Autonomous Underwater Vehicle based Electric and Magnetic Field measurements applied to Geophysical Surveying and Subsea Structure Inspection

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OFG Ocean Floor Geophysics Inc.

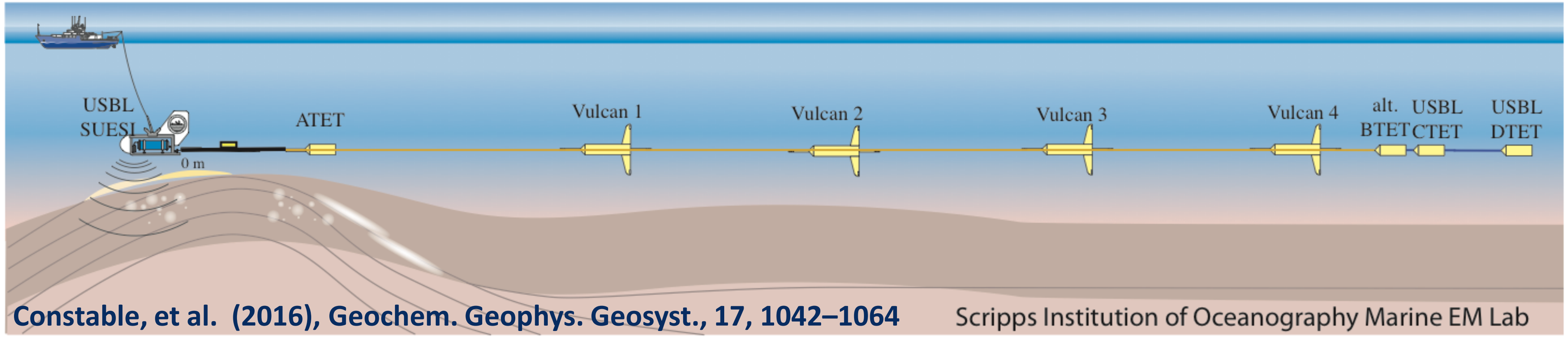
EMinar Series. November 25, 2020 16:00 UTC

