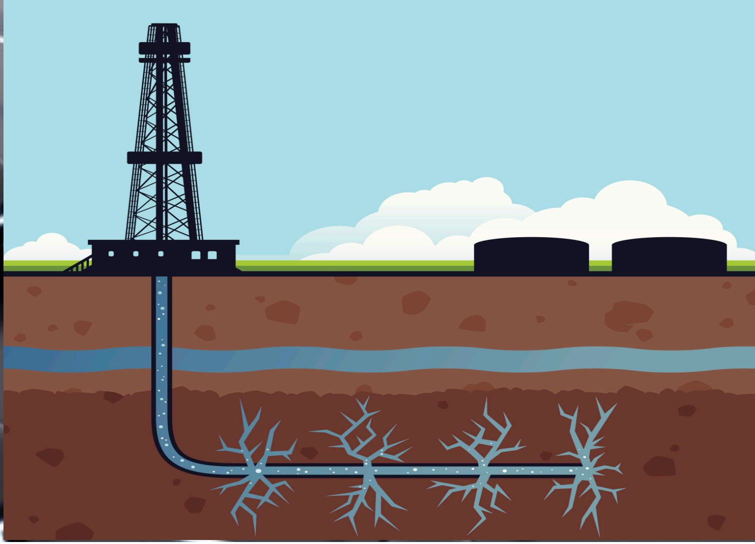


The Role of Distributed Wireless Sensor Network Systems in Industrial Automation

Case Study: Hydraulic Fracturing for Pre-conditioning of Underground Mines

Amirali Soroush, Ph.D. & Vincent Mow & Sam Cantrill | 27 October 2019

Australia's National Science Agency

CSIRO

Who are we? **CSIRO**

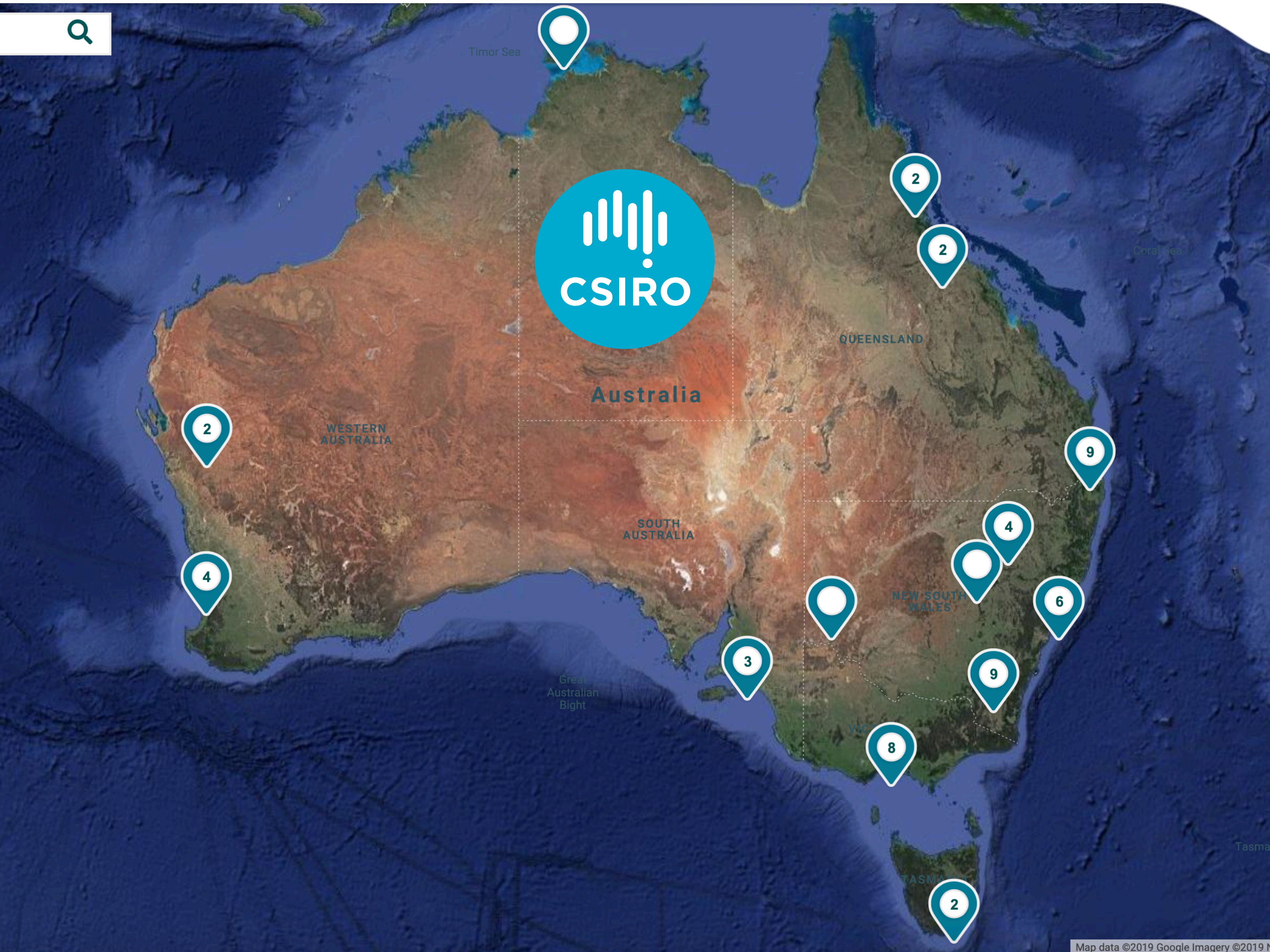
- Conduct and encourage the uptake of world-class scientific research
- We deliver on this objective through our Business Units and Future Science Platforms

Business Units

- Agriculture and Food
- Data61
- Energy
- Health and Biosecurity
- Land and Water
- Manufacturing
- Mineral Resources
- Oceans and Atmosphere

Future Science Platforms

- Active Integrated Matter
- Artificial Intelligence and Machine Learning
- Deep Earth Imaging
- Digiscape
- Environomics
- Hydrogen Energy Systems
- Precision Health
- Probing Biosystems
- Space Technology
- Synthetic Biology


CSIRO
Timor Sea
QUEENSLAND
Coral Sea
Australia
WESTERN AUSTRALIA
SOUTH AUSTRALIA
NEW SOUTH WALES
Great Australian Bight
2
2
2
9
4
4
6
3
9
8
2
Map data ©2019 Google Imagery ©2019

CSIRO invented **Wi-Fi!**

Dr O'Sullivan et. al. CSIRO Astronomy, 1996

(https://en.wikipedia.org/wiki/John_O%27Sullivan_(engineer))

Summary

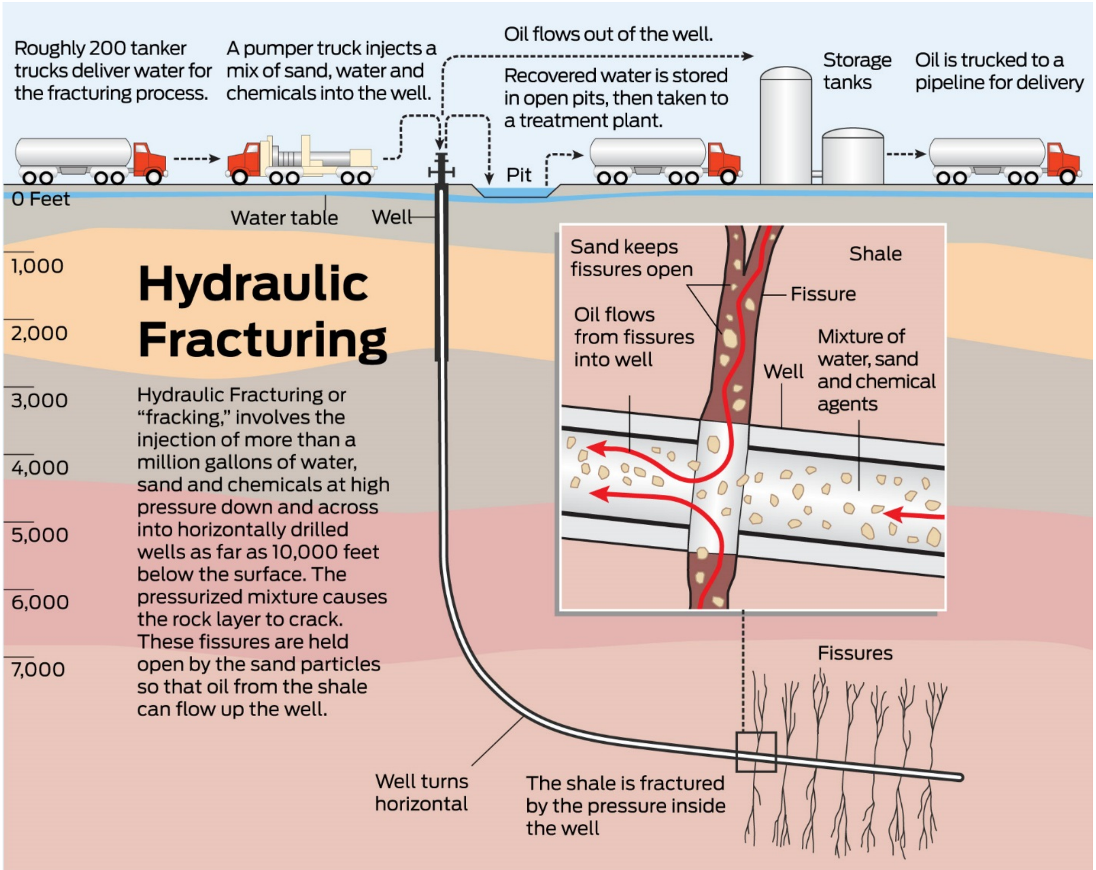
- Introduction to Hydraulic Fracturing
  - What is hydraulic fracturing?
  - Modelling, laboratory experiment, and, field operations
  - CSIRO's Hydraulic Fracturing team
- Hydraulic Fracturing Monitoring Automation
  - Distributed Wireless Sensor Network Systems for tilt monitoring
  - Open-source electronics platform
- Hydraulic Fracturing Automation
  - Wi-Fi Network for operation automation
- Conclusion and Future Works

Section 1:

Introduction to Hydraulic Fracturing

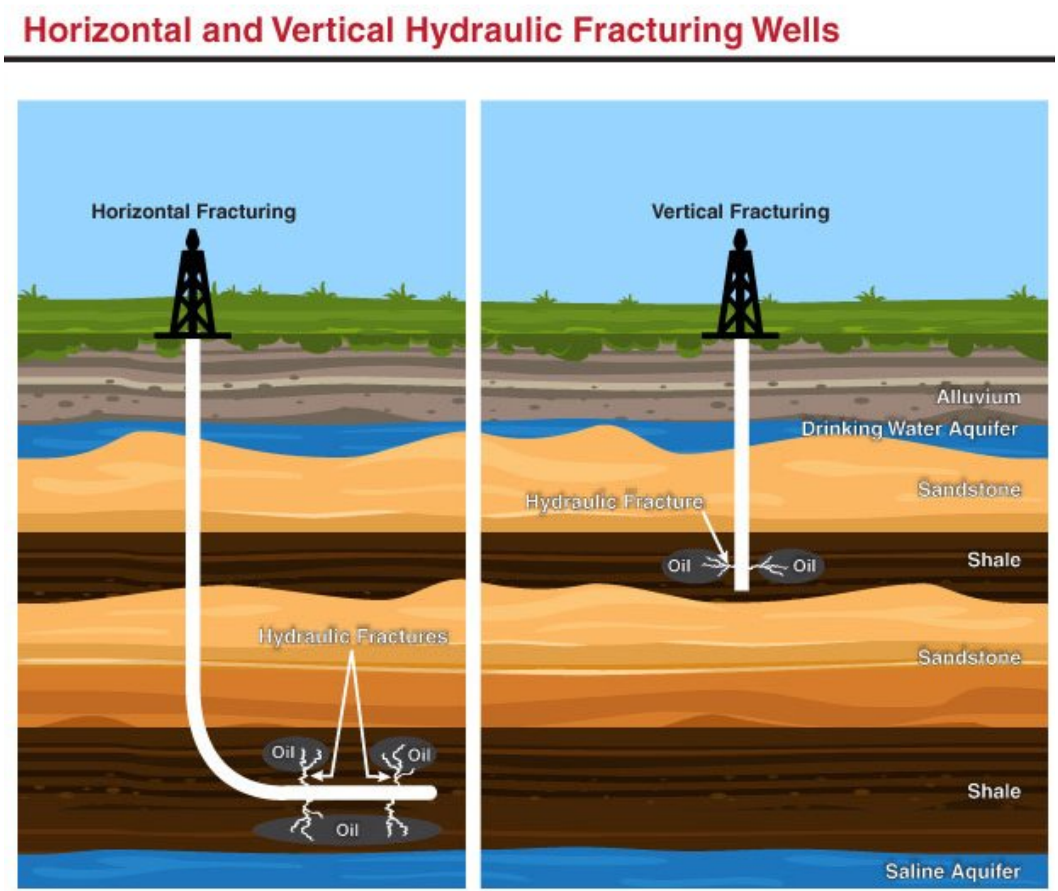
What is Hydraulic Fracturing?

What is Hydraulic Fracturing?

