

Oil Field Deformation Monitoring with RADARSAT-2*

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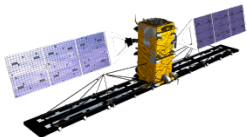
Abstract

The focus of this study was to use InSAR to monitor surface deformation that occurs when bitumen is extracted using a process termed Cyclic Steam Stimulation (CSS). CSS results in significant volumetric strain of the reservoir, so deformation is of interest. The surface deformation can provide insight into the recovery process effectiveness, casing, and surface facility integrity.

The approach entailed the installation of corner reflectors on pipeline-pilings which respond to the surface deformation induced by the CSS process. RADARSAT-2 UltraFine data were acquired every 24 days. MDA-developed InSAR algorithms were applied to the data to estimate millimeter-scale surface deformation. A reservoir dilation model was used to calculate the amount of surface heave and the model results were compared with the InSAR measurements. The model had a number of variable parameters of which the initial pore pressure, the failure pore pressure, and the dilation between the initial and the final pore pressures are the most significant.

There was good agreement between the InSAR and model with respect to surface heave or subsidence, but not with the magnitude of the deformation. To better understand why the magnitude differed, two wells were analyzed. For study well F07, using the standard parameters for the dilation calculation, the heave model only predicted ~30 mm of heave versus ~120 mm of InSAR-measured heave. Good agreement between the model and InSAR was obtained if the dilation prior to fill-up was increased to account for the larger depleted zone of a late-cycle CSS well. For study well U, the heave model predicted over 110 mm of heave versus ~80 mm from InSAR. Good agreement was obtained if the dilation at fill-up was eliminated since the steam was injected into a new reservoir.

A geomechanical heave model is a valuable predictive tool for enhanced oil recovery operations; however each well has different steam chamber and overburden structure and responds differently to steaming. InSAR deformation measurements can be used to improve a heave model using physically meaningful calibration parameters and to monitor the surface deformation over time to verify the heave model's predictive accuracy.



Oil Field Deformation Monitoring with RADARSAT-2

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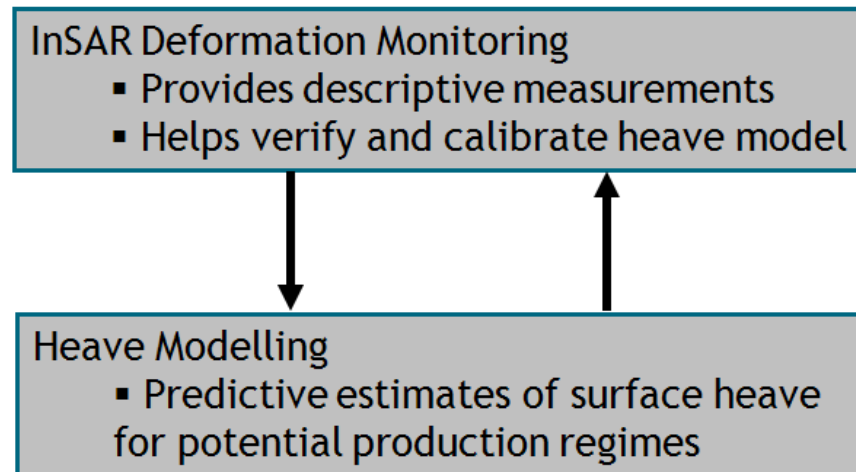
Outline

- Introduction
 - Study site
 - Corner reflector installation
 - InSAR concepts
- Heave Model
- Results
- MultiTrack InSAR
- Summary

Introduction

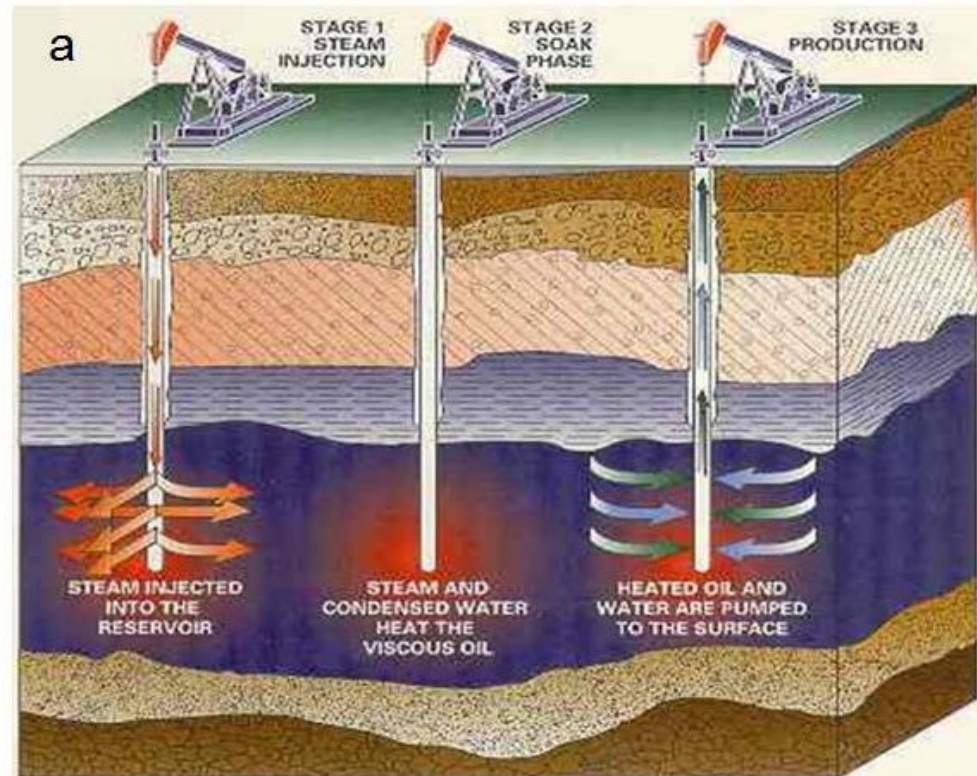
- The objective of this project was to assess the integration of spaceborne InSAR and a geomechanical model to understand and measure ground deformation from the Cyclic Steam Stimulation (CSS) process that is used to extract bitumen.
- CSS results in significant volumetric strain of the reservoir which can result in surface heave. Measuring the surface heave can provide insight into:
 - recovery process effectiveness;
 - casing and surface facility integrity;
 - environmental impacts.