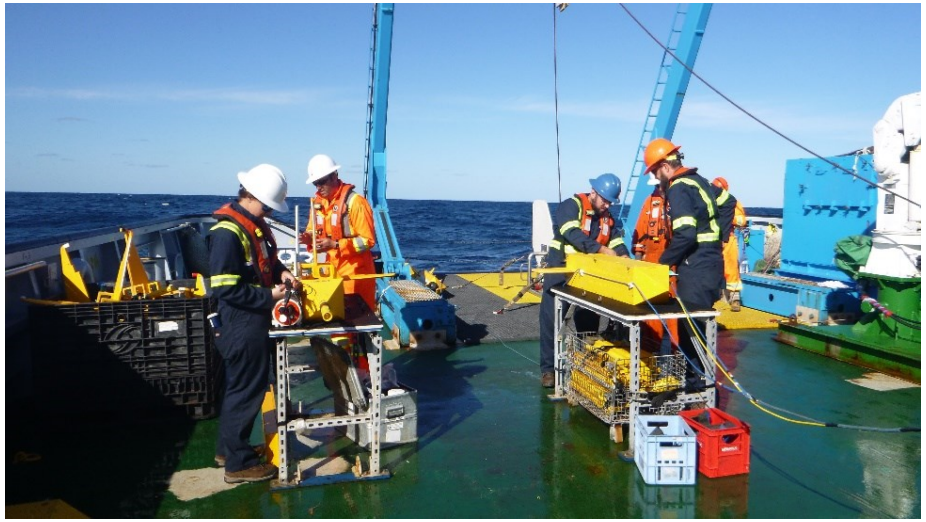
OFG Ocean Floor Geophysics

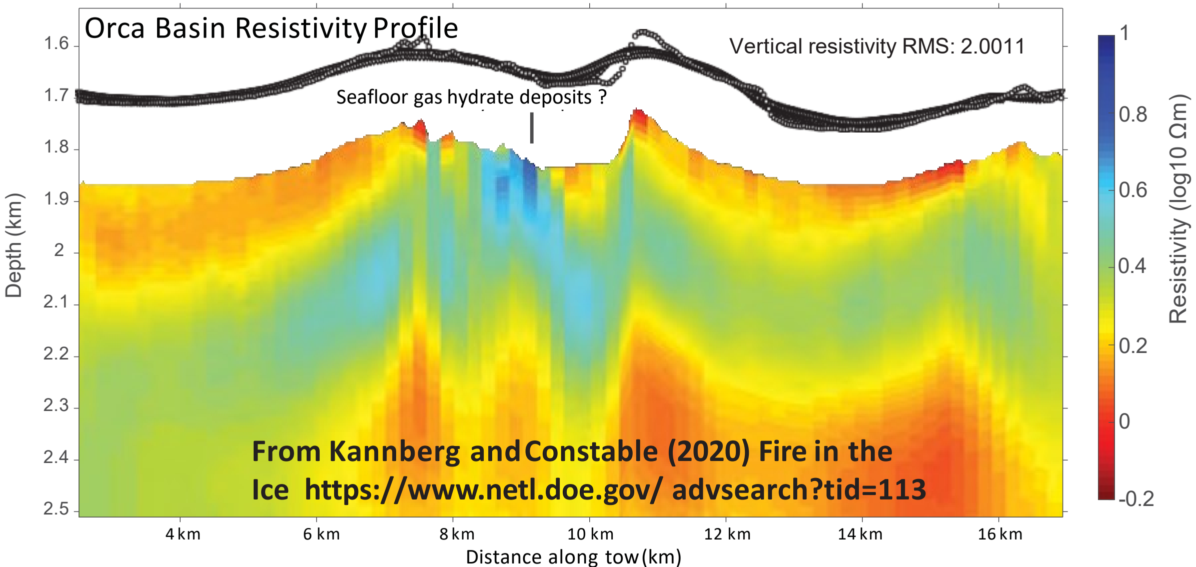
Development

Marine controlled source electromagnetic methods using a deep-towed transmitter and array of electric field receivers

- Precision electric field measurements from quiet towed platforms







The AUV Electric Field Development Time Line

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Development Partners

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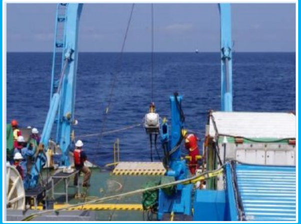
FUKADA SALVAGE & MARINE WORKS CO., LTD.

ISES

2014

First commercial CSEM-Vulcan gas hydrate survey



Discussions about putting electric field sensor onto an AUV

2015

Second commercial CSEM-Vulcan gas hydrate survey

Field Trials of AUV outfitted with electric field sensor

2016

Engineering Test of AUV-CSEM and AUV-SP Surveys

2017

Noise test of electric field measurements on the OFG AUV 'Chercheur'

Third commercial CSEM-Vulcan gas hydrate survey

2018

Field trials of AUV-iCP on a North Sea pipeline using 'Chercheur'

First commercial AUV-CSEM and AUV-SP survey

2019

Test of AUV-iCP system on synthetic pipeline in a pool

Two Commercial AUV-iCP surveys

Two commercial AUV-SP surveys carried out

2020

Remote Field Trials of iCP and SCM on ROV for structure surveys

2021

Field Trials of iCP and SCM for EM ship signature characterization

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Electric Fields

2015

2016

Development Partners

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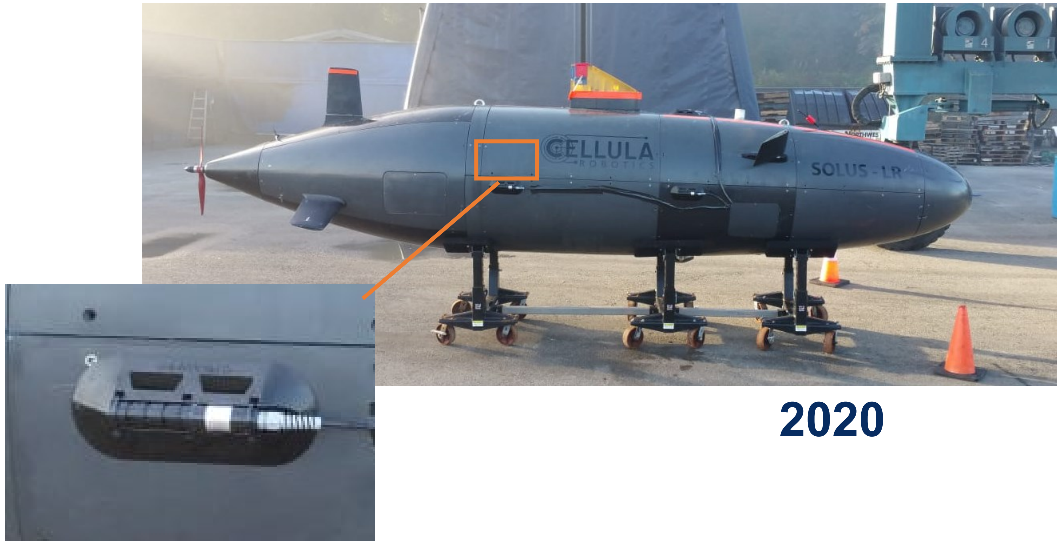
FUKADA SALVAGE & MARINE WORKS CO., LTD.