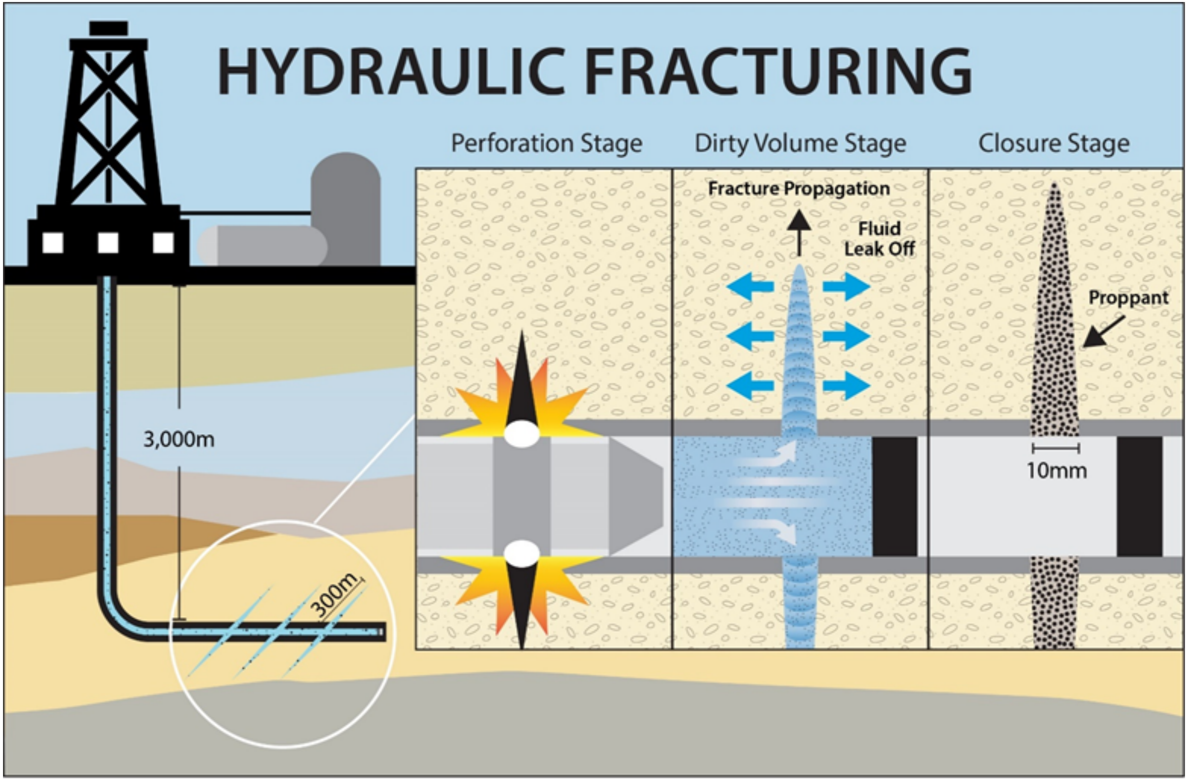


Source: goodyearlake.org

Vertical vs Horizontal HF

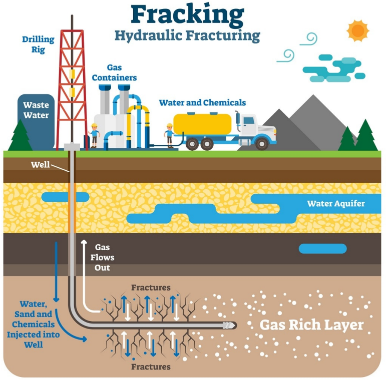


How it is done?

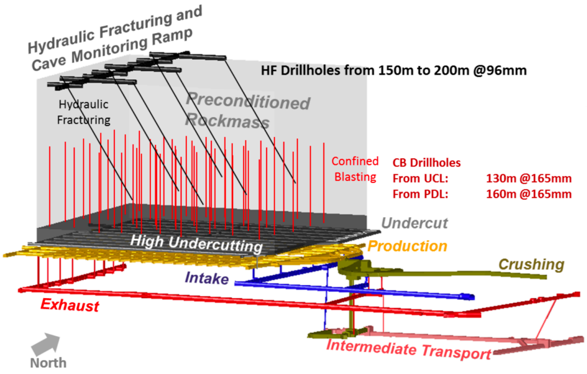


Applications of Hydraulic Fracturing?

- Oil & Gas Industry
  - Well stimulation technique for unconventional resources



- Mining Industry
  - Mine Preconditioning
  - Seismic mitigation
  - Gas drainage



Who are we?

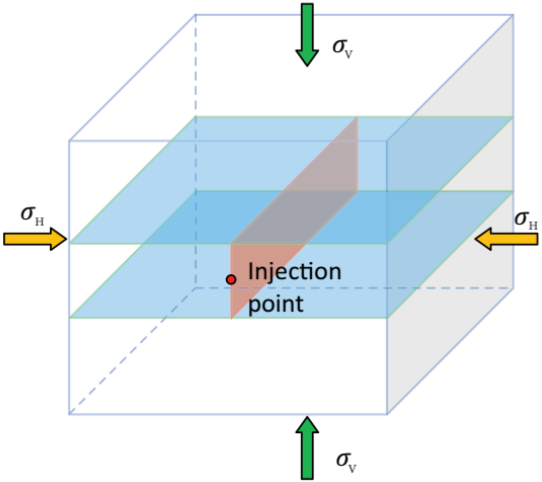
Hydraulic Fracturing Team

Since 1992

- Five Research Scientists
- Four Experimental Research Engineers
- Four Research / Fieldwork Technicians

What we do?

- Hydraulic Fracturing Modelling
  - Numerically model hydraulic fracture growth in complex systems
  - Interpret and analyse fracture growth monitoring data



(a) a 3-layer formation

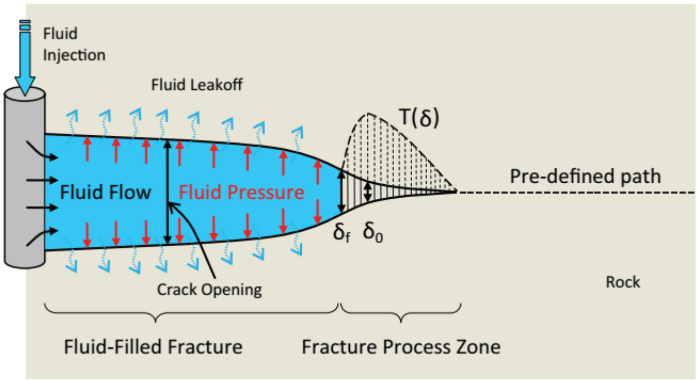
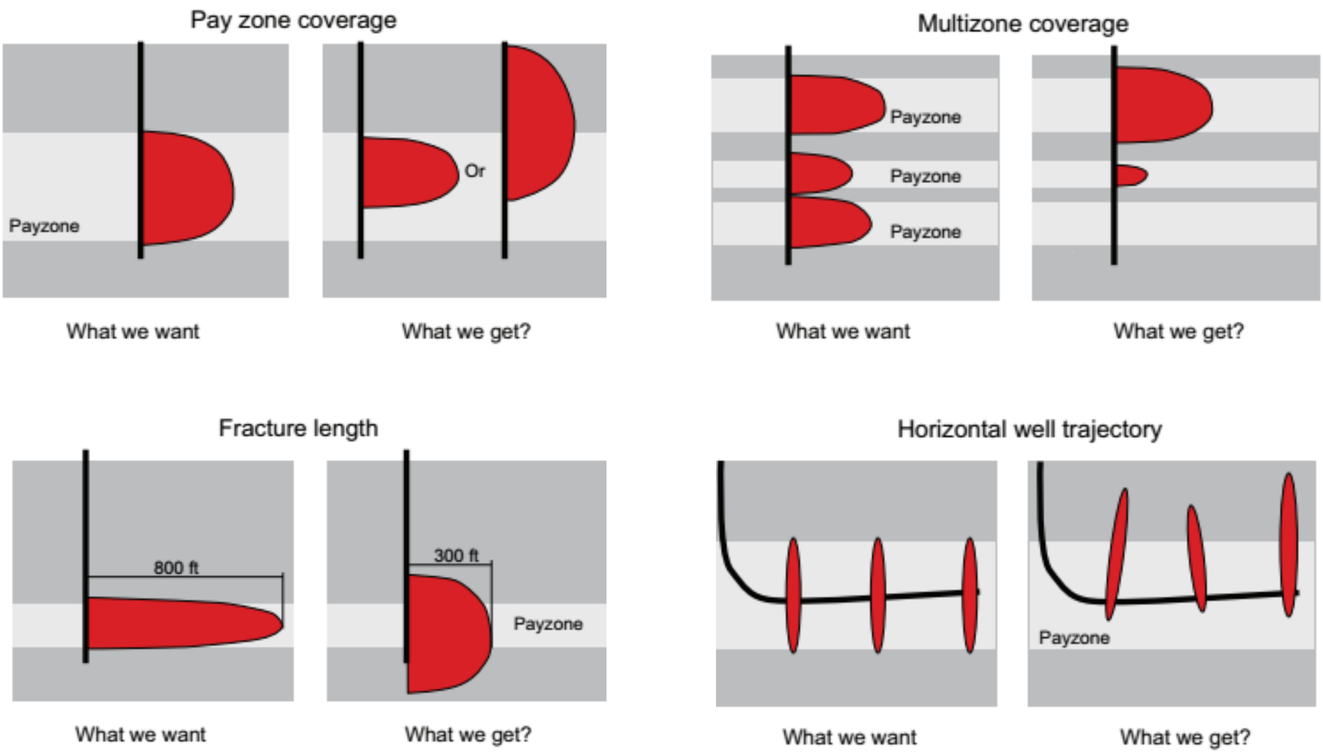


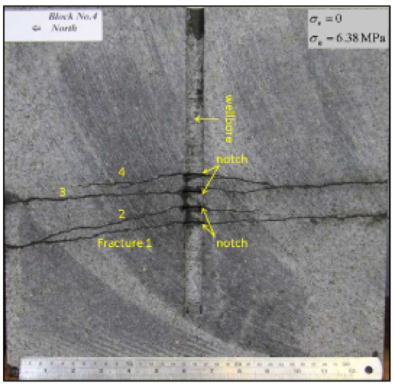
Figure 1. Cohesive zone hydraulic fracture model (After Chen (2012)).

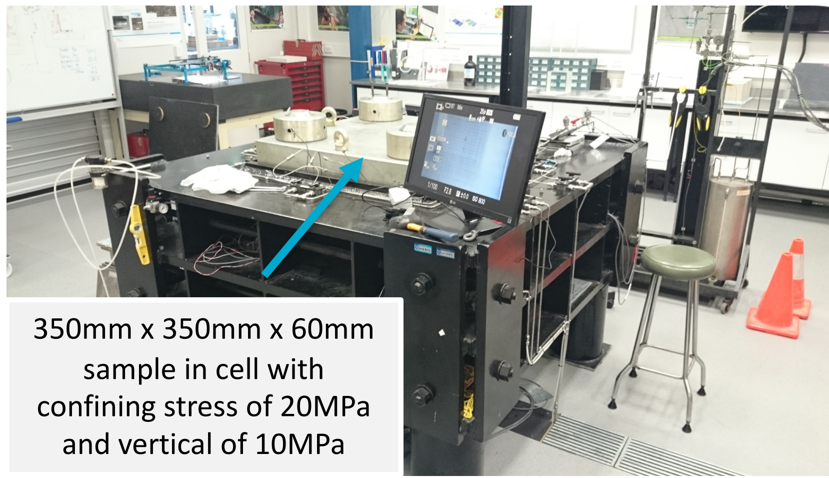
Understanding HF growth?



What we do?

- Laboratory Experiments
  - Design and conduct hydraulic fracture growth laboratory investigations
  - Develop and deploy data measurement and analysis tools



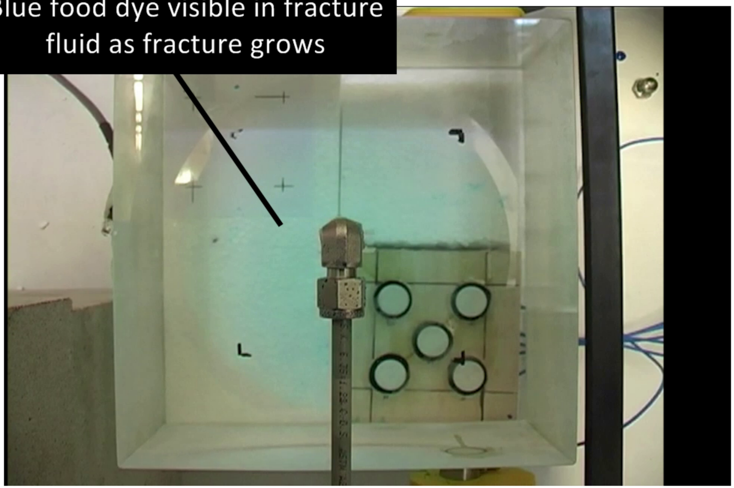


350mm x 350mm x 60mm sample in cell with confining stress of 20MPa and vertical of 10MPa

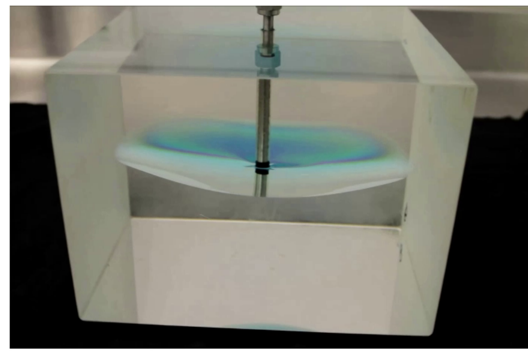
Polyaxial cell (true triaxial cell)

Laboratory experiments?

Blue food dye visible in fracture fluid as fracture grows



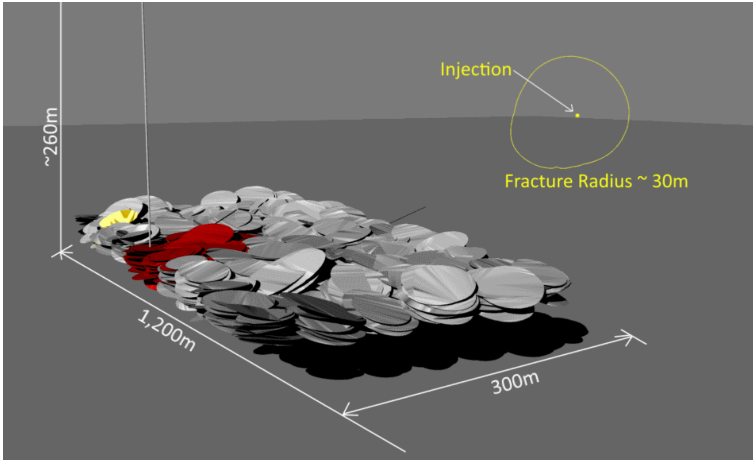
Glass sample containing hydraulic fracture