- Approach:

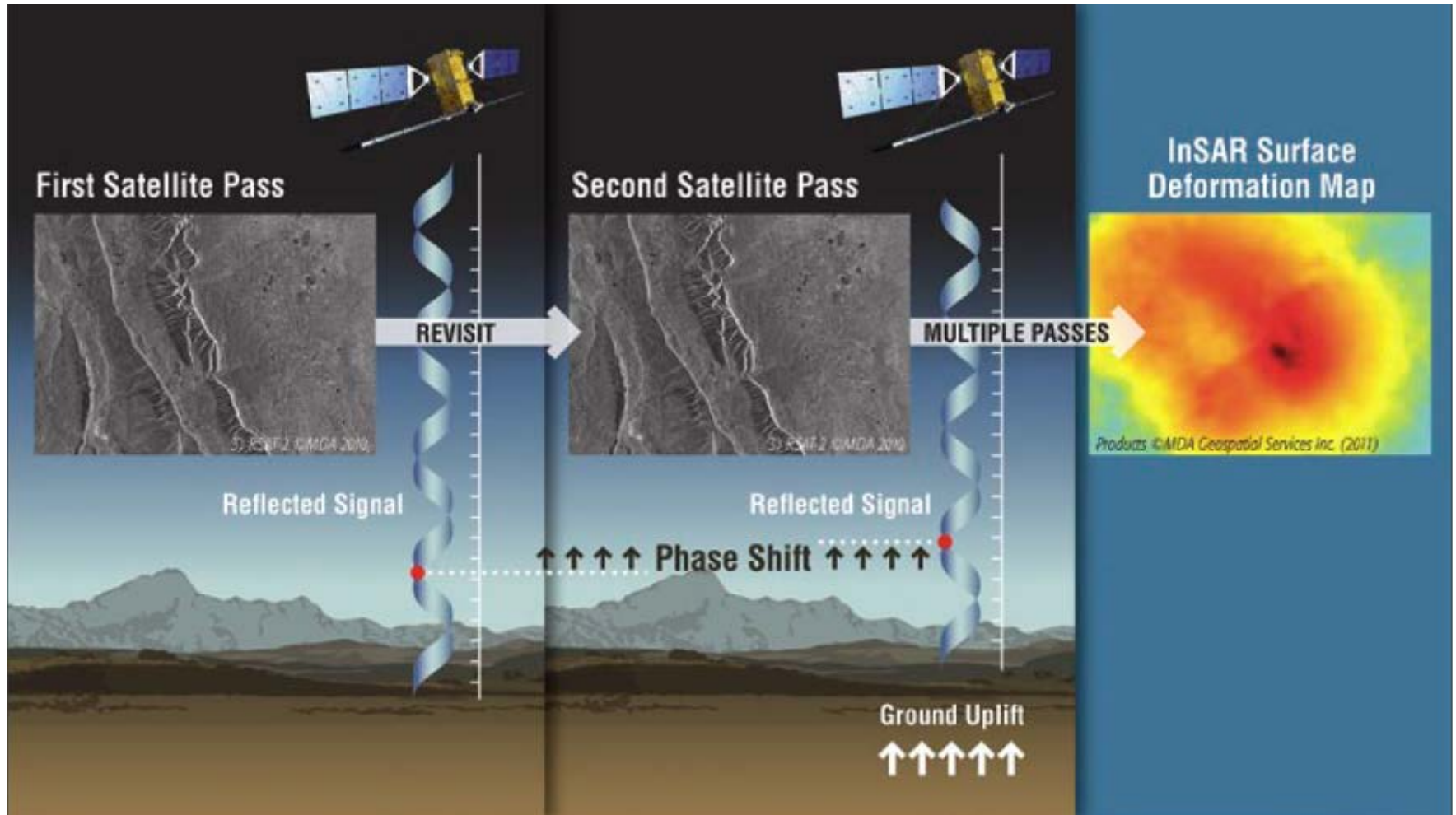


Bitumen Extraction: Cyclic Steam Stimulation

- The Cyclic Steam Stimulation (CSS) process to extract bitumen consists of three phases:
 - Steam Injection.
 - Soak.
 - Production.
- The purpose of the steam injection phase is to supply heat to the reservoir in order to mobilize the bitumen by lowering its viscosity.
