Ground motion monitoring with radar technology – Case study of SAGD operations of Leismer: Results of ground motion monitoring during first year of steam injection and preliminary comparison with reservoir performance data

JOHANNA GRANDA
Altamira Information

TORE INDREITEN, Statoil ASA
KJELL MORTEN SVILAND, Statoil ASA
MARK SAVAGE, Statoil Canada Ltd
ALAIN ARNAUD, Altamira Information
GERAINT COOKSLEY, Altamira Information
ERLINDA BIESCAS, Altamira Information

This paper has been selected for presentation and/or publication in the proceedings for the 2012 World Heavy Oil Congress [WHOC12]. The authors of this material have been cleared by all interested companies/employers/clients to authorize dmg events (Canada) inc., the congress producer, to make this material available to the attendees of WHOC12 and other relevant industry personnel.

Abstract

Ground motion monitoring involves measuring the surface heave or subsidence of oil production projects with a certain frequency (e.g. monthly or every 3, 6 or 12 months) in order to retrieve spatial and temporal ground motion information that can contribute to understanding the behavior of the reservoir.

Ground motion monitoring using radar satellite technology is increasingly applied in extra heavy oil operations in Alberta, Canada, particularly in high pressure cyclic steam operations and increasingly in lower pressure Steam Assisted Gravity Drainage (SAGD) operations, to identify potential over-pressure zones, ground surface disturbance and to contribute to monitoring the integrity and safety of SAGD operations and infrastructure.

The advantage of this radar satellite technology (Interferometry for Synthetic Aperture Radar or InSAR technology) is its precision, cost efficiency and the possibility gather measurements during the whole year, even in areas that are difficult to access in summer, such as areas with muskeg, common in Alberta’s Athabasca oil sands deposits.

This paper shows preliminary ground motion monitoring results of the KKD oil sands partnership’s (KOSP’s) Leismer SAGD operations (KOSP is a partnership of Statoil and PTTEP) during its first year of steam injection. Steam injection started in September 2010 and a network of corner reflectors was installed in winter 2010/2011. Since then, ground motion has been measured on a monthly basis.

Ground motion monitoring results are compared to steam injection activities and the main uplift areas will be analyzed.

Furthermore this paper explains how measurement results are integrated into internal GIS systems and published for non-GIS expert users.

Finally the main conclusions of using radar technology for ground motion monitoring are summarized.

1 Introduction

Ground motion monitoring involves measuring the surface heave or subsidence of oil production projects with a certain frequency (e.g. weekly, monthly or every 3, 6 or 12 months) in order to retrieve spatial and temporal ground motion information that can contribute to understanding the behavior of the reservoir.

Ground motion monitoring using radar satellite technology is increasingly applied in extra heavy oil
operations in Alberta, Canada, particularly in high pressure cyclic steam operations and increasingly in lower pressure Steam Assisted Gravity Drainage (SAGD) operations, to identify potential over-pressure zones, ground surface disturbance and to contribute to monitoring integrity and safety of SAGD operations and infrastructure.

2 Overview InSAR technology

InSAR technology is used to detect millimetric ground motion. InSAR stands for “Interferometric Synthetic Aperture Radar.”

The “Synthetic Aperture Radar” is an imaging radar system mounted in this case on a satellite, and “Interferometric” refers to the superimposition of waves to detect differences over time in fractions of wavelength.

These satellites capture images by precisely recording the travel phase between ground surface and sensor. If several measurements are compared over time, the difference between measurements indicates ground motion over time. Additional effects have to be filtered such as atmospheric changes and position of the satellite.

2.1 Radar satellites

Radar satellites continuously orbit the earth on a fixed polar orbiting track, taking more or less 100 min to complete one full orbit. Since the earth is rotating below the satellite, its path successively moves around the globe, meaning that over time satellites build up complete images of the whole globe. The satellite revisits the same location after some 11 to 46 days, depending on the satellite.

For ground motion monitoring, the following radar satellites are available: The new generation X-band satellite constellations, such as the TerraSAR-X satellites (2 satellites) launched in 2007 and Cosmo-SkyMed satellites (4 satellites) launched between 2007 and 2010, and also the C-band satellite Radarsat-2 (1 satellite) launched in 2007.