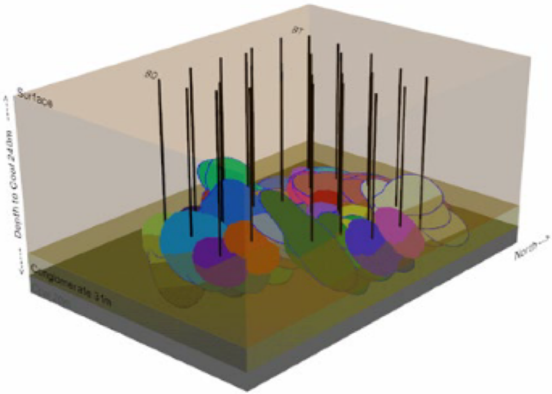


Labscale hydraulic fracture experiments in Glass

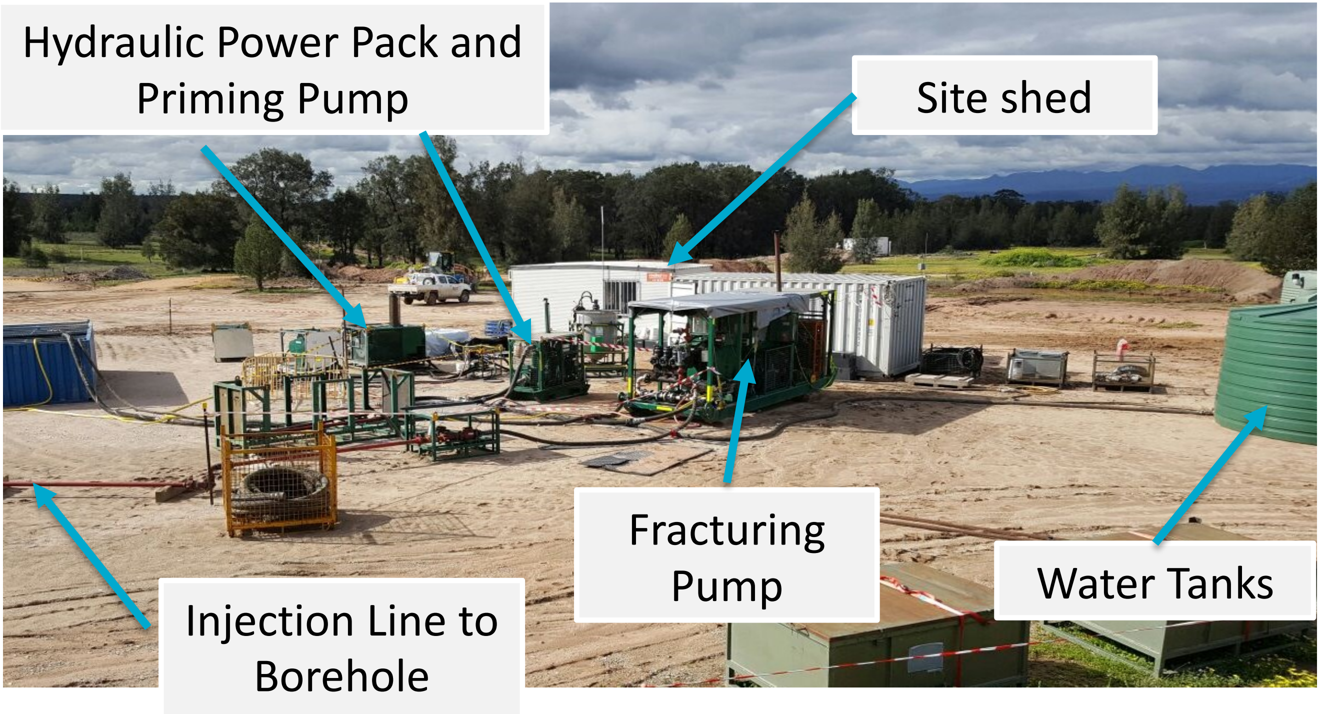
What we do?

- Field Operations
  - Conduct hydraulic fracturing fieldwork at client sites in Australia and internationally
  - Grow, monitor and analyse hydraulic fracture treatments





Field operation?



Why pre-conditioning?

Longwall Underground Mine

MINE BLAST

17 men injured in shaft explosion

UP TO 17 workers have been injured, two seriously, after a huge blast rocked a coal mine today.

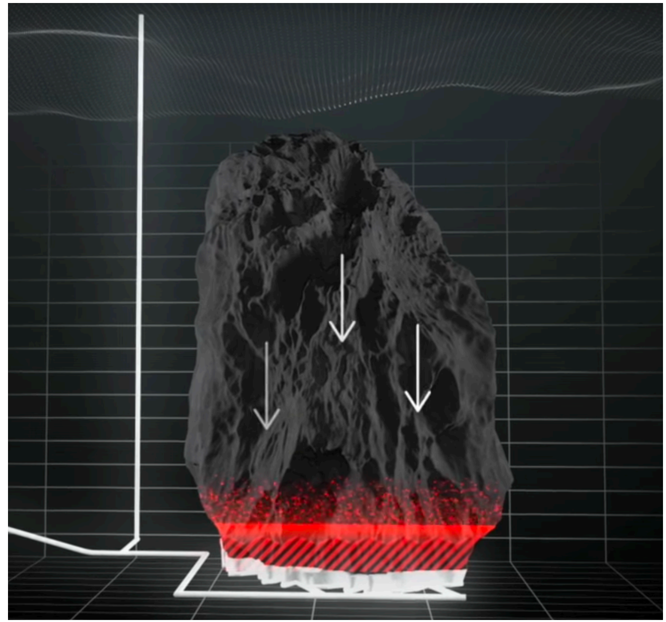
Four miners killed in Australian mine disaster

By Terry Cook
2 December 1999

The accident that claimed the lives of four mine workers on November 24 at the Northparkes copper and gold mine near Parkes, in central west New South Wales, again focuses attention on the issue of safety standards in the mining industry.

Why pre-conditioning?

Subsidence of the surface

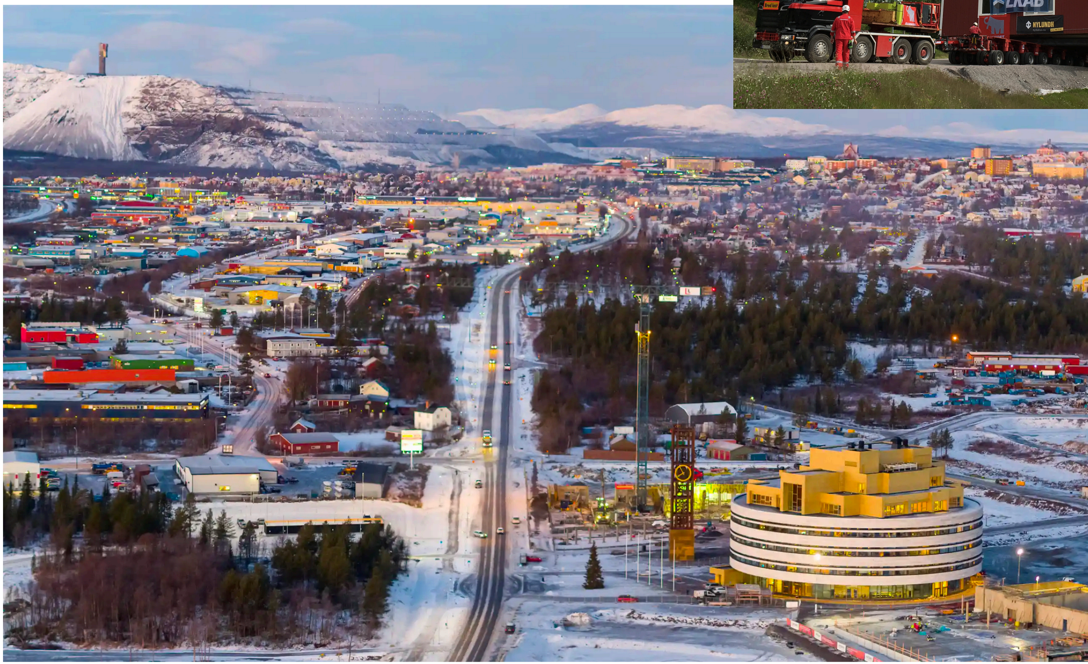


Caving process underground

Block cave Mine

Caving hazards

'Will I have existed?' The unprecedented plan to move an Arctic city



▲ Kiruna's new City Hall, lower right, by Henning Larsen architects, sits about 3km from the world's biggest iron mine, top left. Photograph: Peter Rosén/LapplandMedia

The world's biggest iron ore tunnel mine is about to swallow the Swedish city of Kiruna. The company's answer? Move the city

Field operation?

Preconditioning

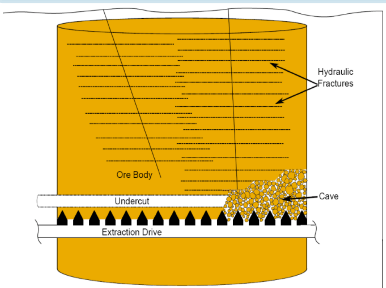
- Fractures placed near or in ore body
- Reduces waiting events
- Improves crushing requirements by reducing rock size
- *Applicable to:* Block cave mining, Long wall mining

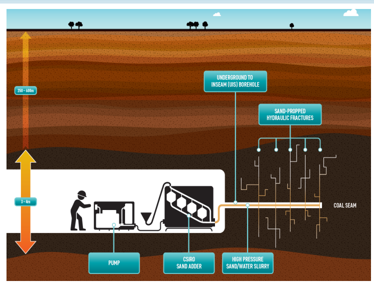
Gas Drainage

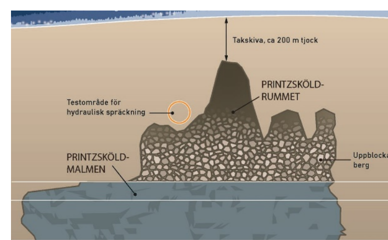
- Fractures placed in coal
- Improve gas drainage through small propped controlled openings
- *Applicable to:* coal mining (deeper than 400m)

Seismic Mitigation

- Removing material during mining changes local stress regime
- Hydraulic fractures used to change rock strength to relieve stresses
- *Applicable to:* All mines (700+m deep)







HF team's field operations worldwide

A$10M revenue in the last 4 years

Section 2:

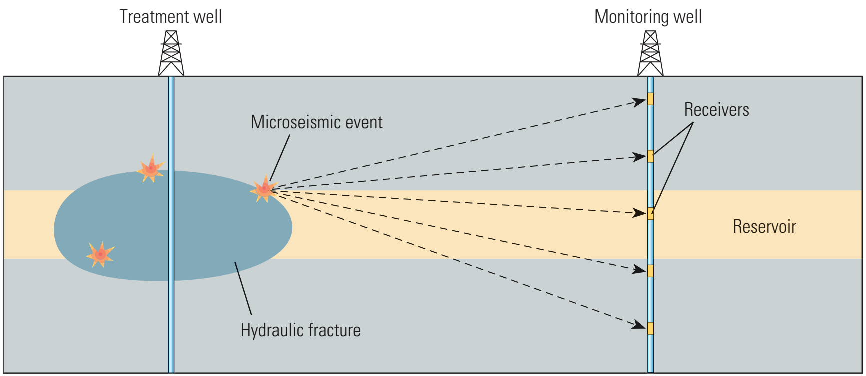
Hydraulic Fracturing Monitoring Automation

How
hydraulically induced fractures
are identified / monitored?

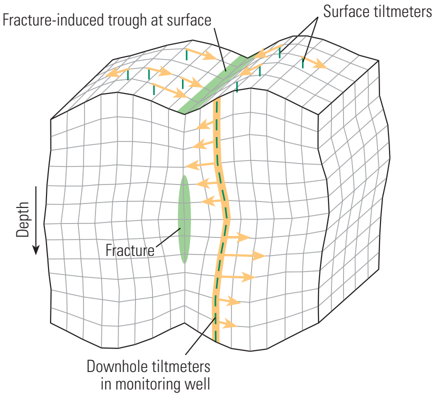
Hydraulic fracturing monitoring?

- What is HF monitoring?
  - identify the extent and directions of hydraulically induced fractures

- How is it done?
  - Micro-seismic monitoring
  - Tilt monitoring

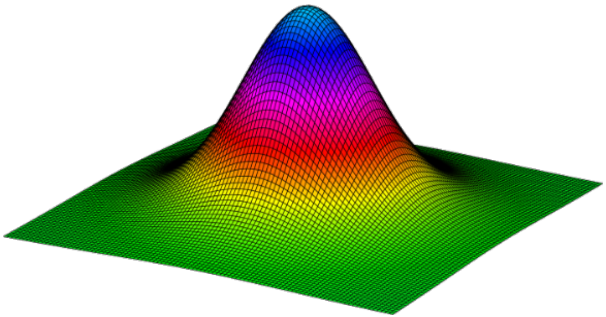


Micro-seismic monitoring

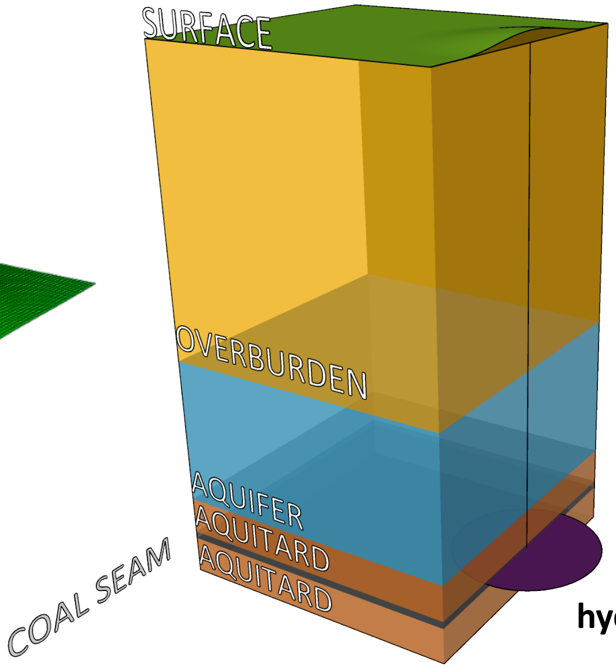


Tilt monitoring

Tilt monitoring of hydraulic fractures



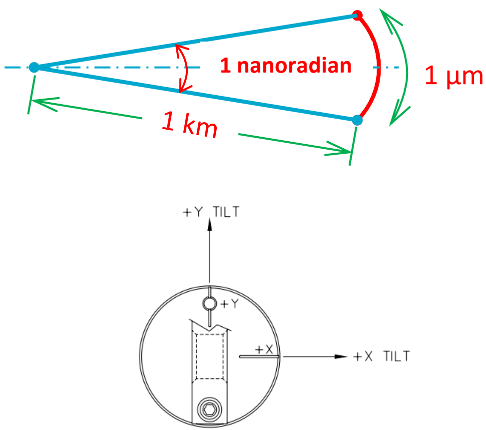
Surface deformation

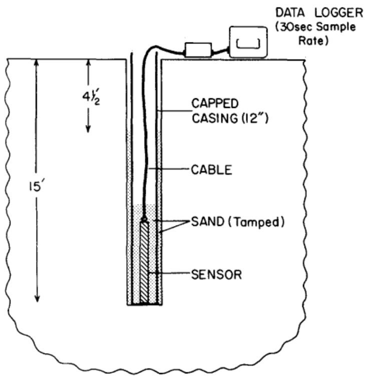


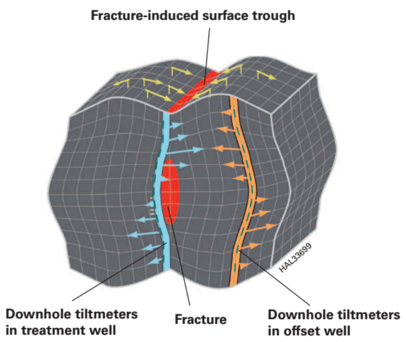
Horizontal hydraulic fracture

What is a tiltmeter?