- During the steam injection phase, the reservoir undergoes significant volumetric strain (dilation) which leads to surface heave.
- The maximum surface heave for one steaming cycle (months) could be as large as 30-40 cm.

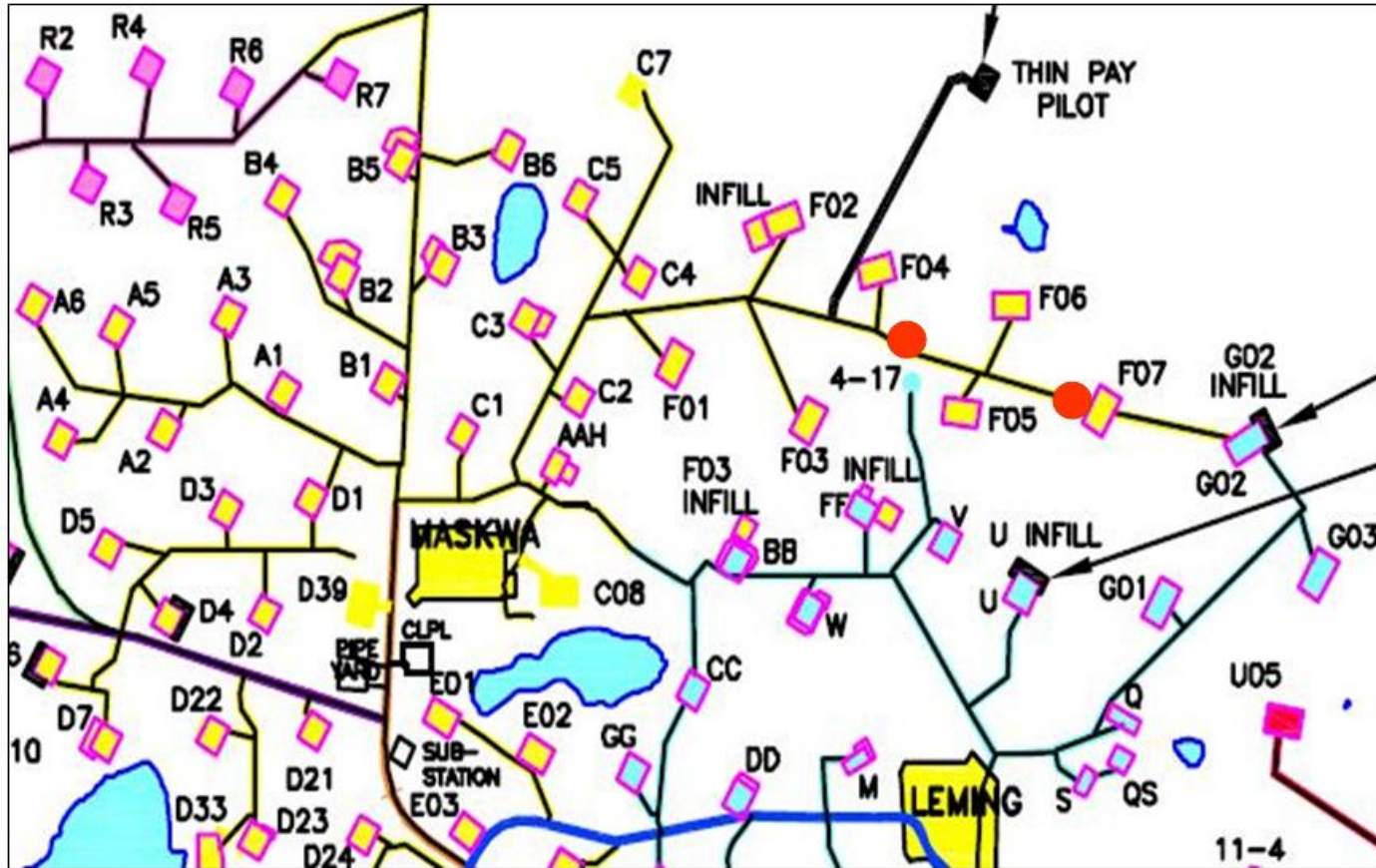


InSAR: The Basics



Study Site

Cold Lake, Alberta, Canada



Ten corner reflectors were installed along the F-Trunk pipeline starting at F07 and ending close to F04 (red-coloured dots). The corner reflectors have a spacing of ~150 m.