For all three systems, the launch of new generation satellites are planned in the near and mid future to secure the continuity of data availability.

2.2 Ground motion measurements

To measure ground motion with millimetric precision, several satellite images covering a series of dates are acquired and processed using the Stable Point Network processing chain.

The Stable Point Network is an advanced differential interferometric processing technique developed by Altamira Information. It is the result of several years of research projects in the DInSAR data analysis field for the CNES (French Space Agency) and ESA (European Space Agency) and today fully operational and validated with traditional ground motion techniques.

One important characteristic of the chain is its flexibility: the software can work with images of any radar satellite, at any resolution and with any extracted pieces of images.

Ground motion measurement results are delivered in the form of ground motion maps where every identified measurement point is shown in a scale of colours indicating the average yearly ground motion rate for that point during the period of analysis.

Furthermore, time series are delivered for each measurement point, indicating the exact ground motion evolution over time.

2.3 Natural measurement points versus Corner Reflectors

Radar measurement points can be of two types: So-called “natural measurement points” are existing radar signal reflection points, such as facilities, roofs, metallic structures, bare, cleared and rocky ground.

![Fig. 1: Radar satellites TerraSAR-X, Cosmo-SkyMed and Radarsat-2](image)

The advantage of these measurement points is that measurements can take place without any installation, since pre-existing measurement points act as radar reflectors. There is even the possibility to measure ground motion in the past, since archive images are available for most areas worldwide from 1992.

New images can be acquired every 1 to 46 days (depending on the satellites used).

The limitation of basing measurements on natural points is that at minimum amount of 12-20 images is required to identify the measurement points and to obtain reliable measurement results.

In areas where there is an absence of natural measurement points, such as areas with forests or dense
vegetation, often characteristic of the areas of heavy oil production in Alberta, Canada, the alternative is to install “Corner Reflectors”. These reflectors are aluminium trihedrals that are installed and oriented towards the satellite to ensure measurement points.

The advantages of Corner Reflectors are the following:
- They provide measurement points in areas lacking a presence of natural measurement points.
- First measurement results can be obtained soon after the acquisition of 4 to 6 images, since the exact measurement point location is already known.
- Furthermore, updates with Corner Reflectors can be frequent (e.g. every week or every month).
- The measurement points are well grounded on piles to minimize the influence of freezing and thawing periods on ground motion results. These reliable measurement points reflect a strong signal to the satellite and can be measured during all seasons, regardless of snowfall.

Most ground motion monitoring projects in heavy oil extraction areas in Alberta measure with Corner Reflectors to provide high measurement frequency and reliable measurement points during the whole year. Natural points are mainly used in combination with Corner Reflectors in order to increase the spatial coverage of measurement points.

It is also possible to use only natural points, however the density and reliability of measurement points depends a lot on the site characteristics such as density of vegetation, ground conditions (muskeg, or wet ground, snow in winter), and the magnitude of the deformation signal to be measured.

3 Ground motion monitoring results for Leismer SAGD operations

3.1 Introduction to the Leismer reservoir

KOSP is developing the Leismer in-situ facility (approximately 100 km south of Ft. McMurray and 25 km north-west of Conklin) as part of their overall Kai Kos Dehseh oil sands project. The plant is employing Steam Assisted Gravity Drainage (SAGD) to recover bitumen with a nameplate capacity of 1,590 m³psd (10,000 bpsd) of bitumen.

The ambition for KOSP is to achieve a production of 200,000 bpd from oil sands upstream post 2020. The current plan is to develop this area through a staged process, where the Leismer Demonstration Plant (LDP) has been the first stage in the total field development of several bitumen upstream hubs and other future mid- and downstream solutions.

Reservoir depth is about 424 m and first steam injection started in Q3 2010.

3.2 Ground motion monitoring results using Corner Reflectors

In March 2011, 89 Corner Reflectors were installed on the Leismer Demonstration Plant, covering the first 4 well pads with their 23 well pairs and the primary steam pipeline.