- Tiltmeters monitor small-scale changes in surface tilt (uplift) caused by injection of a volume of fluid or gas
- Data is analysed to provide location and volume information on injected material
- Precision tilt sensors (with nanoradian resolution) sense angular movement in two orthogonal vertical planes



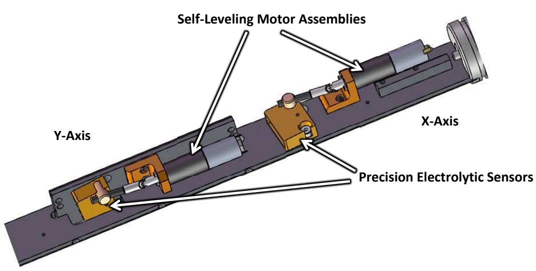


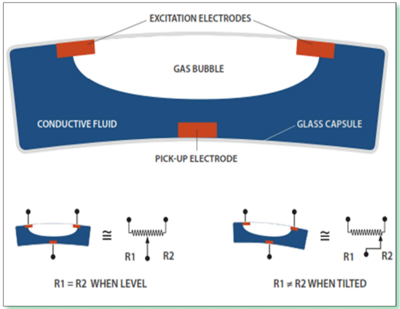


Commercial tiltmeters

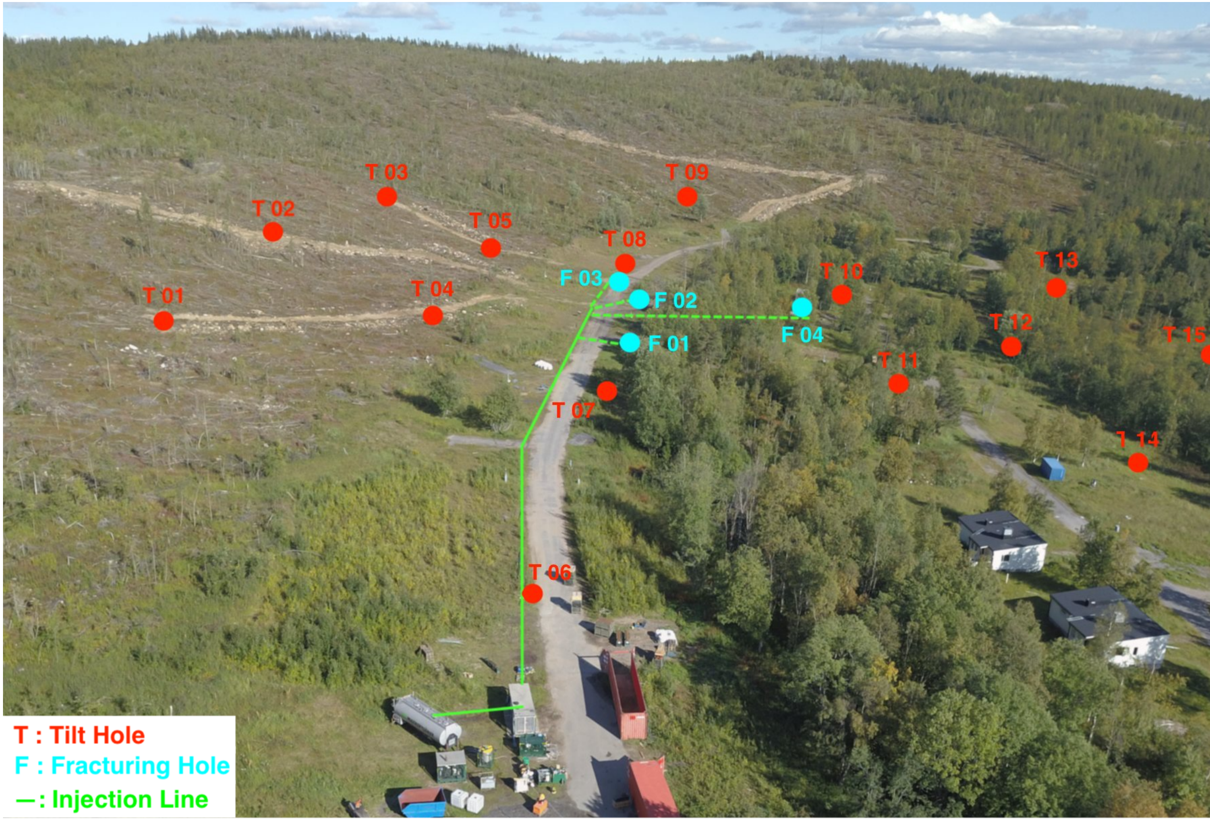
- Lily Borehole Tiltmeter
  - Resolution < 5 nanoradians
  - Price: AUD $30K each
  - Output: ASCII via RS232 or RS485
  - Installed in 10~15 [m] deep boreholes
  - The borehole is sanded to create coupling

Specifications	
Channels	X tilt, Y tilt, azimuth, temperature
Resolution	< 5 nanoradians
Repeatability	Same as resolution under static conditions
Dynamic Range	±330 μradians
Self-Leveling Range	±10 degrees
Non-Linearity	0.2% of full span
Frequency Resonse	< 1 Hz
Ks Temp Coefficient (%/°C)	±0.02%/°C
Kz Temp Coefficient (bias/°C)	±3 μradian/°C
Azimuth detection	On-board magnetic compass, 0° to 360° output
Output	RS232 and RS422 standard (user selectable)
Baud rate	9600, 19200 (default), 28800, 57600, 115200, 230400
Sample rate	User programmable from 10 samples/sec to 1 sample/day
Output Format	NMEA XDR, Trimble TCM, Ashtech, Simple (Timestamp, X, Y, Temp, Compass, S/N)
On-board Memory	2 Megabytes nonvolatile Flash memory (64,000 samples)
Real-time Clock	Accurate to 10 minutes/year or better
Power	7 to 28 VDC @ 30 mA (< 10 mA sleep); 250 mV ripple max., reverse polarity protected
Environmental	-25°C to +85°C operational, -30°C to +100°C storage. 3000 psi
Weight	4.5 kg (10 lb)
Materials	304 stainless steel, nonmagnetic (6Al-4V Titanium available on request: to +5000 psi)



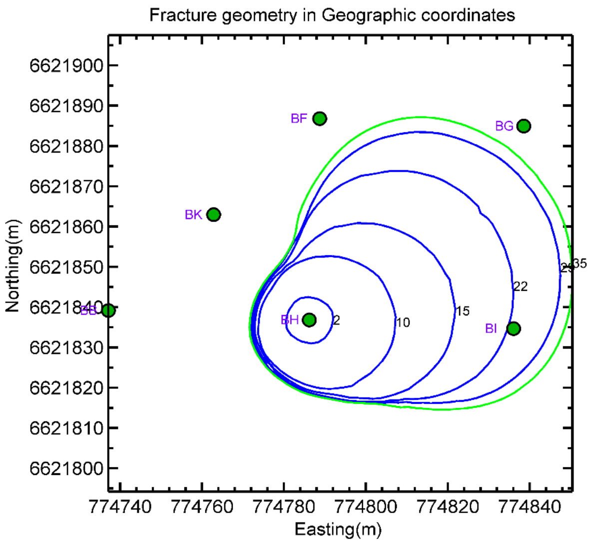


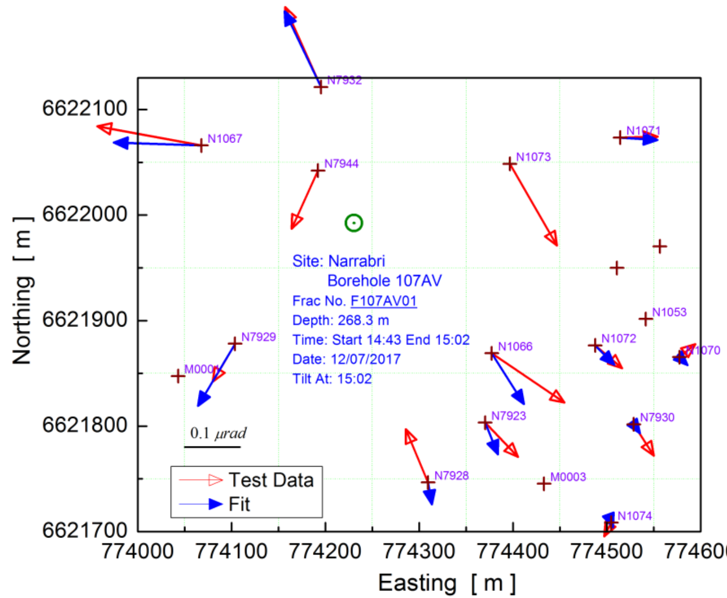
HF monitoring in the field



CSIRO's Preconditioning Site and Tilt Monitoring Array
LKAB Iron Ore Mine, Malmberget, Sweden, July 2017

Fracture Growth Map





Several Components of the System

- **Sensor**
  - Ultra-high resolution tiltmeter (1 nanorad as compared to commercial 5 nanorad)
  - Low cost (reduce the purchasing cost by 70%) and low power consumption (solar powered)
  - State of the art electronics and robust mechanical design
- **Wireless Sensing Technology**
  - Novel long-range (~10 [km]) Distributed Wireless Sensor Network (DWSN)
  - Bi-directional communication for real-time monitoring of tilt data and sensor health, as well as remote sensor calibration
  - Flexible and can be integrated with any digital and/or analog sensors on site
- **Real-time Display**
  - Innovative tailor-made real-time dashboard
  - Intelligent monitoring, preliminary processing, QC/QA, sensor control and alarms
  - Real-time analytics and advanced visualization for on-site decision making

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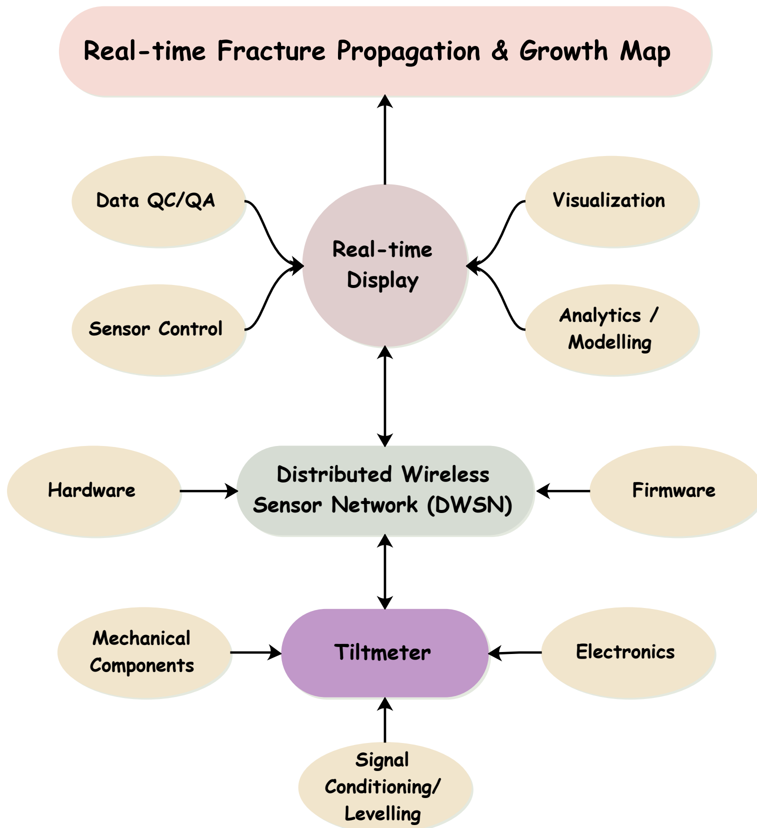
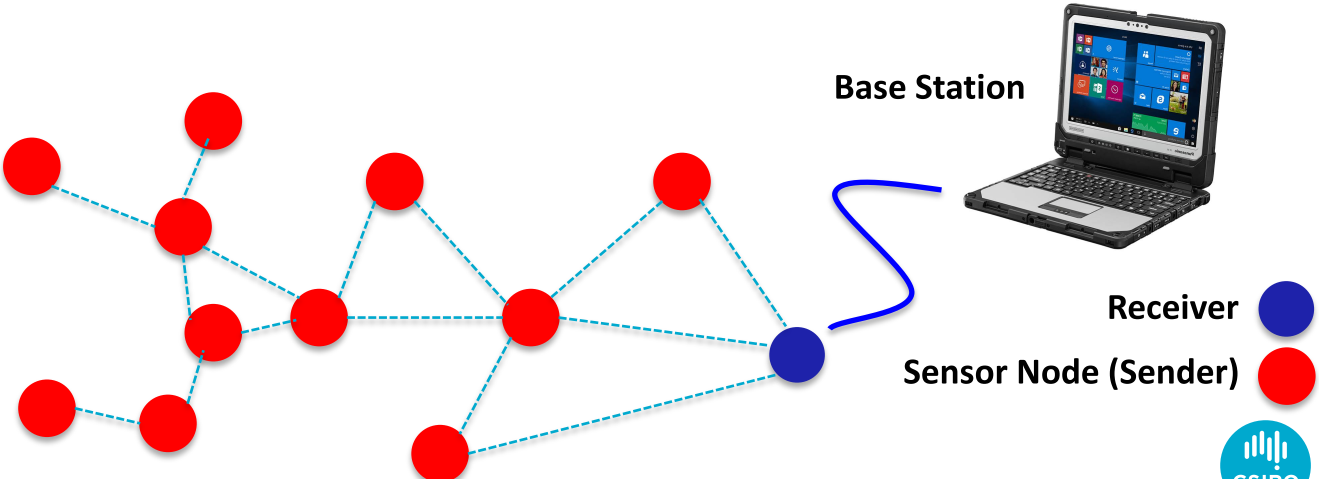
HF monitoring architecture



Distributed Wireless Sensor Networks

- What is a Distributed Wireless Sensor Network system?
  - Monitor and control various physical and environmental parameters in real-time such as temperature, humidity, air pollutant, etc.
  - Continuously collect data and transfer them to a central aggregation point (base station) over radio frequencies
  - Plug & play, low maintenance, minimum user interference, low cost



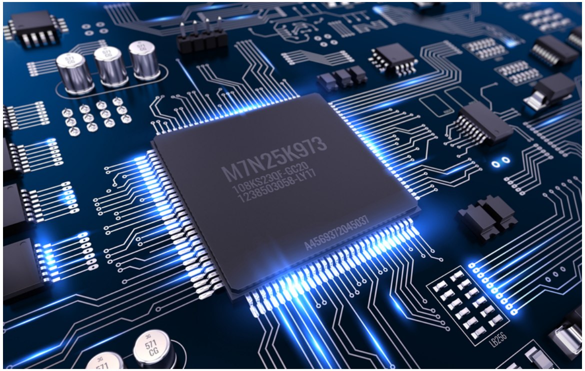
Commercial DWSN systems

- **What is available in the market at the moment?**
  - Offered by several companies
  - Specs vary significantly from one product to another
  - Limited flexibility

- **Cost (50 Nodes + Gateway)**
  - ~20k to 75k
  - License Renewal

Way to go?