F-Trunk Steam Line showing Corner Reflectors

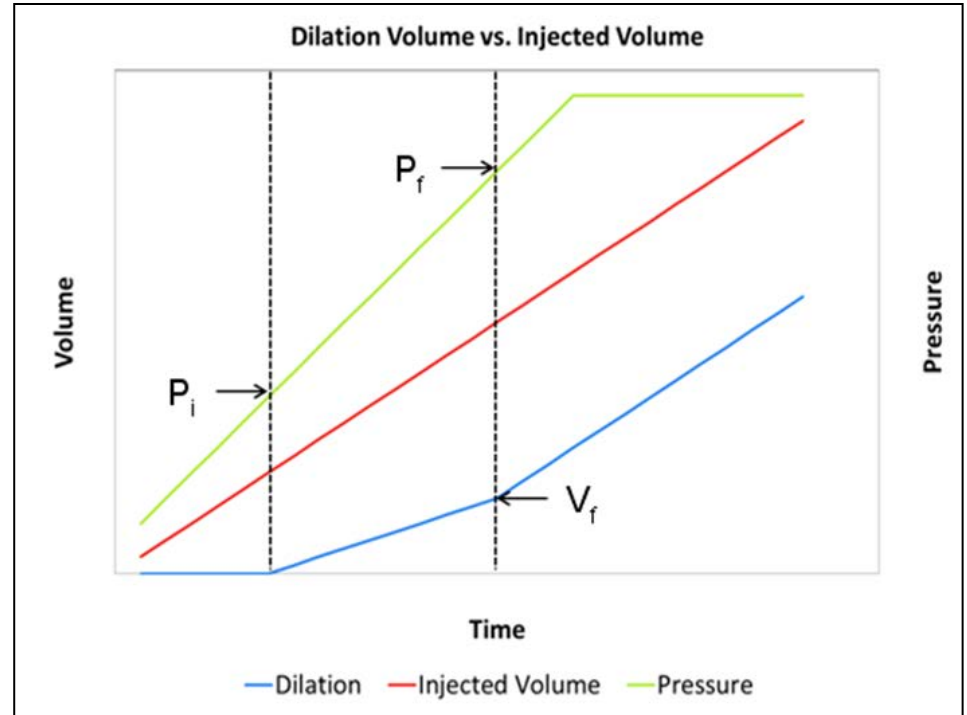




Photograph of installed corner reflectors (left). The cover is radar-transparent and designed to keep snow from accumulating in the base of the reflector. Detail view of the top mount (top right). The ~1 m long mounting pole is attached to the pipeline sleepers (bottom right).

Heave Model

- The surface heave is calculated with an analytical function that relates heave to dilation volume.
- The amount of dilation caused by steam injection depends on the injection pressure :P
 - $P < P_i$ no dilation.
 - $P_i < P < P_f$ elastic strain.
 - $P > P_f$ plastic strain.
- The total surface heave is calculated by superimposing the heaves induced by each well.

