Using Low-frequency Fiber-optic DAS for Slow Deformation and Geomechanical Monitoring

Verónica Rodríguez Tribaldos
(and many collaborators)

DAS Virtual Workshop and Tutorial
August 17th, 2020
DAS: Much More than a Broadband Seismic Array

DAS is a broadband sensor commonly used for seismological applications:

- Active seismic exploration (e.g. VSP) - f > 20 Hz
- Traffic noise interferometry - f ~ 5-30 Hz
- Earthquake detection - f < 1Hz
- Hydraulic tests, long-term deformation – periods > 100 s

DAS response is flat at low frequencies ⇒ we can potentially measure near-DC strain

Lay and Wallace (1995)
Lindsey and Martin (2018)
Lindsey et al. (2020)
Paitz et al. (2020), under review
Applications of Ultra Low Frequency DAS Analysis

- Hydraulic fracture geometry characterization – Jin and Roy (2017), The Leading Edge
  - **Experiment:** DAS in monitoring wells during stimulation of an adjacent well
  - **Acquisition parameters:** spatial sampling of 1 m, gauge of 5 m, sampling frequency of 10 kHz
  - **Processing:** downsampling (1s) followed by median removal and low-frequency filtering (0.05 Hz)

**Observations:** fracture dynamics (opening/closure), stress shadow creation and relaxation…

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[Diagram of DAS monitoring setup and fracture dynamics]

**Integration to strain**
Applications of Ultra Low Frequency DAS Analysis

- **Strain at Earth tides frequencies** – *Becker and Coleman (2019), Sensors*
  - **Experiment**: measuring oscillatory strain in the µHz frequency range in a laboratory setting
  - **Acquisition parameters**: spatial sampling of 0.25 m, gauge of 10 m, sampling frequency of 1 kHz
  - **Processing**: conversion to displacement rate, calculation of mean amplitude over fiber and integration

Observations:
- Oscillatory signals at frequencies corresponding to half-day lunar tidal cycles (23 µHz)
- Strain magnitude 10 times larger (165,000 nε) than tidal-induced strains (23 nε)
- Question remains: can we use DAS to measure tidal strains in boreholes?
Case Studies

1) Monitoring Long-term Subsidence in an Induced Permafrost Warming Experiment

2) Tracking Hydraulic Fracturing at an Enhanced Geothermal System Experiment

Processing Scheme to Extract Low-frequency Signals
(in these two studies)

- Raw strain-rate records (100’s Hz to kHz sampling)
- 1. Decimation to 1 Hz and concatenation
- 2. Despike and median removal (to remove outliers and instrumental noise)
- Long-term strain-rate
- Temporal integration and detrending
- Strain since start of measurement
Case Study 1: Monitoring Long-term Subsidence in an Induced Permafrost Warming Experiment

Verónica Rodríguez Tribaldos, Nate Lindsey, Aleksei Titov, Anna Wagner, Arthur Gelvin, Ian Ekblaw, Craig Ulrich, Barry Freifeld, Jonathan Ajo-Franklin
Monitoring Permafrost Degradation During a Controlled Warming Experiment

- **Controlled permafrost thawing** experiment at the US Army Corps of Engineer’s Permafrost experiment Station in **Fairbanks, Alaska**

- 121 electrical heaters placed over an area of **10.5 m x 12.7 m**

- Heating lasted from **August 5th through to November 11th 2016**
Monitoring Permafrost Degradation During a Controlled Warming Experiment

Monitoring instrumentation:

- 4000 m-long 2D array fiber-optic cable for DAS, DSS and DTS
  
  - Channel spacing = 1 m
  - Gauge length = 10 m

- Thermistor arrays
- Electronic Distance Measuring (EDM)
- LiDAR
- 10 DTS wells
- 1 Geophone array
- 2 Broadband seismometers
- 2 ERT lines
- 2 NMR wells
- Moisture content probes

DAS acquired between August 5th and October 4th

Wagner et al. (2018)
Monitoring Permafrost Degradation During a Controlled Warming Experiment

- Temperatures were increased from slightly below 0°C to 25 °C
- The permafrost table was lowered by 1.25 m to 1.5 m
Evidence of Subsidence From Mechanical Deformation Measurements

- EDM and LiDAR measure surface subsidence of **up to 10 cm** over 4 months of heating
- Surface deformation observable **starting ~ August 22**

**Electronic Distance Measuring (EDM)**

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**Differential LiDAR**

(EDM contours superimposed) at end of experiment

**Cross-section of elevation change across heated area along profile A-A’**

Can we use DAS to record long-term strain related to ground subsidence?