- **Design and Development by an External Company**
  - ~20K for PCB Design & Firmware
  - Additional Costs for Development
  - No Control over the Firmware
  - Extra Costs for Future Upgrades



- **In-house Design and Development**
  - Open Source Electronics / Microcontrollers
  - Capability Development
  - Full control over Hardware / Firmware

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Required DWSN system

- **Necessary Specifications**
  - Long Range, non L.O.S Environment
    – ~1 [km]
  - Analogue & Digital Input
  - Clock Synchronisation / GPS
  - Two-way Communication / Sensor Calibration
  - On-board Memory / Data Security
  - Low Power Consumption / Solar Power
  - Mesh Network / Self Healing
  - Durability (heat, moisture, etc)

ACUMESH
WIRELESS RS485 NETWORK

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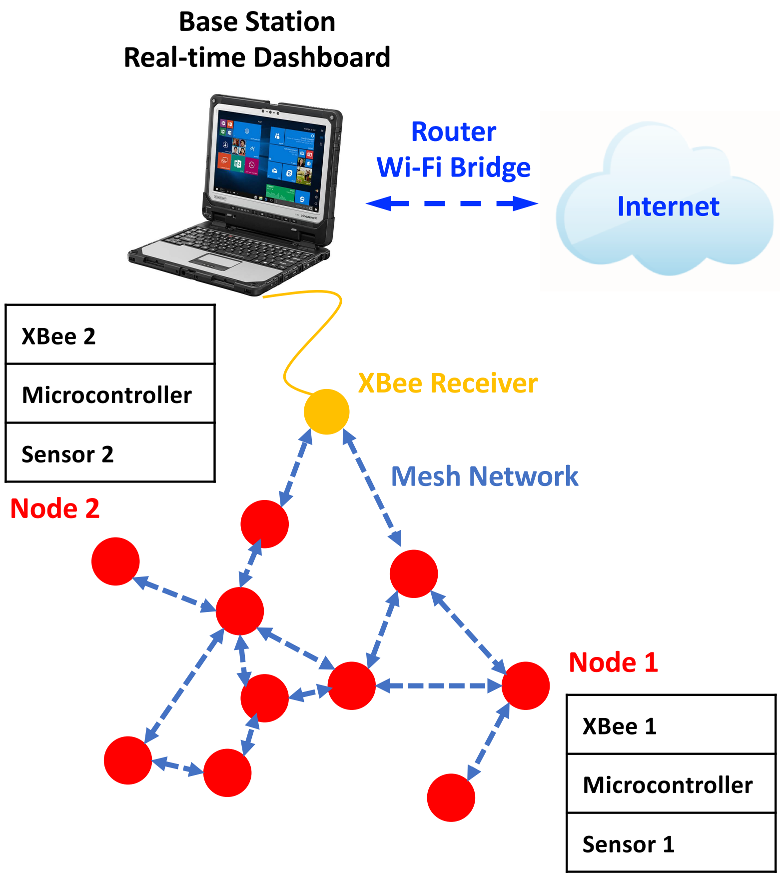
Overall DWSN system architecture



Choice of microcontroller

ARDUINO
OPEN-SOURCE
COMMUNITY

Arduino Due
SAM3X8E Microcontroller

OVERVIEW | TECH SPECS | DOCUMENTATION

Microcontroller	AT91SAM3X8E
Operating Voltage	3.3V
Input Voltage (recommended)	7-12V
Input Voltage (limits)	6-16V
Digital I/O Pins	54 (of which 12 provide PWM output)
Analog Input Pins	12
Analog Output Pins	2 (DAC)
Total DC Output Current on all I/O lines	130 mA
DC Current for 3.3V Pin	800 mA
DC Current for 5V Pin	800 mA
Flash Memory	512 KB all available for the user applications
SRAM	96 KB (two banks: 64KB and 32KB)
Clock Speed	84 MHz
Length	101.52 mm
Width	53.3 mm
Weight	36 g

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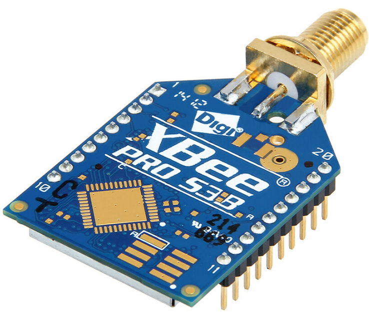
Choice or radio transceiver



Digi XBee-PRO 900HP
~ 9 [km] LOS range

SPECIFICATIONS	Digi XBee-PRO® 900HP	Programmable Digi XBee-PRO® 900HP
HARDWARE		
PROCESSOR	ADF7023 transceiver, Cortex-M3 EFM32G230 @ 28 MHz; Programmable includes: Freescale MC9S08QE32	
FREQUENCY BAND	902 to 928 MHz, software selectable channel mask for interference immunity	
ANTENNA OPTIONS	Wire, U.FL and RPSMSA	
PERFORMANCE		
RF DATA RATE	10 Kbps or 200 Kbps	
INDOOR/URBAN RANGE*	10 Kbps: up to 2000 ft (610 m); 200 Kbps: up to 1000 ft (305 m)	
OUTDOOR/ LINE-OF-SIGHT RANGE*	10 Kbps: up to 9 miles (15.5 km); 200 Kbps: up to 4 miles (6.5 km) (with 2.1dB dipole antennas)	
TRANSMIT POWER	Up to 24 dBm (250 mW) software selectable	
RECEIVER SENSITIVITY	-101 dBm @ 200 Kbps, -110 dBm @ 10 Kbps	
FEATURES		
DATA INTERFACE	UART (3V), SPI	
GPIO	Up to 15 Digital I/O, 4 10-bit ADC inputs, 2 PWM outputs	
NETWORKING TOPOLOGIES	DigiMesh, Repeater, Point-to-Point, Point-to-Multipoint, Peer-to-Peer	
SPREAD SPECTRUM	FHSS (Software Selectable Channels)	
PROGRAMMABILITY		
MEMORY	N/A	32 KB Flash / 2 KB RAM
CPU/CLOCK SPEED	N/A	HCS08 / Up to 50.33 MHz
POWER		
SUPPLY VOLTAGE	2.1 to 3.6 VDC	2.4 to 3.6 VDC
TRANSMIT CURRENT	215 mA	229 mA
RECEIVE CURRENT	29 mA	44 mA
SLEEP CURRENT	2.5 uA	3 uA
REGULATORY APPROVALS		
FCC (USA)	MCQ-XB900HP	
IC (CANADA)	1846A-XB900HP	
C-TICK (AUSTRALIA)	Yes	
ANATEL (BRAZIL)	Yes	
IDA (SINGAPORE)	Yes	

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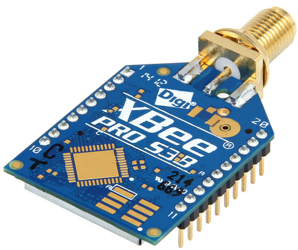
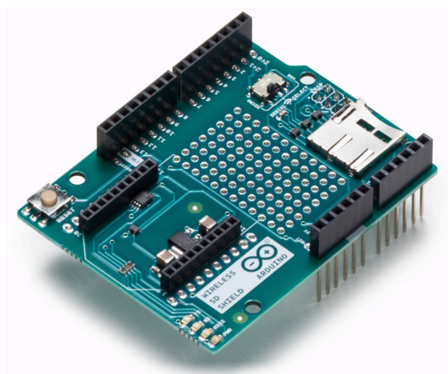
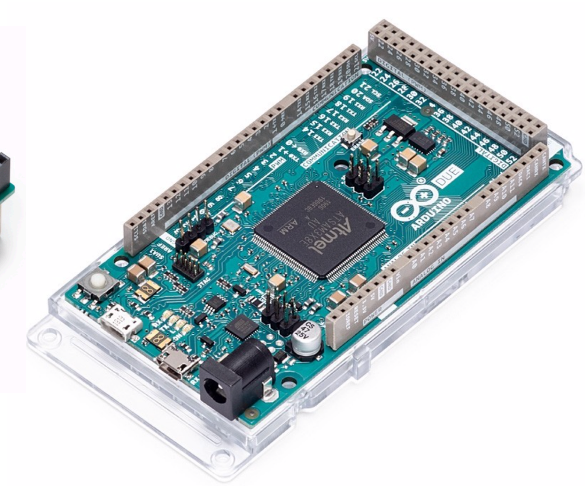
Integration of various components







Digi XBee-PRO 900HP
~ 9 [km] LOS range

Arduino Wireless SD Shield
Compatible with XBee modules

Arduino Due
SAM3X8E Microcontroller

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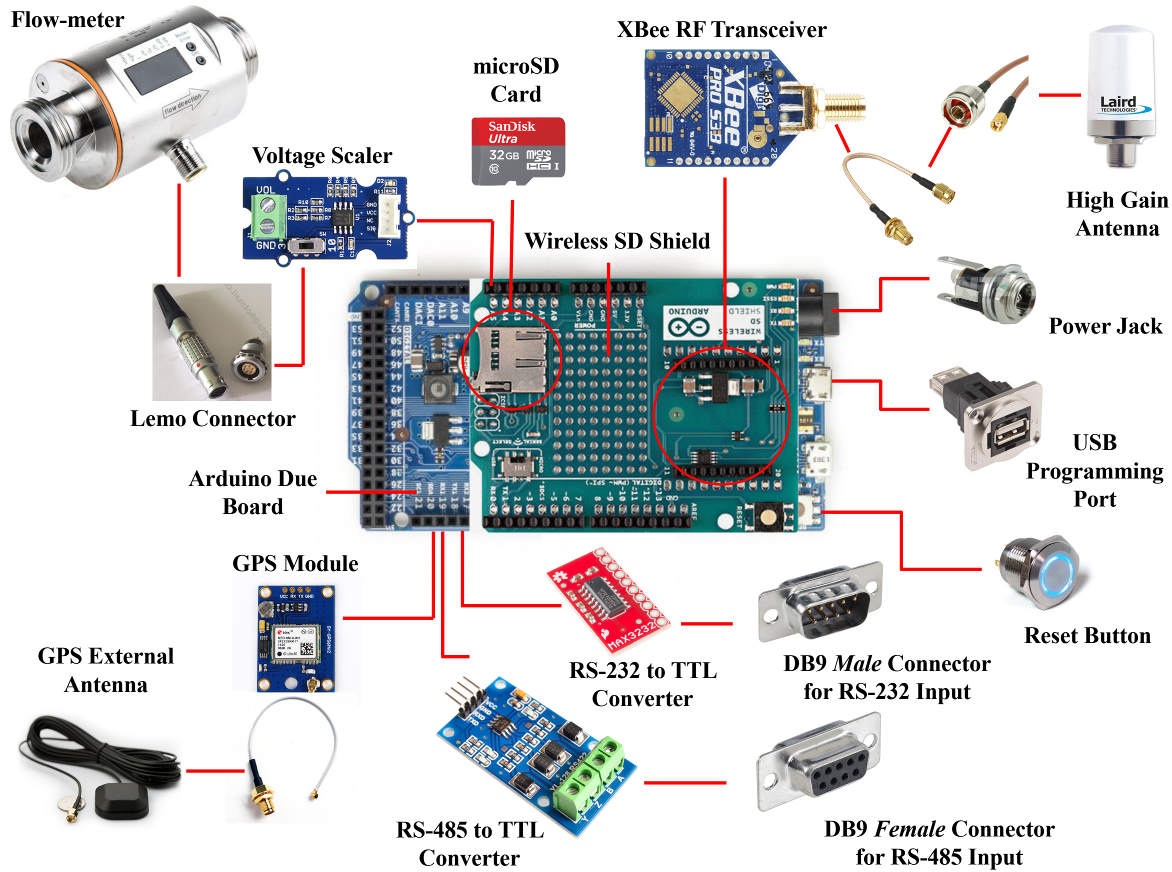
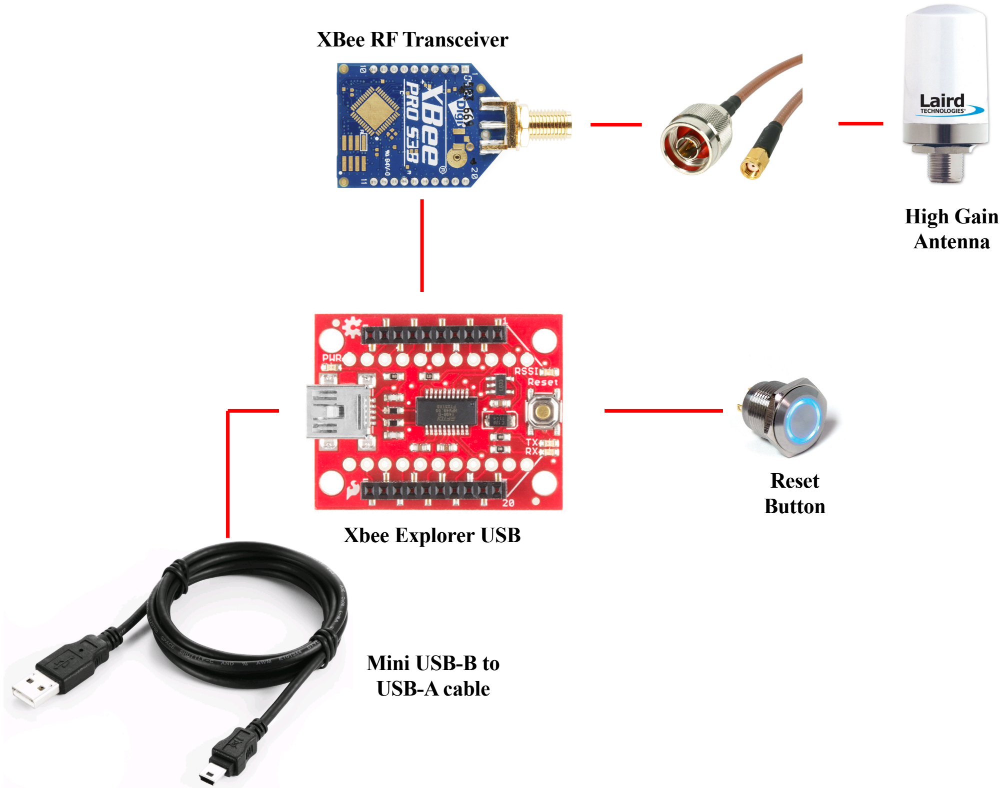
Sensor node layout