The resulting network is quite dense, especially in the East-West direction. The rationale for designing such a high density network for the Leismer Demonstration Plant was twofold:
- In case of ground motion, to be able to deduce which well pair is causing the ground motion: Therefore the location of a Corner Reflector over each well pair and in between each well pair.
- To assess the optimal Corner Reflector density for expansion areas in the future: Only by installing a dense network, can any differences in ground motion monitoring results for Corner Reflectors located near to each other be identified.
InSAR ground motion monitoring updates of Corner Reflectors are delivered every month. Each update is based on 3-4 new radar images.

The satellite used for these updates is the X-band satellite constellation Cosmo-SkyMed. Given that this constellation consists of 4 radar satellites, a new image can be acquired every 1 to 8 days.

The advantage of using several images per measurement update is that measurement results provide an accurate account of ground motion over time; they rely on information from dates spread out over the period of study, rather than just one new image.

The use of a satellite constellation also means that should one or more of the satellites fail to deliver images temporarily or permanently then data is still available from the remaining satellites of the constellation (data from the satellite constellation is compatible and directly interchangeable).

Ground motion measurements using Corner Reflectors during the first year of measurement are presented in the following illustrations, quarter by quarter (Q2, Q3 and Q4 2011 and Q1 2012).
Overall, the highest heave values are identified in the center of the well pad areas. The Eastern and Western outer edges are quite stable.

The results show that ground heave accelerated during the first quarter of 2012.

During the first year of monitoring, ground heave reached a maximum rate of 25 mm per year (Corner Reflector in area “A” in Fig. 10) with an acceleration of heave during the last quarter:

![Fig. 11: Time series for Corner Reflector in Area “A” of Fig. 10 (Corner Reflector with maximum heave during first year)](image)
Subsidence can be observed on the Corner Reflector in area “B” of Fig. 10. However this subsidence area has been stabilizing over the last four months, and is judged to be unrelated to the SAGD operations, but rather linked to groundworks:

In terms of spacing of Corner Reflectors, in area “C” of Fig. 10 it can be observed that Corner Reflectors located close together (with approximately 50 m between each other) do measure local differences in the heave monitored:
- The western-most Corner in area “C” indicates a heave of 15 mm with most heave acceleration during Q4 2011.
- The Corner Reflector in the center of area “C” is quite stable, with light heave of 8 mm over the course of the whole year.
- The Corner Reflector located to the East of area “C” was quite stable at the beginning of the study and has experienced accelerated heave during the last month so that, in total, heave during the year reached nearly 15 mm.

Even in a relatively deep reservoir of more than 400 m, such as Leismer, ground motion monitoring results can be different for Corner Reflectors located close to one another (50 m). Therefore the denser the Corner Reflector network, the more differentiated ground motion information can be retrieved. The only disadvantage of a denser network is the higher installation costs (additional piling and reflector production and installation costs) and increased surface disturbance.

A common approach for oil operators is to install a denser network during the first phase of a project in order to closely observe ground motion and the specific characteristics of the reservoir that may be affecting this motion, and then to decide later upon the optimal reflector density for the expansion areas.
3.3 Results with Natural Measurement Points in combination with Corner Reflectors

In addition to the Corner Reflector study, a Natural Measurement Points study has been conducted:

Ground motion studies based on Natural Measurement Points complement the measurements obtained with Corner Reflectors since they cover a wider area with no need for any on-site installations. In Figure 17 strong heave area in the center of the wells is even stronger slightly further South; this result was only detected with the addition of a study based on Natural Measurement Points. Additionally, the extension of the subsidence area in the Northeastern area is well mapped with the Natural Measurement Points Study.

However in winter (Figure 17), some Natural Measurement Points are lost; the coverage of Natural Measurement Points in winter is worse than in summer (Figure 16) due to the impact of snow on the ground; the natural reflectors that remain are more related to structures.

The Natural Measurement Points study can take advantage of the Corner Reflectors installed by utilizing them as a reliable starting point from which the SPN technique can be applied to extract those natural reflectors in the region. The SPN analysis of Natural Reflectors does reveal a few regions where the results differ slightly - due to the fact that Corner Reflectors are well grounded and measure mainly the underlying SAGD heave, and are therefore not affected by seasonal heave, which can dominate the Natural Reflectors signal.