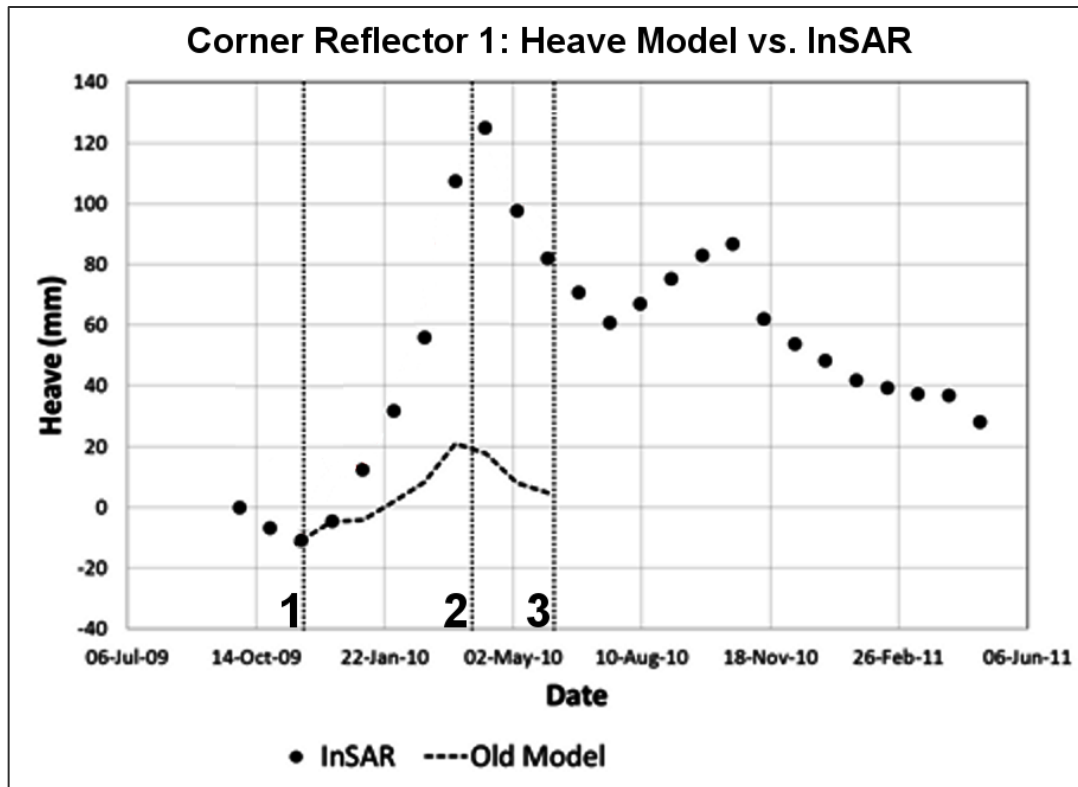


Injected Volume - Known
Pressure - Known
Dilation Volume - Modelled

P_i - Initial pore pressure
 P_f - Fill-up pressure
 V_f - Dilation volume prior to fill-up

Initial Results: Model vs. InSAR

- The InSAR results captured the steaming cycles, but either over or under predicted the magnitude of the heave with-respect-to the model.
- The performance of the InSAR had been validated thus suggesting the discrepancy was due to erroneous assumptions with-respect-to the model parameters.



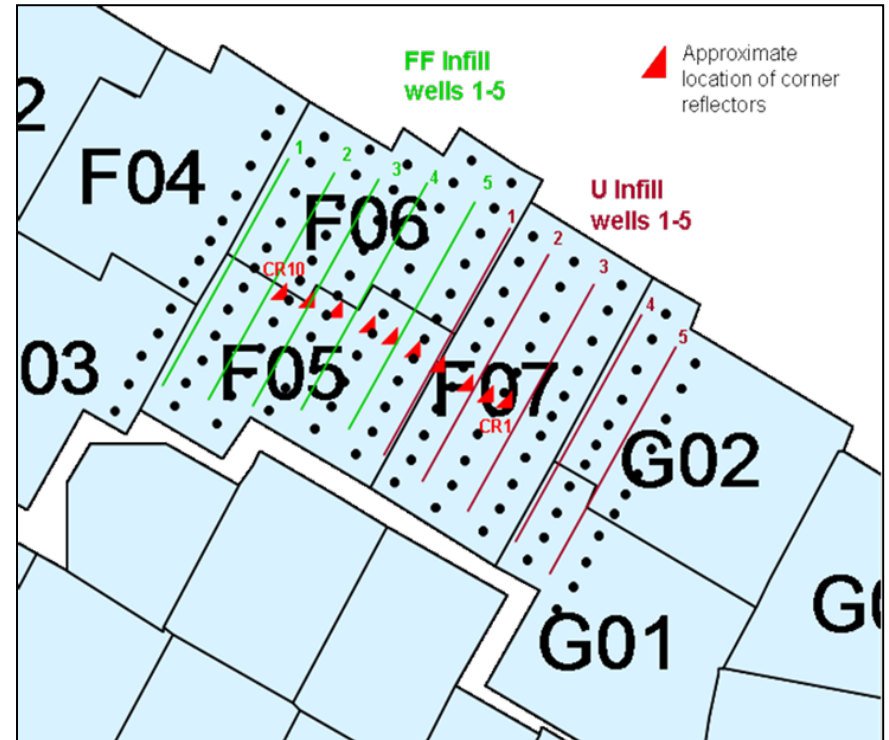
- Stages of Steaming:
1. Steaming starts
 2. Some wells shut in
 3. All wells shut in

Investigation of Heave Model Parameters

InSAR and Heave Model Comparison

- There were three significant steaming events during the period of InSAR heave measurements at F Trunk.

	Start Date	End Date
FF Infills:		
Large volume, low pressure.	02/2009	03/2010
F07 Pad:		
Large volume, low pressure.	11/2009	06/2010
U Infills:		
Low volume, high pressure.	08/2010	10/2010



Map of F trunk showing the bottom-hole locations of the CSS wells for F05, F06, and F07 pads, the approximate location of the FF and U horizontal infill wells, and the locations of the 10 corner reflectors.

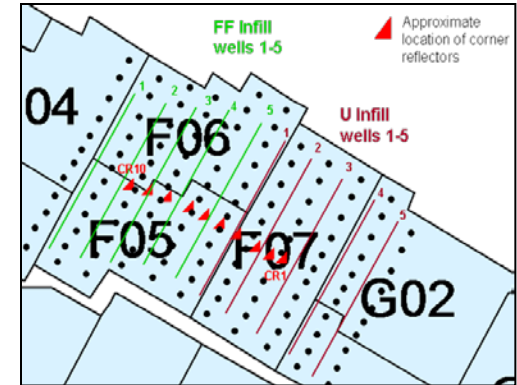
Results: F07 Pad

InSAR Measurements:

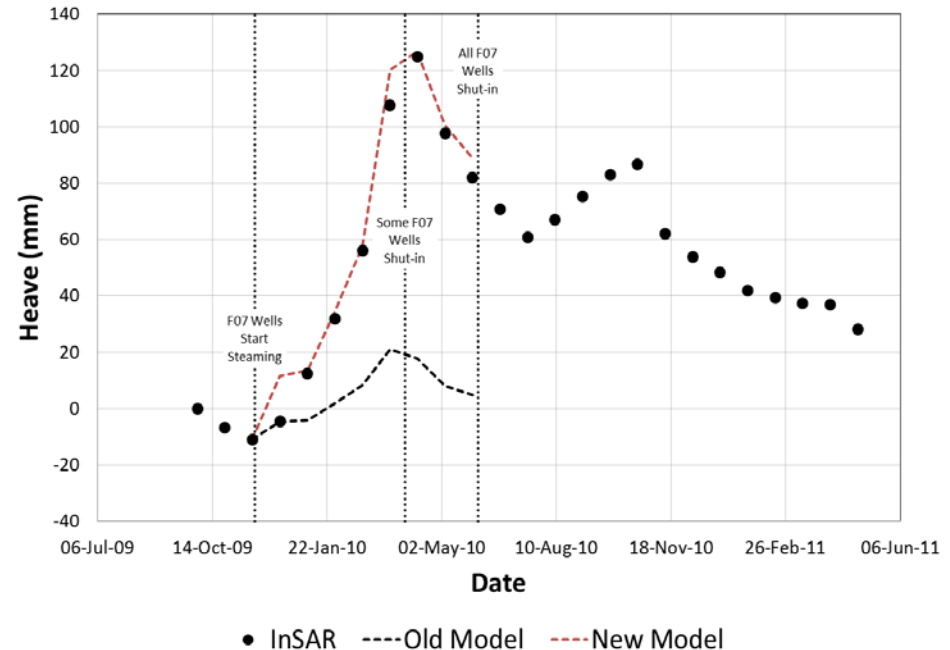
- Surface heave of ~130 mm
- Heave response lines up with steam timing.

Heave Model:

- With the standard parameters for the dilation calculation, the heave model only predicts ~30 mm of heave.
- To obtain a match:
 - The dilation prior to fill-up was increased to account for the larger depleted zone of a late-cycle CSS well.
 - A lower fill-up pressure was used (based on previous studies)



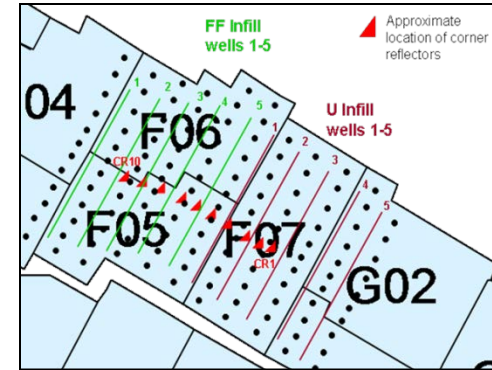
Corner Reflector 1 Response to F07 Steaming (COE)



Results: U Infills

InSAR Measurements:

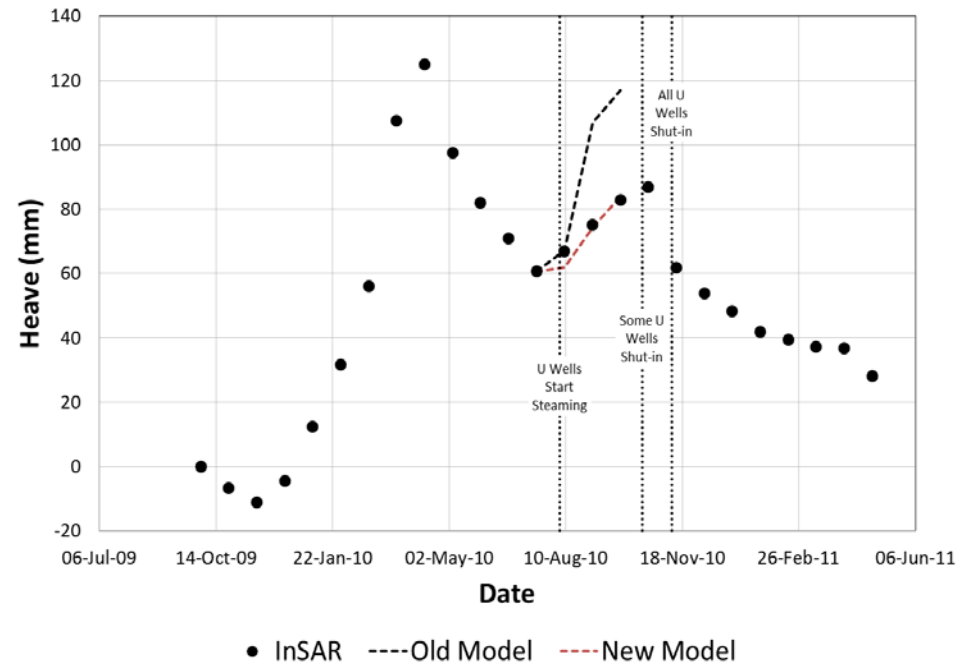
- ~30 mm of heave during U infill steaming.
- The measured heave response lines up with steam timing.