Receiver Layout



Firmware development

Xbee_RXTX_03Narrabri | Arduino 1.8.8

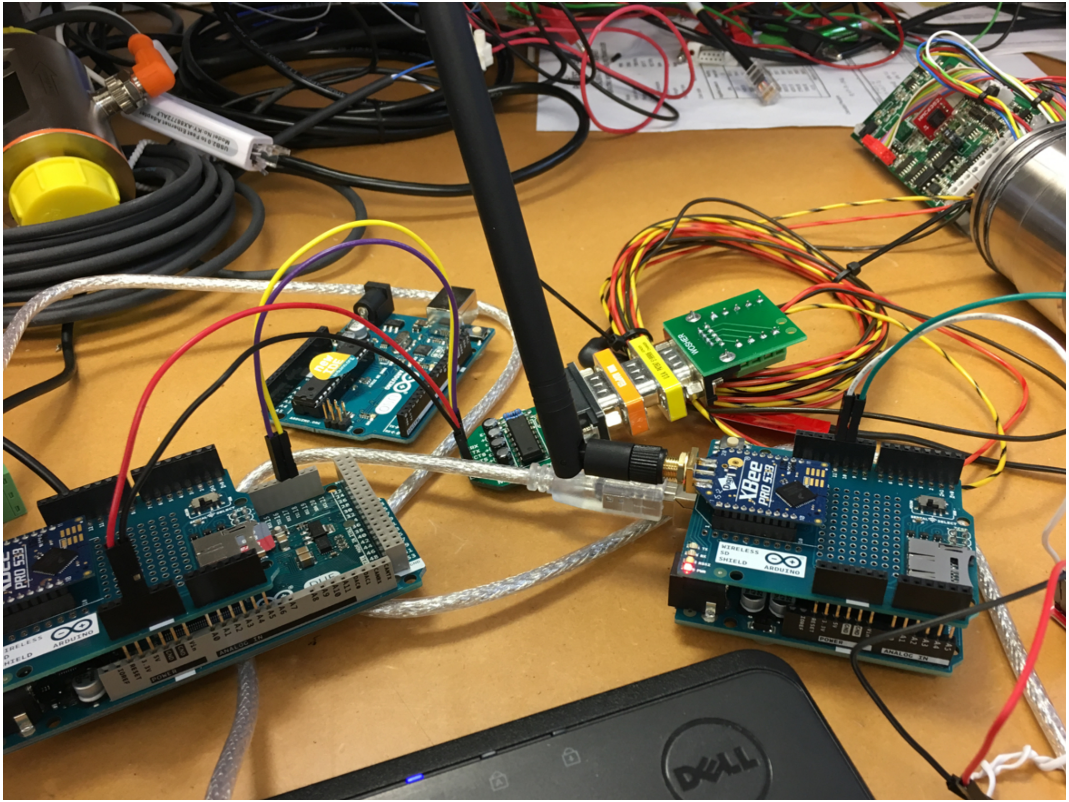
Xbee_RXTX_03Narrabri §

```
/* 17 Feb 2017
  This is a firmware for Hydraulic Fracturing Wireless Sensor Network for Tiltmeter array.
  Developed by Amirali Soroush for Arduino Due boards
  Version 1.0
  The code is able to read data from Lily and Lippmann tiltmeters and also send commands to both sensor types
*/

#include <XBee.h>
#include <SD.h>
#include <TinyGPS++.h>

// create the XBee object
// TX
XBee xbee = XBee();
// RX
XBeeResponse response = XBeeResponse();

// Payload size for Lipmann Tiltmeter
//uint8_t payload[60];

// Payload size for Lily Tiltmeter
//uint8_t payload[62];
uint8_t payload[65];

// Payload size for Ublox Neo-6M GPS
//uint8_t payload[64];

static const uint32_t GPSBaud = 9600;

// The TinyGPS++ object
TinyGPSPlus gps;

const int chipSelect = 4;

char in_byte;
char in_byte1;
```

12

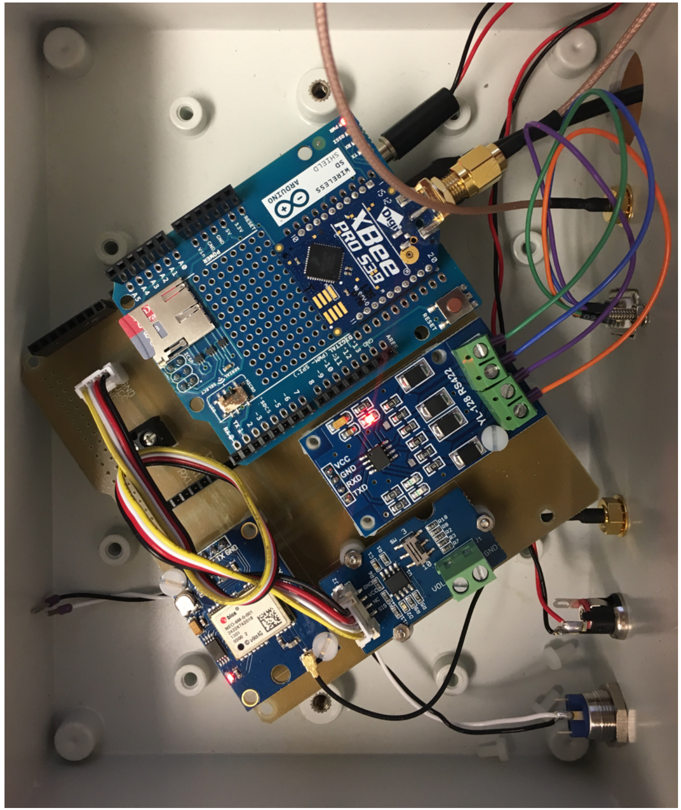
Arduino Due (Programming Port)

Prototyping



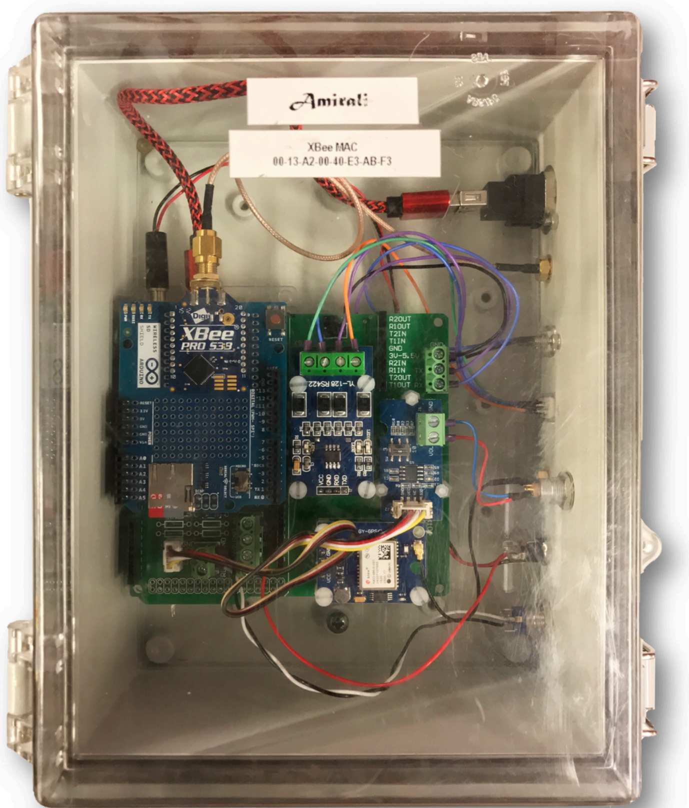
Laboratory Design, Development and Testing January-February 2017

Prototyping



First Prototype March 2017

Prototyping



Radio Module Box – Hardware cost: 250 AUD per node

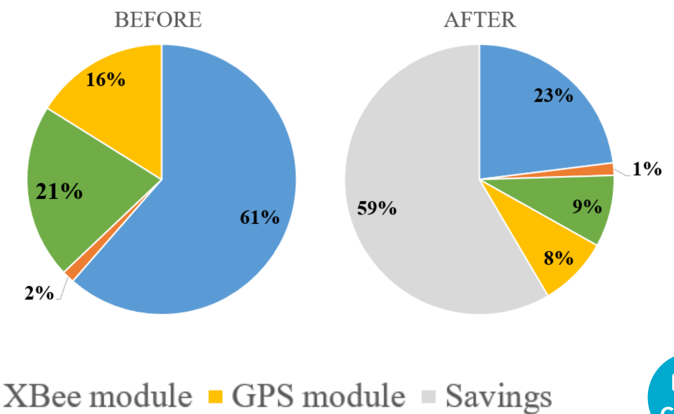
Development

Development of 50 radio box modules - April 2017

Updates and revisions

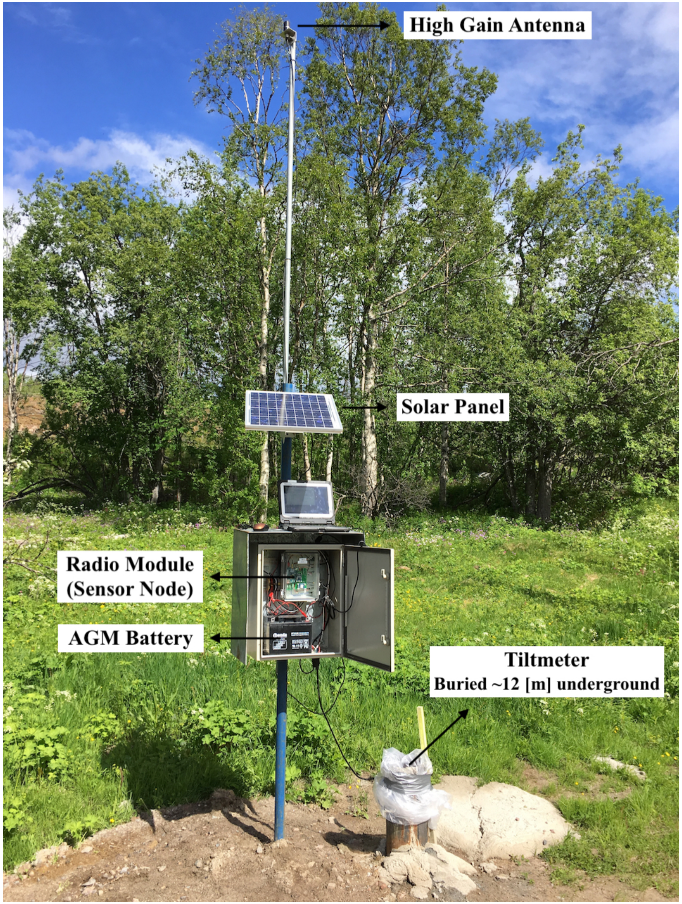
- **Hardware**
  - Replaced MAX RS422 chip for better performance
  - Replaced GPS chip to reduce power consumption
- **Firmware**
  - Optimised the code to minimise current draw
  - Added the ability to update the firmware over the air

