoustic noise as source signal which is powerful and stable and generated by a permanent continuous source.
Such a source signal exists in the omnipresent and omnidirectional natural seismic background noise [1].
The principle of analysis follows here the principles of analyzing the behavior of a technical dynamic system by pulse response or "white noise" response [4].
The technical method is to record and analyze from the surface the spectral deformation of the seismic background and its changes in a frequency range between 0.1 and 30 Hz.
Any seismic signal can be construed as a convolution of a series of filters [2]:

$$W(t) = S_1(t) \cdot A_2(t) \cdot A_3(t) \cdot A_4(t) \cdot I_5(t)$$

where

- $W(t)$ Recorded signal
- $S_1(t)$ Undisturbed source signal
- $A_2(t)$ Filter characteristic of the storage
- $A_3(t)$ Filter characteristic of the cap rock
- $A_4(t)$ Filter characteristic of the transition zone between cap rock and surface
- $I_5(t)$ Instrument characteristic.

It is a fundamental criterion for a complex "Storage System" like CCS that all geological, lithological, geophysical, geochemical, and physical rock properties are well known – otherwise it doesn't make sense selecting this system and using it as a Carbon Capture Storage – as opposed to a hydrocarbon reservoir under development. And for this reason based on detailed knowledge of all storage properties it is possible to associate the system elements and its filter characteristics to the signal pattern components.
Marmot's CCSM technology is a spin-off of the ULF-PSSM – 5D Monitor [3] for permanent monitoring of producing oil fields and "Time Variant Visualization of Fluid and Non Fluid Reservoir Dynamics". This technology is based on the spectral analysis of the omnipresent and omnidirectional seismic background noise of the earth (RSSN = Random Spread Spectrum Noise).
This ULF-PSSM technology (Fig. 2) is non-invasive using the seismic background noise as source signal – it is operated with surface or near-surface broadband signal converter (Resonance Spectrometer) and it delivers a broad spectra of information from which in reservoir monitoring the following phenomena are observed and used as processing parameter:

- Frequency conversion power caused by fluid saturation parameter in porous media (non-linear transfer function for a limited frequency band)

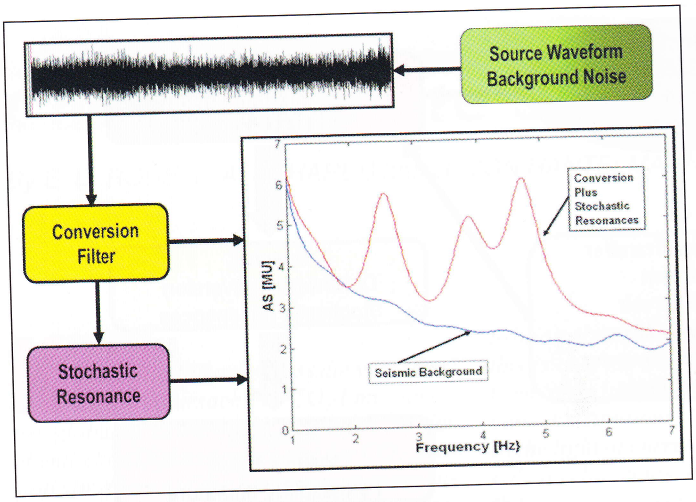

Fig. 3 **Frequency conversion & stochastic resonances**

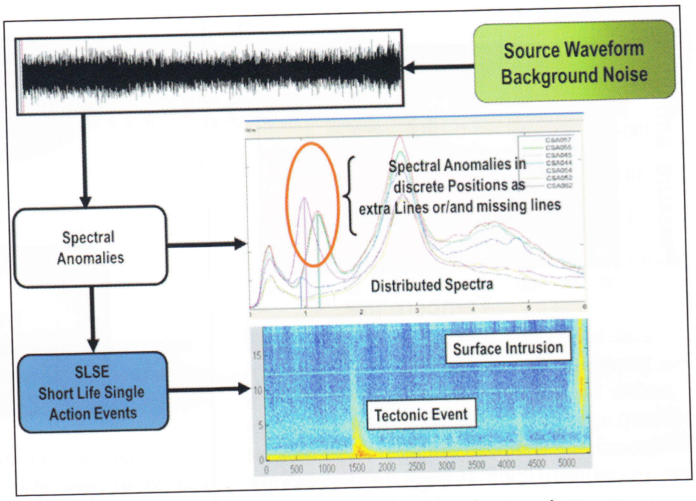

Fig. 4 **Spectral anomalies and short life single action events**

- Stochastic resonances caused by secondary permeability fluid spaces which act as $\lambda/4$ resonators and indicate rock properties [6, 7]
- Spectral anomalies indicating complex faulting systems or/and spatial rock unconformities which transform mechanical energy into chemical energy [8]
- SLSE – Short Life Single action Events indicating spontaneous lithological changes.