Heave Model:

- With the standard parameters for the dilation calculation, the heave model predicts over 60 mm of heave.
- To obtain a match:
 - The dilation at fill-up was eliminated since the steam was injected into a new reservoir.
 - The same lowered fill-up pressure was used as for the F07 model.
- A good match was obtained despite the added uncertainty in the reservoir pressure due to steam injection through horizontal infill wells.

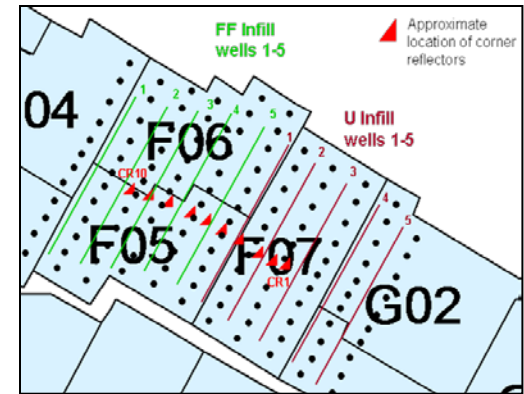
Corner Reflector 1 Response to U Infill Steaming (COE)



Results: FF Infills

InSAR Measurements:

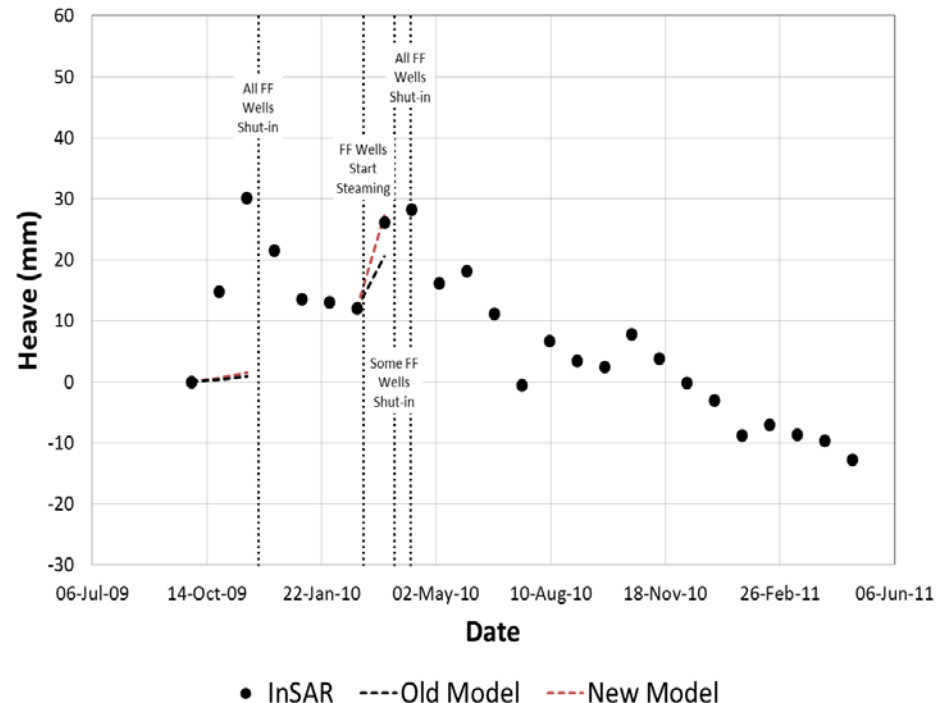
- ~30 mm during the first wave of FF infill steaming, and ~20 mm of heave during the second wave.
- The measured heave response lines up with steam timing.



Heave Model:

- No physically realistic combination of parameters could be found to match the first steam injection.
- The uncertainty in the reservoir pressure introduced by steaming through horizontal wells is most likely the cause of the discrepancy.
- The magnitude of the heave during the second wave of steam can be matched, but since there is only one data point, the result is not significant.

Corner Reflector 7 Response to FF Infill Steaming (COE)