Sensor node power consumption before and after optimization

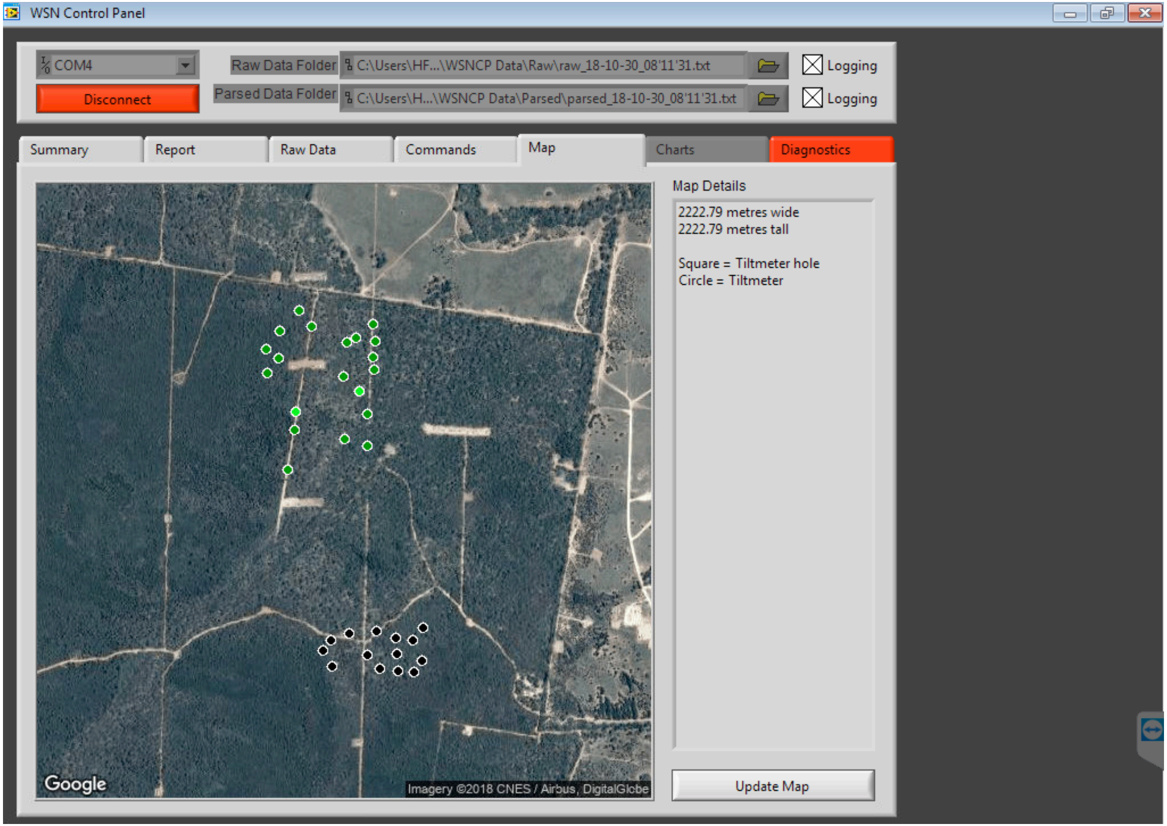


Field deployment

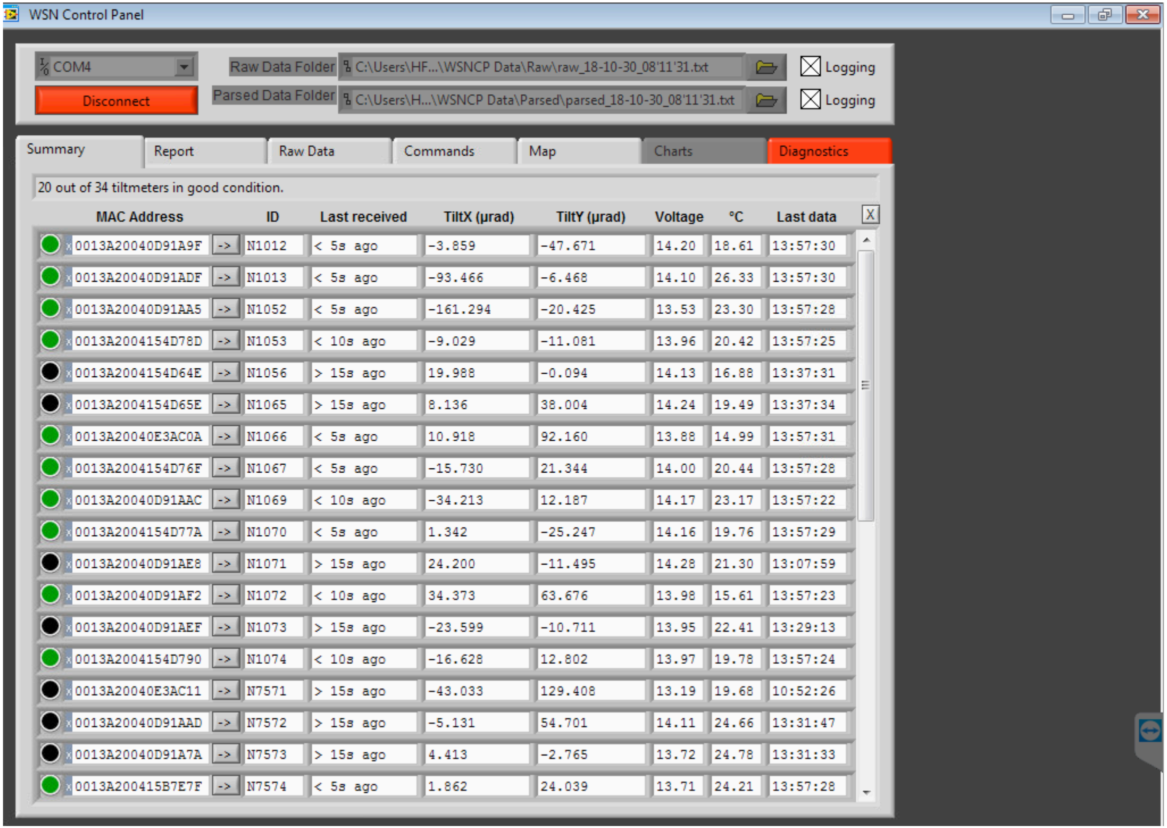
DWSN system node surface setup. Monitoring Hydraulic Fracturing operation at LKAB iron-ore mine in Malmberget, Sweden, July 2017.



Real-time Dashboard

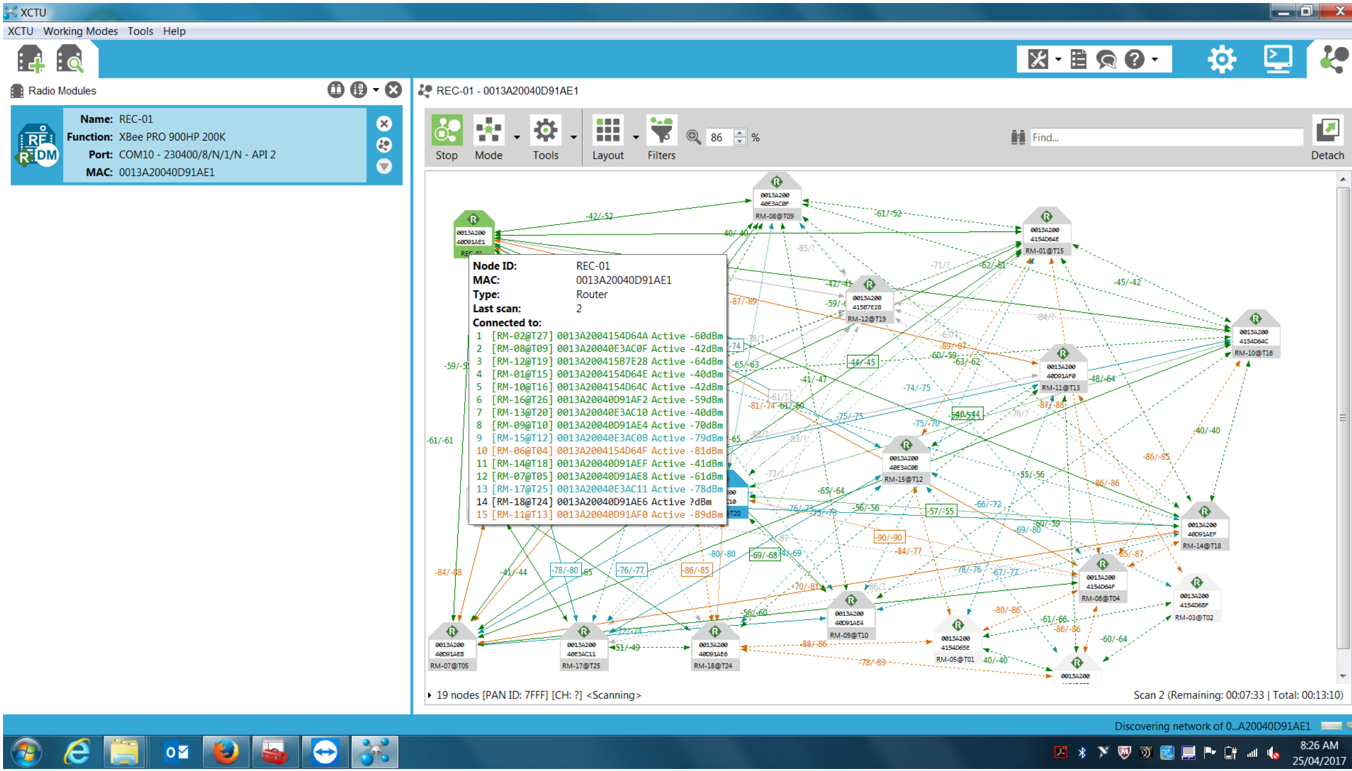


Real-time Dashboard



MAC Address	ID	Last received	TiltX (μrad)	TiltY (μrad)	Voltage	°C	Last data
0013A20040D91A9F	N1012	< 5s ago	-3.859	-47.671	14.20	18.61	13:57:30
0013A20040D91ADF	N1013	< 5s ago	-93.466	-6.468	14.10	26.33	13:57:30
0013A20040D91AA5	N1052	< 5s ago	-161.294	-20.425	13.53	23.30	13:57:28
0013A2004154D78D	N1053	< 10s ago	-9.029	-11.081	13.96	20.42	13:57:25
0013A2004154D64E	N1056	> 15s ago	19.988	-0.094	14.13	16.88	13:37:31
0013A2004154D65E	N1065	> 15s ago	8.136	38.004	14.24	19.49	13:37:34
0013A20040E3AC0A	N1066	< 5s ago	10.918	92.160	13.88	14.99	13:57:31
0013A2004154D76F	N1067	< 5s ago	-15.730	21.344	14.00	20.44	13:57:28
0013A20040D91AAC	N1069	< 10s ago	-34.213	12.187	14.17	23.17	13:57:22
0013A2004154D77A	N1070	< 5s ago	1.342	-25.247	14.16	19.76	13:57:29
0013A20040D91AE8	N1071	> 15s ago	24.200	-11.495	14.28	21.30	13:07:59
0013A20040D91AF2	N1072	< 10s ago	34.373	63.676	13.98	15.61	13:57:23
0013A20040D91AEF	N1073	> 15s ago	-23.599	-10.711	13.95	22.41	13:29:13
0013A2004154D790	N1074	< 10s ago	-16.628	12.802	13.97	19.78	13:57:24
0013A20040E3AC11	N7571	> 15s ago	-43.033	129.408	13.19	19.68	10:52:26
0013A20040D91AAD	N7572	> 15s ago	-5.131	54.701	14.11	24.66	13:31:47
0013A20040D91A7A	N7573	> 15s ago	4.413	-2.765	13.72	24.78	13:31:33
0013A200415B7E7F	N7574	< 5s ago	1.862	24.039	13.71	24.21	13:57:28

Wireless communication quality



XCTU software for monitoring the connection quality of XBee radio transceivers.

CSIRO

What was delivered?

- **Hardware**
  - 50 radio modules (sensor nodes) and 8 receivers were manufactured.
  - The radio modules were deployed within the following projects:
    - Whitehaven Coal Mine, Narrabri, NSW (since April 2017, ongoing)
    - LKAB Iron Ore Mine, Kiruna, Sweden (Deployed Underground, May 2017)
    - LKAB Iron Ore Mine, Malmberget, Sweden (Deployed on Surface, July-August 2017)
- **Firmware**
  - Developed the code in C (Arduino IDE Environment)
  - Additional level of data security provided by using on-board memory
  - GPS for clock synchronisation as well as location identification
  - API mode enabled for XBee modules (packets / frames / checksums)
  - Power management system / Sleep Mode
- **Real-time Display**
  - Data visualization, real-time diagnostics, quality control, sensor calibration

Section 3:

Hydraulic Fracturing Automation

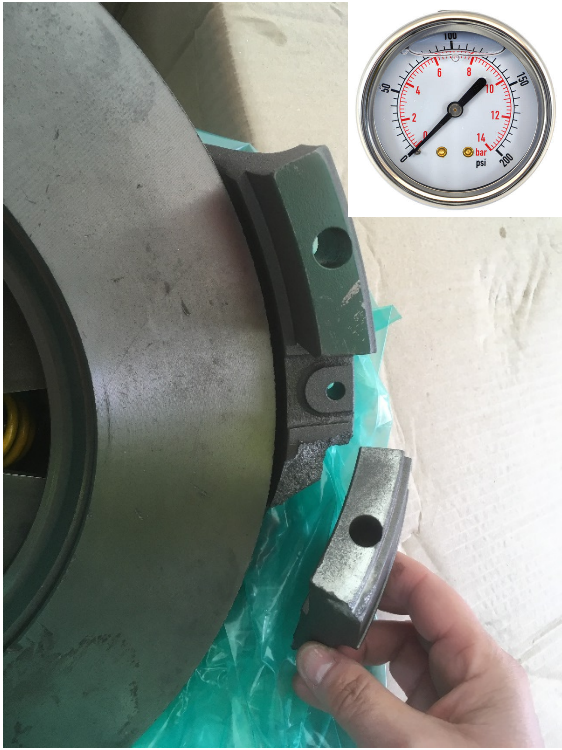
Hydraulic Fracturing Equipment

- Provide high-pressure and flowrate for injection into the borehole.

- Traditionally operator sits in a drivers cabin or stands next to the pump.

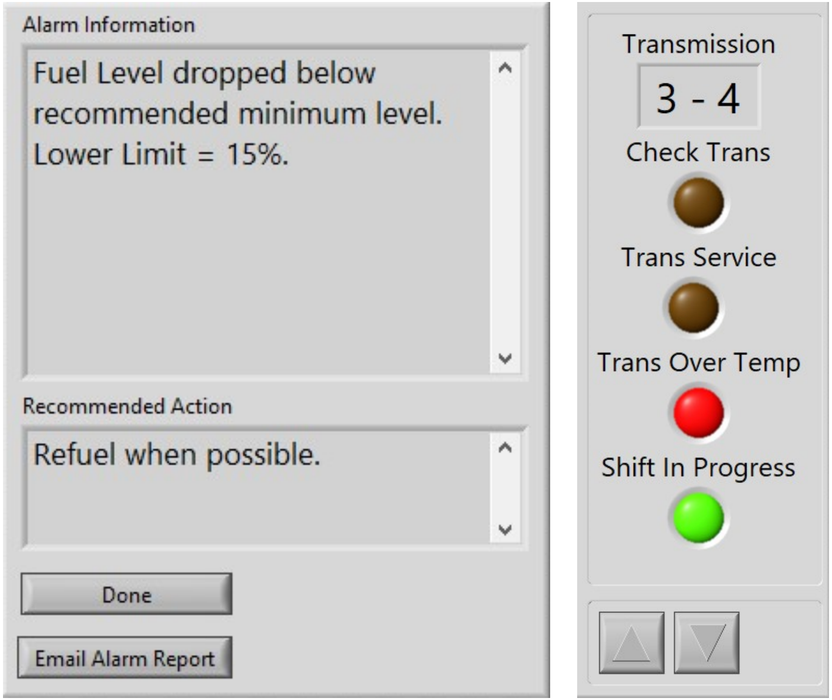
Current Issues

- Too many parameters for a single person to watch & react to in case of an error.
- Damaged equipment results in high cost due to downtime and repairs.
- Operators must be next to the equipment to operate it.



Value of Equipment Management System

- Remote monitoring of operational parameters can catch these issues & trigger safety system.
- Less cost & downtime for repairs & maintenance.
- Increased safety of operators.



Equipment Management System

- No single solution exists on the market that suits our needs.

- Pre-existing platforms exuberantly expensive.

- Develop a remote monitoring solution in-house harnessing open source electronics.

Instrumentation

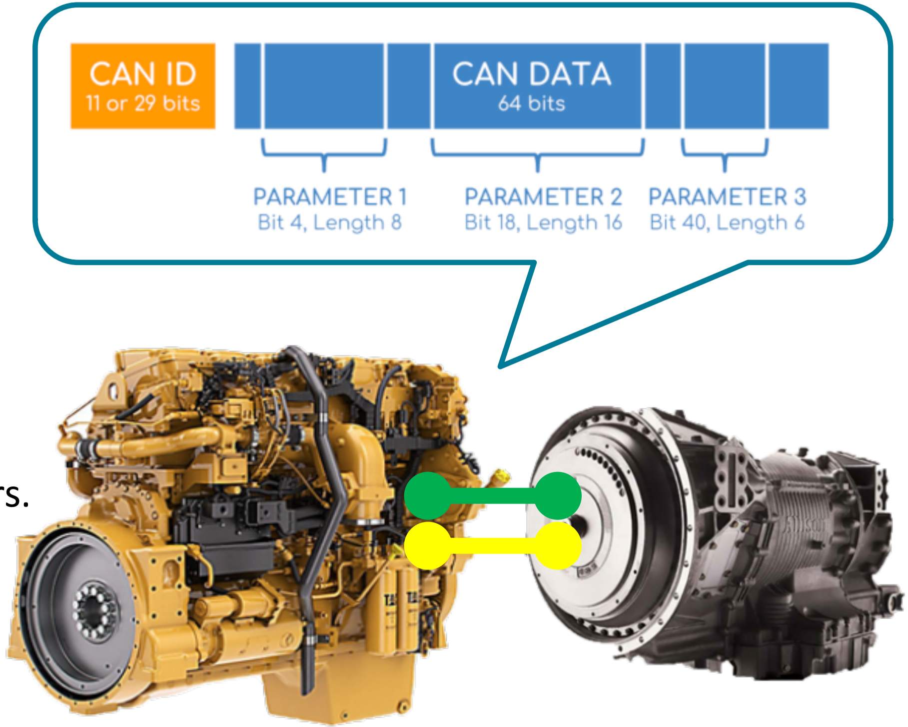
- Operational information used directly by the operator using the equipment.