ISIES

Transition of electric field sensor elements used in deep-towed CSEM onto an AUV

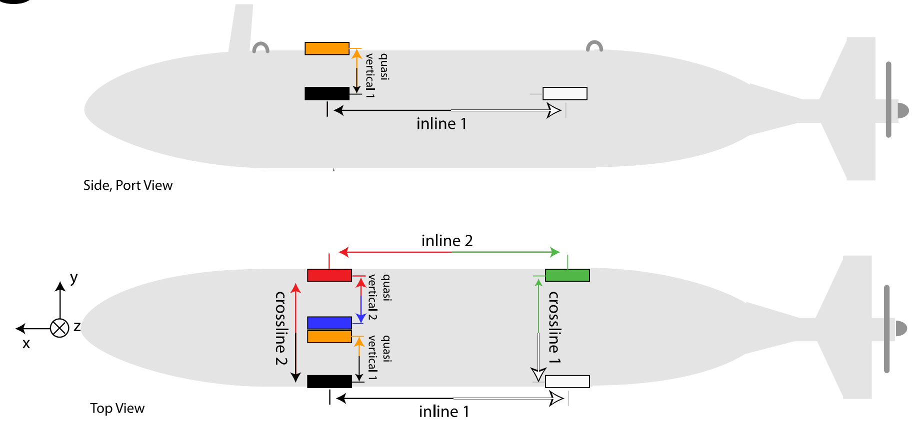
- Use of seafloor transmitters
- Trials in 2015, 2016
- First commercial survey in 2018
- OFG system adapted from the towed system for AUV
- Smaller, tighter integration of electrodes to AUV body