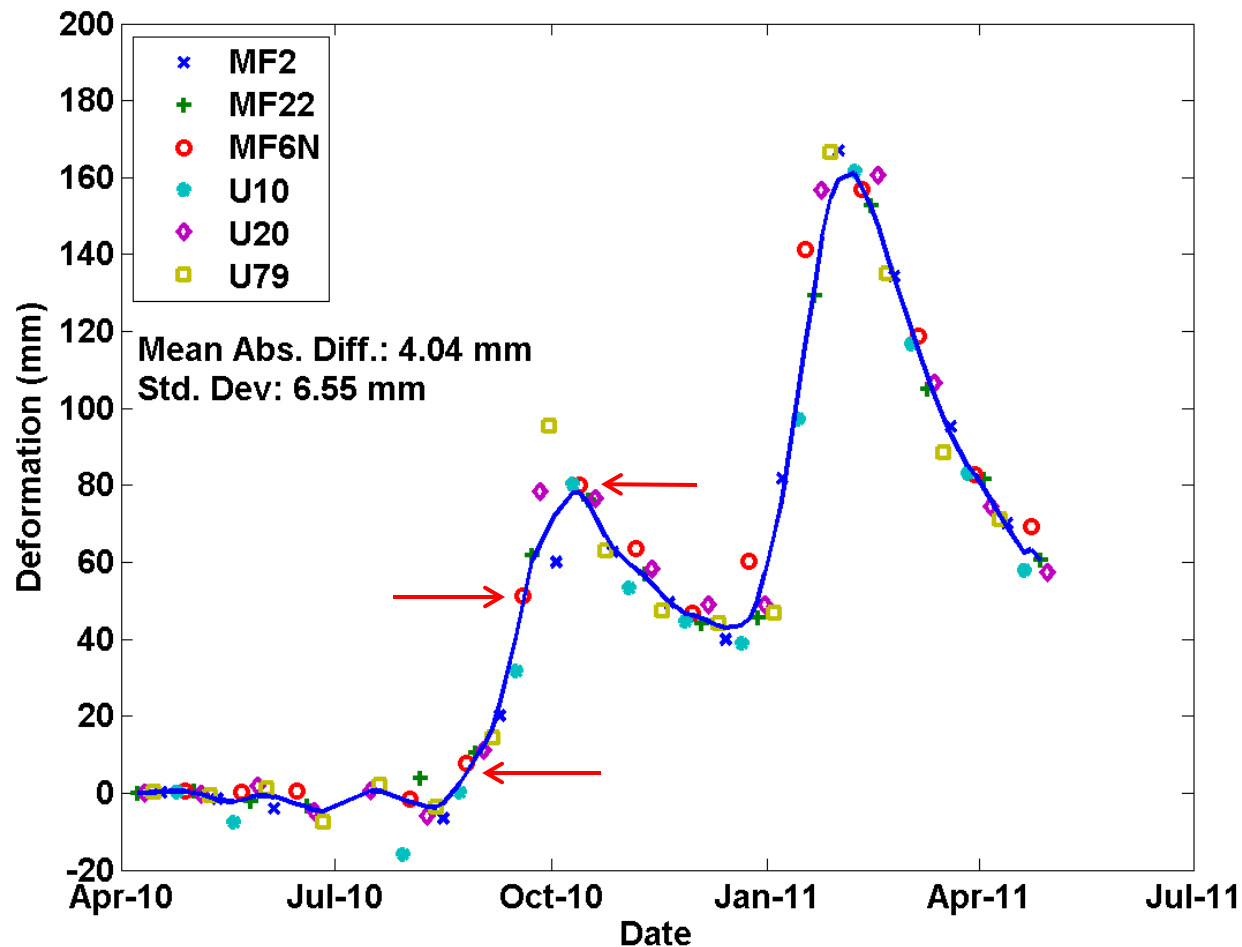


MultiTrack InSAR

- An operational limitation of the use of spaceborne SAR for InSAR deformation mapping rests with the re-visit frequency of the sensor.
- To address this constraint, a cross-correlation technique was developed that increased the temporal resolution by combining different imaging modes and different sensors¹
- Benefits:
 - Very high temporal resolution (days) which is important in regions of rapid deformation
 - Increased temporal information leads to improved operational information
 - Seamless integration of different RADARSAT-2 imaging modes and different SAR sensors, e.g. TerraSAR-X and Cosmo SkyMed and the planned RADARSAT Constellation Mission.

1. Deschamps, B.; Henschel, M. D.; Walter, G.; Chen, J.; Sato, S. & Gravelle, S., Multi-sensor/multi-beam InSAR ground deformation monitoring of water-flood oil Fields, *Proceedings of the 7th International Workshop on the Analysis of Multi-temporal Remote Sensing Images*, 2013 .

Increased Temporal Resolution with MutliTrack InSAR



Henschel, M. D. & Lehrbass, B., Operational Validation of the Accuracy of InSAR Measurements over an Enhanced Oil Recovery Field, *Proceedings Fringe 2011*, 2011

Summary

- A geomechanical heave model is a valuable predictive tool for enhanced oil recovery operations, however:
 - Each well has different steam chamber and overburden structure and responds differently to steaming
 - A well's steam chamber structure changes over time
 - There is increased well-connectivity as the reservoir ages
- InSAR deformation measurements can be used to improve a heave model using physically meaningful calibration parameters and continuously verify the heave model's predictive accuracy
- InSAR can be used to:
 - Ensure well casing and facility integrity
 - Evaluate enhanced oil recovery effectiveness
 - Assess and mitigate environmental impacts
- MultiTrack InSAR can be used to increase the temporal sampling which is important in areas where changes occur on the order of many days.