4 Preliminary comparison of InSAR ground motion results with reservoir performance data

A one-year period of study of ground motion monitoring measurements is quite short to deliver a complete comparison of InSAR results with reservoir performance data (mainly steam injection rates). However, a preliminary analysis has been conducted for each well pad. In Figure 18 the ground motion monitoring results are shown with an index of the different well pads.
The L1-L4 scheme performance until January 2012:

Comparing the performance rates of the four well pads, it can be seen that Pads L1 and L3 have the highest steam injection rates whereas steam injection rate for Pad L2 is slightly lower. The lowest steam injection rate obtained was for the case of Pad L4.

This data appears to correlate with ground motion monitoring results. Pads L1 and L3 show globally the highest uplift while Pad L2 shows uplift in the western area located next to Pad L1, however the eastern area is quite stable. Finally, Pad L4 shows stability with exception of the southern area, which can be influenced by the uplift of Pad L1.

These conclusions are still preliminary since one year is a short time to undergo complete comparisons when the measured motion until Q4 2011 hardly reaches 10 mm. In addition, the steam injection started at different dates for each Pad. However, this first correlation between steam injection and uplift shows that InSAR ground motion monitoring results may contribute to the location of steam chambers.

5 Integration of InSAR ground motion monitoring results into the internal Statoil GIS and Webmap

After delivering InSAR ground motion results on a monthly basis, they are implemented in the internal Statoil Geographical Information System (GIS) and stored in the corporate Statoil GIS database. The GIS database does not only include InSAR data but also additional data about the reservoir, for instance information about the existing pipeline infrastructure within the license area.

All geospatial information is furthermore published in an internal Statoil Webmap to give easy access of data to non-GIS expert users with the advantage to easily handle and distribute ground motion data to everybody involved in the project.

An example of InSAR results together with horizontal well locations published in the internal Statoil Webmap is illustrated in Figure 23: Ground motion of Corner Reflectors is shown with colored circles. The red dots indicate the location of Natural Measurement Points. And for the corner reflector highlighted with a white square the evolution of ground motion is mapped:

Fig. 19-22: Scheme Performance Pads L1-L4

Fig. 23: InSAR results published in the internal Statoil Webmap
6 Outlook for the future

Ground motion measurements with InSAR technology will continue on a monthly basis during the following years.

The goal for the future is to integrate InSAR ground motion results with 4D seismic data and other available data sources in order to get a complete view of the impact of steam injection and oil production activities on its surroundings.

7 Conclusions

InSAR has proven to be a useful technique for detecting and quantifying ground motion in SAGD operations.

The density of a Corner Reflector network depends on the monitoring requirements; the denser the network, the more detailed and localized the information that will be obtained.

The frequency of ground motion measurement updates is flexible and can be adapted to the project’s requirements; updates can be provided with a frequency of e.g. one week, one month, 3, 6, or 12 months.

In order to provide measurement updates every one to four weeks, the X-band satellite constellations are recommended because of their high image acquisition frequency; in order to obtain the most reliable measurement results possible, at least 3-4 new images for each monthly update are recommended.

The best results in terms of precision, update frequency and spatial coverage are achieved by combining studies with both Corner Reflectors and Natural Measurement Points.

By comparing ground motion results with reservoir performance data (mainly steam injection rates), existing correlation between steam injection and heave shows that InSAR ground motion monitoring results may contribute to the location of steam chambers.

The integration of InSAR ground motion data into internal GIS systems and publication of integrated data into an internal commonly accessible Webmap helps to distribute results to all the people involved in the project, including non-GIS expert users.

Acknowledgement

Altamira Information would like to thank the KKD Oil Sands Partnership (PTTEP and Statoil) for the opportunity to publish these results of InSAR ground motion measurements for the Leismer SAGD operations.

Nomenclature

CNES = Centre d’Études Spatiales (French Space Agency)
CR = Corner Reflector
ESA = European Space Agency
GIS = Geographical Information System
DInSAR = Differential InSAR
Fig = Figure
InSAR = Interferometric Synthetic Aperture Radar
KKD = Kai Kos Dehseh
KOSP = KKD Oil Sands Partnership
LDP = Leismer Demonstration Plant
M = Meter
PTTEP = PTT Exploration and Production Public Company Limited
SAGD = Steam Assisted Gravity Drainage
WHOC = World Heavy Oil Congress