These observed phenomena are demonstrated and explained in the following.

The creation of sidebands caused by frequency conversion at non-linear transfer elements is a well known effect in communication instruments and electronic devices [5] but the same theory applies for acoustic wave propagation in geological formations. A fluid saturated porous "body" is a frequency converter in a distinct frequency window building lower and higher sidebands from the incoming Random Spread Spectrum Noise (RSSN) of the seismic background. At the surface these conversion products can be recorded but because of non-symmetric wave propagation in the lithosphere only the lower sidebands make a significant contribution and can be used for calculation of fluid saturation because conversion power and fluid saturation are directly related.

The second phenomenon which contributes to the analysis of rock properties – secondary permeability – is the appearance of stochastic resonances caused by fluid prone fractures where the fluid column acts as a $\lambda/4$ resonator due to its geometrical and fluid properties. Each reservoir has a characteristic resonator pattern depending on the rock properties (Fig. 3).

Figure 4 shows two more phenomena which are used as monitoring tools and for reservoir or storage characterization. Spectral anomalies as emission or absorption spectra indicate changes in the fluid – rock system which may occur in space or even in time, when system properties are changing.

The next indicator which is very important especially in CCS monitoring is the SLSE which provides a huge amount of information including indication of micro seismic or micro tectonic events caused by micro fractures or macro fractures (in the case of macro fractures we have to expect land slide, earthquakes or avalanches).

In the case of a CCS system or in general a "disposal system" these events are crucial and they have to be "captured" with 100% reliability and each of these events may happen only once – only once in the whole lifetime of the storage – or the system – and one of those events can be the trigger for the system collapse or can predict the system collapse and for this reason *permanent monitoring* is mandatory for system control – this is the same in oil reservoir monitoring but there the direct hazardous component is missing – the task is different.

4 Principles of Information Analysis

Principally we have to distinguish between signal analysis and information analysis. From the continuous signal stream information elements are separated and from those information elements an information vector

$$(x, y, z, A_1, A_2, A_3, \ldots, A_n)$$

is created. A manifold of these information vectors builds over time a so-called "event space" from which each (finite) element is attributed with a "probability"

$$\{(x, y, z, P_1, P_2, P_3, \ldots, P_n)\}(t)$$

The projection from the event space into the initial 3D cube allows the dynamic visualization of the storage "MODEL".

It is important to understand that (Fig. 5).

- The information parameter – or information vector components – are sparsely known, only a few of them (see above conversion power, stochastic resonances, spectral anomalies, SLSE) are known and others have to be learned and for this reason:
- The "event space" is a forensic n-dimensional vector array on a dynamic system which therefore allows calculation of entropy for the dynamic system – a means of 3D projection of the storage model [3, 9].
- The buildup of a forensic event space enables forward and backward modeling and also eliminates all "errors" over time and for this reason continuous data recording is mandatory to reduce the uncertainty about events which at the onset are unknown.

The schematic process flow is shown in Figure 6 and it demonstrates the incubation of the calculated entropy model into the pre determined 3D Cube.

5 Operating Method

All data are recorded by near-surface so called "signal converters" (SC) which are broadband ultra low frequency displacement receivers.

The recorded signals from the seismic background are analogue signals representing "mechanical speed" (displacement) converted into electrical signals with the dimension [V· s/m] before digitizing.