- External sensors
  - Magnetic flowmeters, pressure transducers, proximity switches.

Instrumentation

- Diagnostic information used to diagnose the health of equipment in real-time.

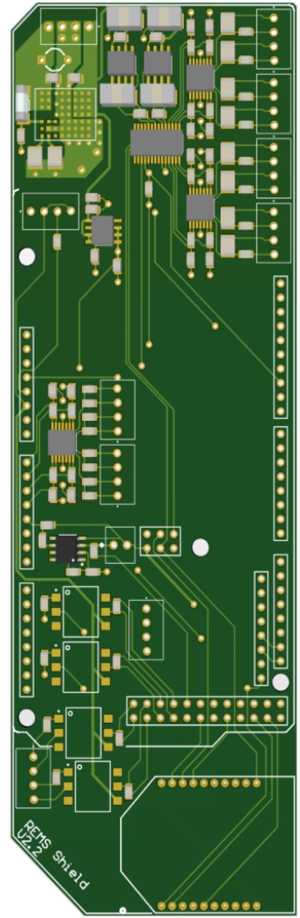
- CAN Bus & external sensors.
  - Engine & Transmission ECU's, pressure and temperature transducers.



Data Acquisition

- Identify sensor outputs and design appropriate input interfaces.
  - 4-20mA analog signal
  - 0-24V digital logic signal
  - 0-180Ω resistive load

- Consider data acquisition requirements.
  - Resolution, Samples Per Second
  - Noise & Filtering



Wireless Network Hardware

- Identify wireless network requirements
  - High-throughput, low-range requirements and ensure delivery of data packets.

- XBee S6B Wi-Fi modules
  - Connect to existing 802.11b/g/n networks
  - Setup Adhoc and Infrastructure networks.

Wi-Fi Network

- DHCP allows networks to be setup dynamically without additional configuration of the modules.
- TCP protocol ensures delivery of data and in correct sequence.
- Through-put and interface data rates meet requirements.

Data Acquisition Boxes

- Open source electronics & libraries allowed rapid development of prototypes.

- Arduino platform provides a lot of support and comes with well vetted software and libraries.

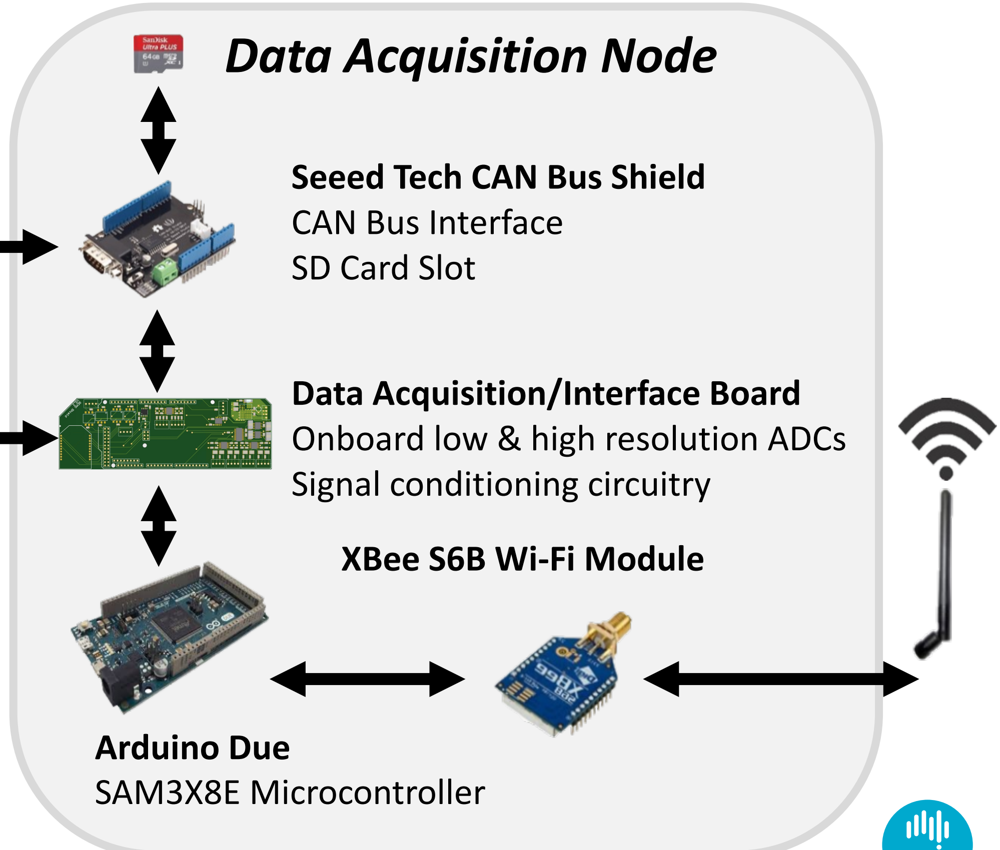
ARDUINO
OPEN-SOURCE
COMMUNITY

CSIRO

Data Acquisition Boxes

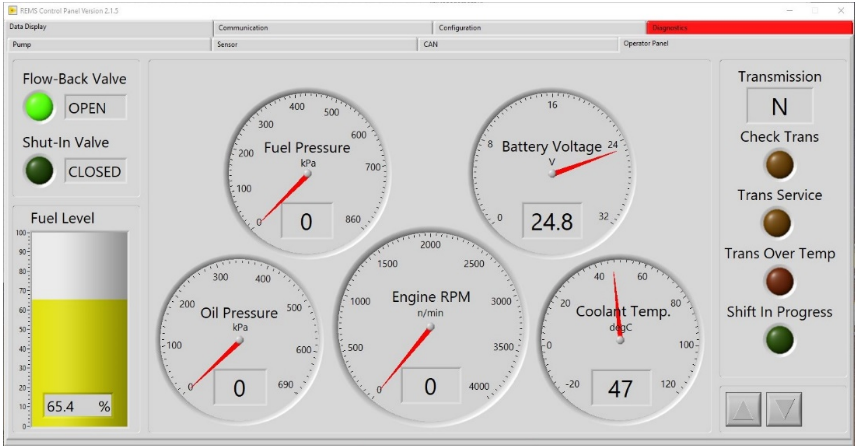
CAN Bus
Transmission ECU's
Engine ECU's

External Sensors
Flowrate Sensor
Pressure Transducers
Temperature Transducers
Fuel Level Sensors
Proximity Switches



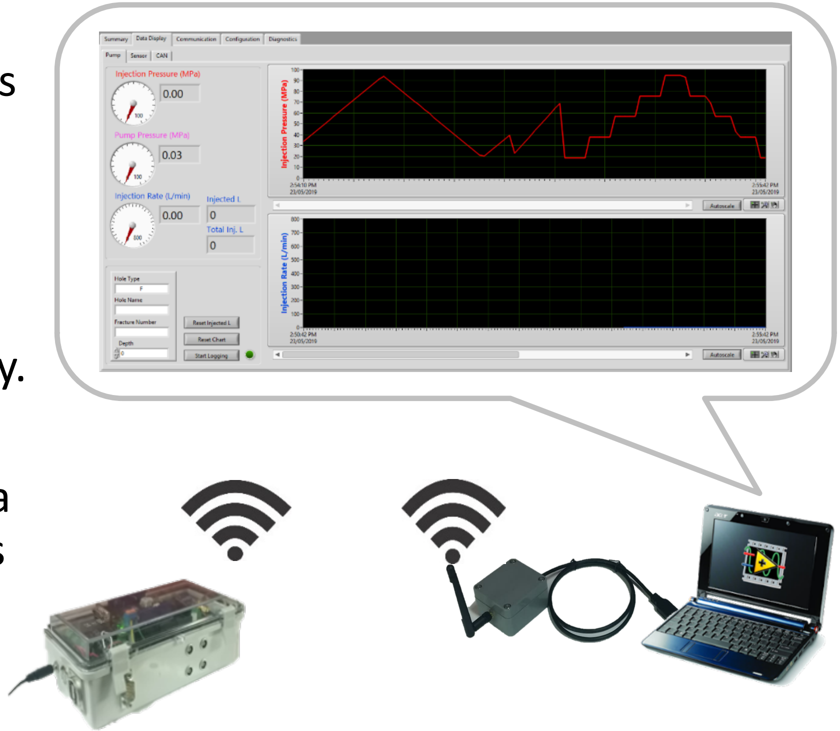
Control Panel

- Data is accumulated at a central point by the LabVIEW control panel program.
- Converts data from the sensors and CAN bus to meaningful values.
- Incorporates data visualisation, data logging, alarm systems, & safety systems.



Equipment Management System

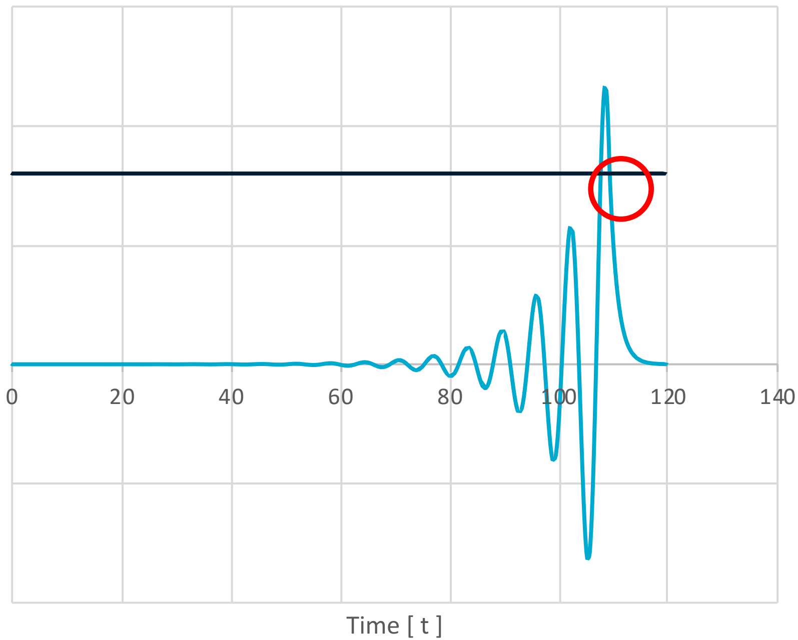
- Data acquisition system allows collection of various operational & diagnostic parameters.
- Wi-Fi modules allow data to be transmitted remotely.
- Control Panel running on a remote computer receives and displays the data. Implemented alarm and safety systems.



CSIRO

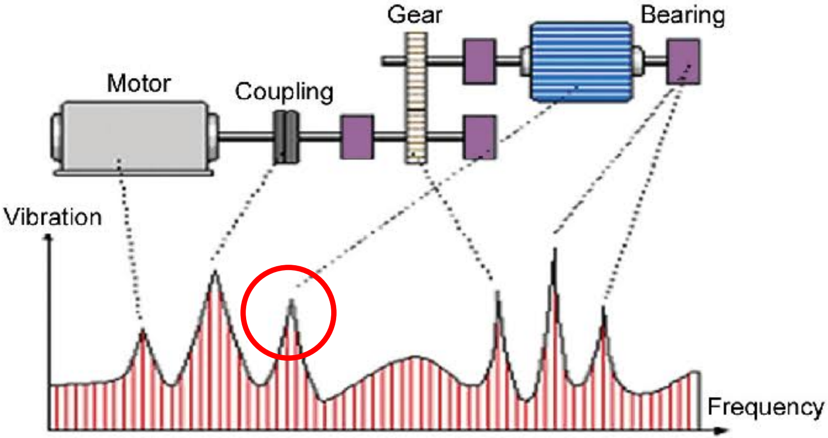
Preventative Control

- Monitoring system can catch issues and alert the user to take action.
- Some safety systems need to be activated immediately.
- Remote control of relays, allowing the equipment to be thrown into neutral mode.



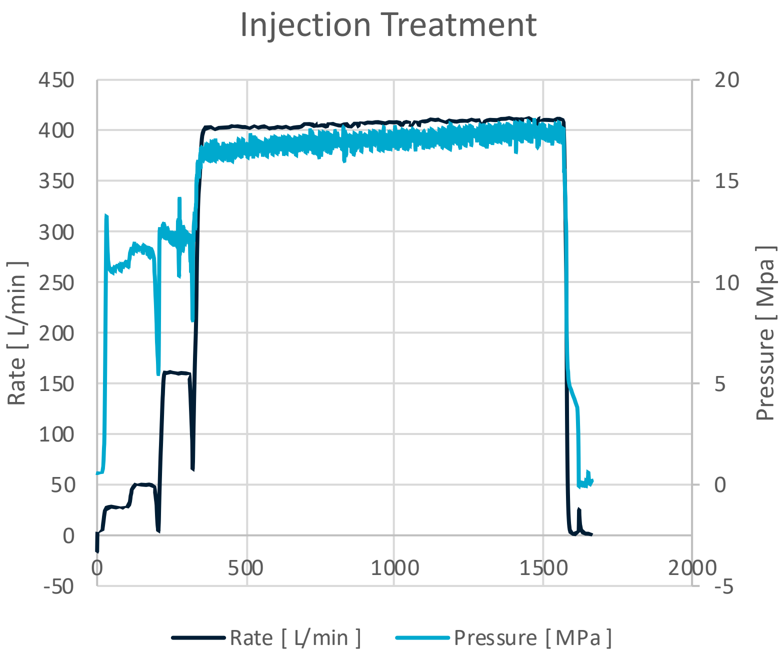
Predictive Maintenance

- Currently planned & corrective maintenance largest factors for downtime.
- Apply machine learning techniques to analyse anomalies in equipment operation
  - Perform maintenance as needed.



Automating/Optimising Fracturing Treatments

- Implement control systems to automate the fracturing process.
- Designing fracturing treatments beforehand.
- Optimise breakdown process & fracturing treatments for each borehole.



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Section 4:

Conclusion and Future Works

Conclusion

- Over a period of two years, the system successfully monitored the placement of more than 2000 hydraulically- induced fractures in real-time.
- The DWSN system provided an average packet delivery success rate of more than 99.995%.
- The DWSN system reduced the time required for sensor calibration from days to minutes.
- The DWSN system improved the quality of the recorded tilt data significantly by minimizing data loss across the network and removing data access latency limitations .
- The DWSN system demonstrates the advantage of developing in-house low-cost (250 AUD per node) and low-power data collection system using open-source electronics platforms with modular components

Future Works

- Reducing the system bandwidth (a potential 70% reduction) by replacing the system data encoding format with binary
- Further reducing system power consumption
- Adding a Wi-Fi module to the node for rapid downloading of microSD data
- Implementing LoRa wireless communication technology in underground conditions

Underground HSE hazards

Thank you

Energy
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