Wagner et al. (2018)
Extracting Low-Frequency Signals in DAS records

Profile B: inside heated area

Strain after temporal integration

Heated area
Extracting Low-Frequency Signals in DAS records

Profile B: inside heated area

Profile A: outside heated area

In both profiles, long-term strain dominated by negative trend

Combination of instrument drift and temperature
Extracting Low-Frequency Signals in DAS records

Profile B: inside heated area

Profile A: outside heated area

In both profiles, long-term strain dominated by negative trend

Combination of instrument drift and temperature

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DAS Virtual Workshop and Tutorial - August 2020
Extracting Low-Frequency Signals in DAS records

- The mean of all channels in profile A and a channel outside of the heated plot for profile B show the same strain.

- Channel inside heated area for profile B shows “residual” negative strain.

- Assumption that line A and line B outside heated plot are affected by the same processes, which we want to remove.

Subsidence signal?
Calculate the mean of all channels in profile A and subtract it from profile B to obtain “residual” subsidence signal.

Negative strain associated with compression of the cable in the subsiding area starting ~ August 26th
Monitoring Subsidence using Low-frequency DAS

Calculate the **mean of all channels in profile A** and **subtract it from profile B** to obtain “residual” subsidence signal.

Negative strain associated with compression of the cable in the subsiding area starting ~ August 26th.
Monitoring Subsidence using Low-frequency DAS

Channel inside the heated area shows significant negative cumulative strain with a maximum of $2 \pm 0.3 \mu e$.
Comparison with Distributed Strain Sensing (DSS) signals

DSS strain for a channel in profile B inside the heated area

DAS strain for a channel in profile B inside the heated area

Work by Aleksei Titov
Comparison with Electronic Distance Measuring (EDM)

Surface subsidence as measured with EDM at reference points near profile B

DAS strain for a channel in profile B inside the heated area
Spatial Distribution of Strain

August 6th
1 day after experiment starts

Heated area

September 28th
53 days after experiment starts

Heated area

strain (mε)
Case Study 2: Tracking Hydraulic Fracturing at an Enhanced Geothermal System Experiment

Verónica Rodríguez Tribaldos, Martin Schoenball, Chet Hopp, Yves Guglielmi, Jonathan Ajo-Franklin and the EGS Collab team
Strain Monitoring with DAS at the EGS Collab Experiment

- EGS Collab project: continuing sequence of meso-scale experiments aiming at improving understanding of hydraulic stimulations in crystalline rock for EGS
- Continuous monitoring of hydraulic fracture creation and stimulation using DAS (amongst many other techniques)
- Continuous ~2000 m long fiber-optic cable looping at bottom hole and going to the next borehole
- Grouted in 6 monitoring boreholes, free-hanging in coils in the drift
- Sampling rate 1 kHz or 10 KHz, 1 m channel spacing, 10 m gauge length
- Hydraulic fracture hits well E1-OT
Ultra-low Frequency DAS during Hydraulic Fracture Stimulation

- DAS captures hydraulic fracture approaching, hit the well and re-opening during later stimulations
- Strong DAS response in well E1-OT (nearest to injection borehole)
- DAS strain response observed in all monitoring boreholes
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Ultra-low Frequency DAS during Hydraulic Fracture Stimulation

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Strong DAS response in well E1-OT (nearest to injection borehole)

DAS strain response observed in all monitoring boreholes
Summary

- DAS is an extremely broadband sensor (mHz to KHz) that can be used for dynamic strain measurement (seismology), but also for geodetic/geomechanics-type observations.

- Extraction of low-frequency component is relatively simple, little processing is required.

- Quantification of strain amplitudes remains a challenge: effects such as instrumental drift and thermal strain affecting the cable need to be understood.

- Best practices include instrument calibration, temperature monitoring and record at “reference/quiet sections” when possible.

- More experimentation in varying fields of application, different instruments, different cables... is necessary!
Thanks for listening!
Questions?

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