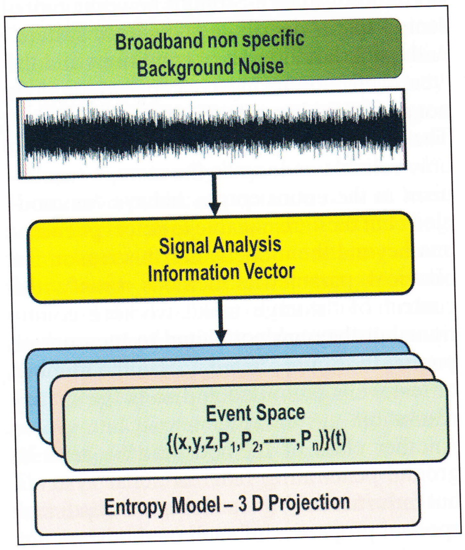

Fig. 5 **Signal information flow**

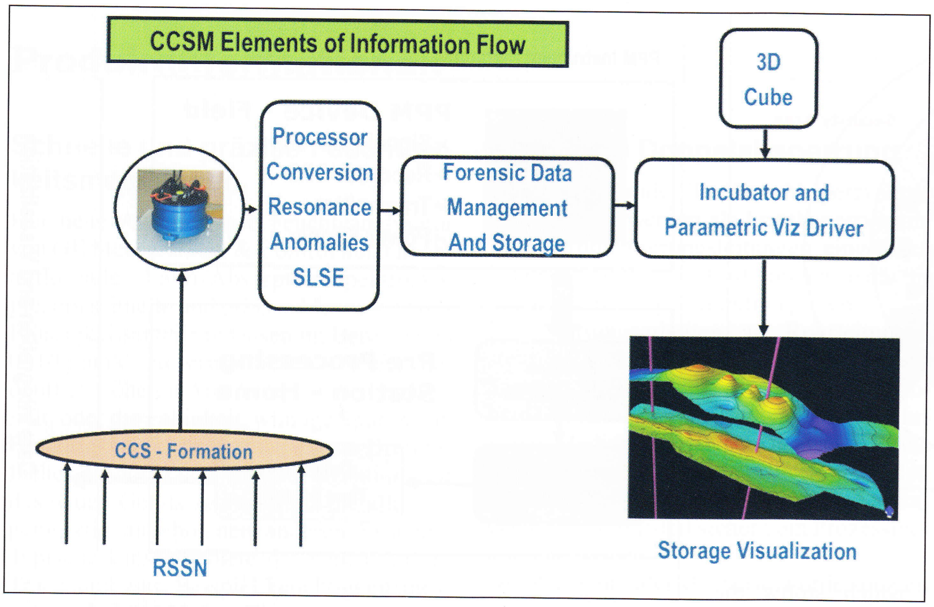

Fig. 6 Schematic process flow

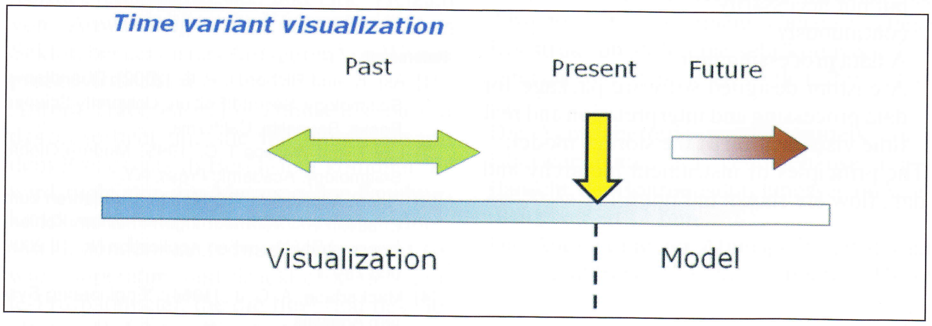

Fig. 7 Principle of time variant modeling

The data transferred to the collector from each station contain the following information:

- A converter/station identification code
- The coordinates of the station UTM
- Operating parameter for system control and maintenance
- A time marker in UTC for signal synchronization
- A continuous digital data stream with a sampling rate of 100 samples per second (SPS).

With these attributes it is possible to extract from the signals of any of the stations synchronic values of magnitude, frequency and phase of any signal at any time and thus from the complete array it is possible to derive a unique information characteristic directed in space and time – the so called "event space", which can be visualized in a 5D model.

Since the data stream is continuous it is possible to create a forensic view from the total storage development (retro perspective) which together or in conjunction with the existing static 3D structure model of the storage allows extrapolating a forward event model from the whole storage – or reservoir (Figs. 6 and 7).

Any single signal stream is in the time domain split into certain time windows – for example 30 seconds which yields a resolution of 0.03 Hz over the whole observation window in the frequency range from 0.1 to 30 Hz. With these frequency windows of 30 Hz bandwidth and an overlap of 15 seconds a "Spectral Profile" in the time domain is created which allows a forensic comparison (model) of the situation in the storage.

The information flow of the recorded signals is shown in Figure 6 and the time variant visualization of the reservoir is shown in Figure 7. This technique using a forensic event space allows an offline modeling of the whole storage space from the very beginning and a probabilistic extrapolation (entropy) of the development in the near future – at any time and for any time window (!), which allows not only extrapolation of storage modeling but also – and this is very important – permanent improvement of accuracy of the whole system. Technically this is very important for the whole storage management because this is the essence of a monitoring system – to act preventively rather than to build a failure indicator – post event.

For this reason data processing and information management are handled actually at two different levels; one is the modeling level (1) and the other is the alert level (2) for immediate interactions, which again is based on the deviations from the model derived in level 1. Processing hierarchy is shown in Figure 8.

The "system hazard alert" is of course the event which has to be prevented by the whole monitoring system but if it happens it will trigger the technically controlled shut down of the whole CO_2 "donator" system and initialize rescue actions.

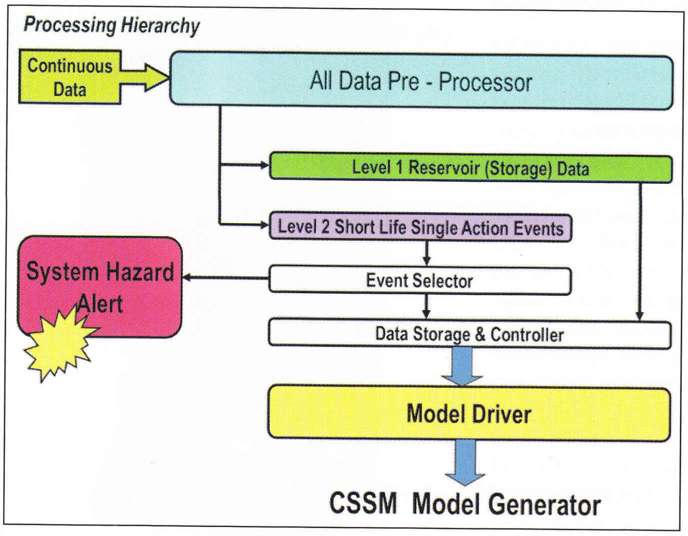

Fig. 8 Processing hierarchy

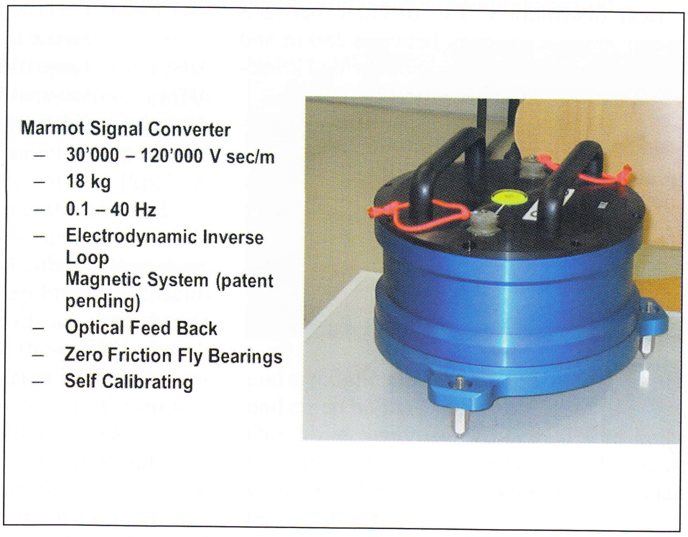

Fig. 9 ULF signal converter (Pat. Application [10])

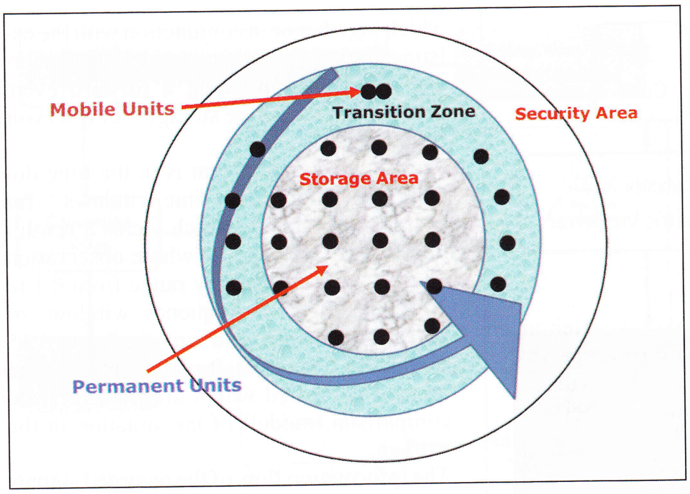

Fig. 10 Terminal array (symbolic)

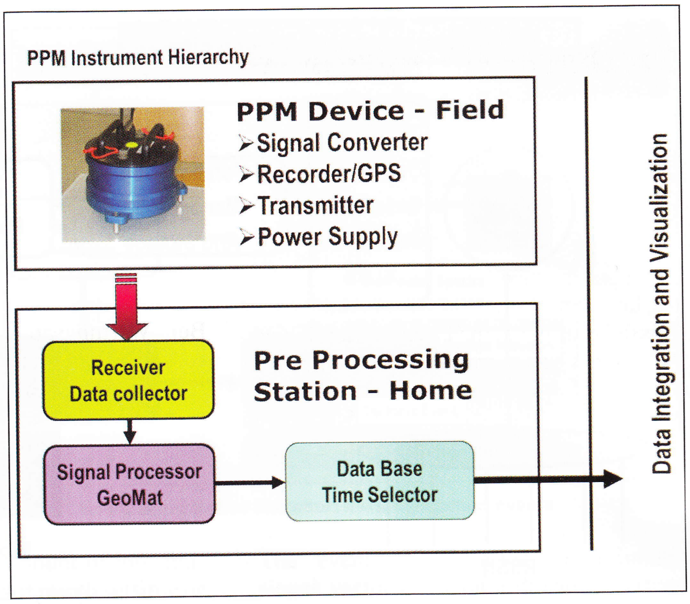

Fig. 11 Instrument hierarchy

6 Instrumentation and Set Up

The core element of the CSSM data acquisition system is the signal converter which was specially designed for ULF reservoir monitoring based on spectral analysis of the seismic background noise (Fig. 9).

The signal converter is part of an autonomous data terminal from which an array is distributed over the surface of the reservoir or storage with a minimum spacing of 250 m. The system is totally flexible and the spacing can be variable but once the array is installed the pattern should not be changed. It can however be extended without any problem – depending on the definition of the event space.

The "apparatus" for permanent monitoring installations consists in general of the following key elements:

- An array of surface mounted "signal converters" (acoustic receivers) (Fig. 9). The signal converters are hosted in a "socket" near the surface and connected to a power supply and data transfer system – collectively called "data terminals". The terminals are totally autonomous
- A grid of such data terminals is arranged over the whole area of the underground storage according to its shape and geometrical distribution. The distance between two stations can vary between 250 m and 3 km and the array might be divided in sections of different priority (Fig. 10)
- A central data collection and storage unit – which stores the data permanently but not necessarily continuously
- A data processing unit
- A custom designed software package for data processing and interpretation and real time visualization of the storage model.

The principles of instrument hierarchy and data flow are shown in Figure 11.

Abbreviations

Atm	atmospheric pressure
C	Celsius
CCS	Carbon Capture Storage
CCSM	Carbon Capture Storage Monitoring
HC	Hydrocarbon
Hz	Hertz
IPDS	Infrasonic Passive Differential Spectroscopy
MU	Measurement Units
PPM	Permanent Passive Monitoring
RSSN	Random Spread Spectrum Noise
SLSE	Short Life Single Action Event
SPS	Samples per Second
ULF PSSM	Ultra Low Frequency Passive Seismic Surface Monitoring
UTC	Universal Time Coordinated
UTM	Universal Transverse Mercator
V· s/m	Volt times second per meter.

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