2020

Main components of AUV Electric and Magnetic Field Measurements

Autonomous Underwater Vehicle (AUV) fitted with



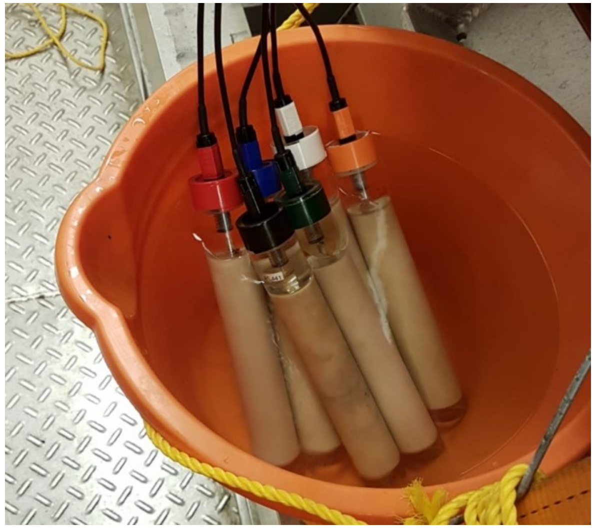
SCM – Self Compensating Magnetometer

3 channel fluxgate magnetometer (X, Y ,Z)
19 Hz sample rate

iCP DAQ– integrated cathodic protection data acquisition unit

6 channel electric field sensor (redundant X, Y ,Z)
100 Hz sample rate

Ag/AgCl electrodes

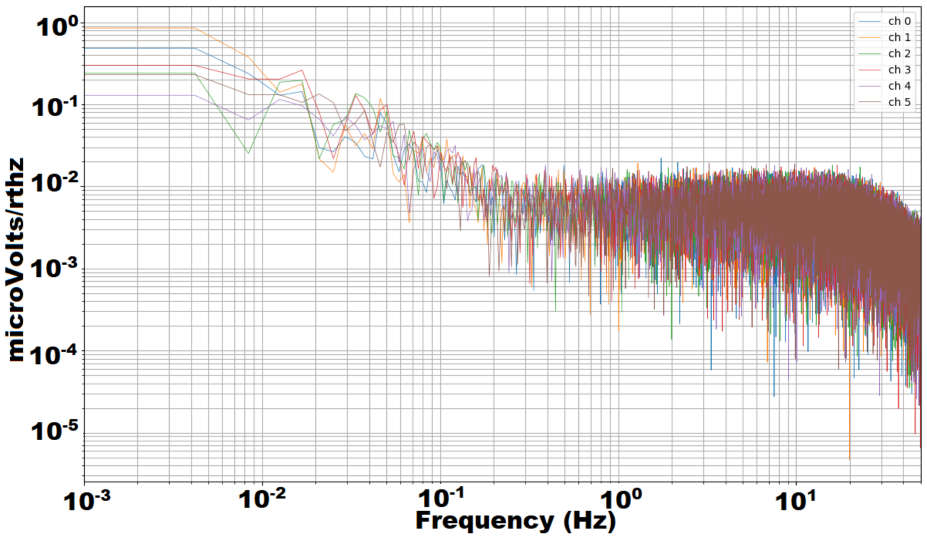


6 low impendence Ag/AgCl electrodes

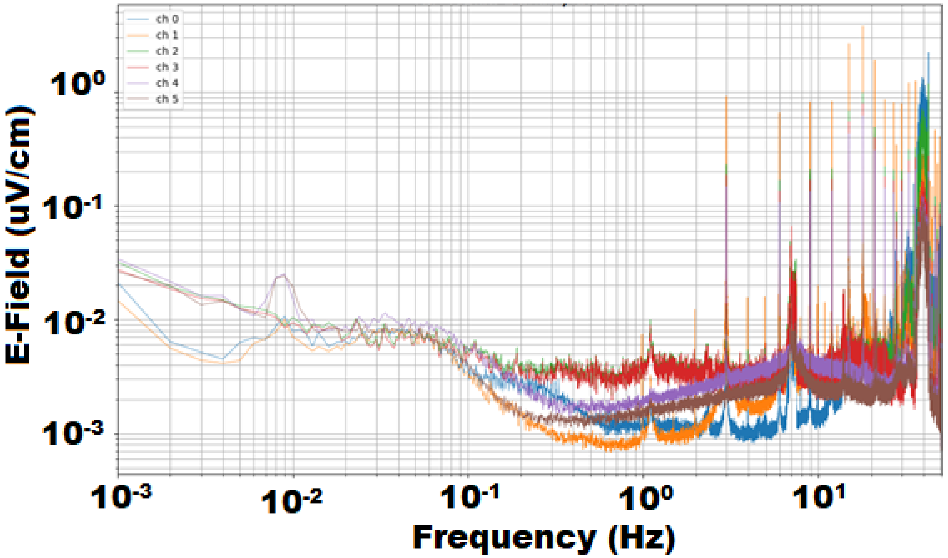
Electric Fields

- Performance/Specifications
  - AgAgCl Electrodes
    - Non polarizing in seawater
  - Digitizer and Amplifier
    - programmable gain array 1X-128X
    - 10Hz – 200Hz
    - Shorted noise performance 12nVrms/rthz at 1Hz
    - Typical installed performance 500nVrms/m/rthz at 1Hz on 1m dipole
  - CSEM
    - Tune transmission frequencies and harmonics around AUV noise peaks
    - Typical frequencies transmitted > 1 Hz

Noise with Shorted inputs (20min)



Noise installed on AUV (~5 hr dive)



Self Compensating Magnetometer Concept

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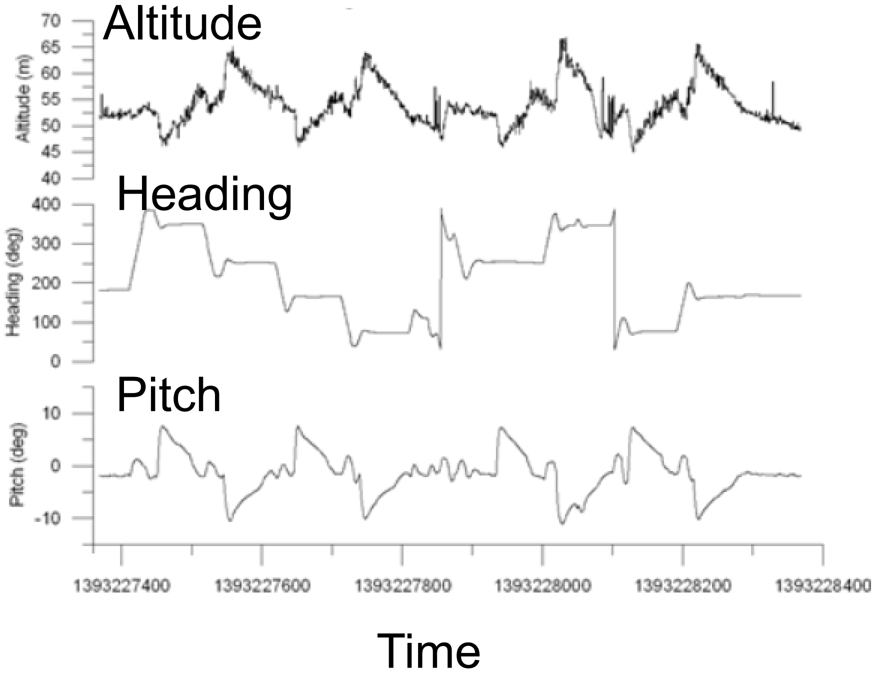
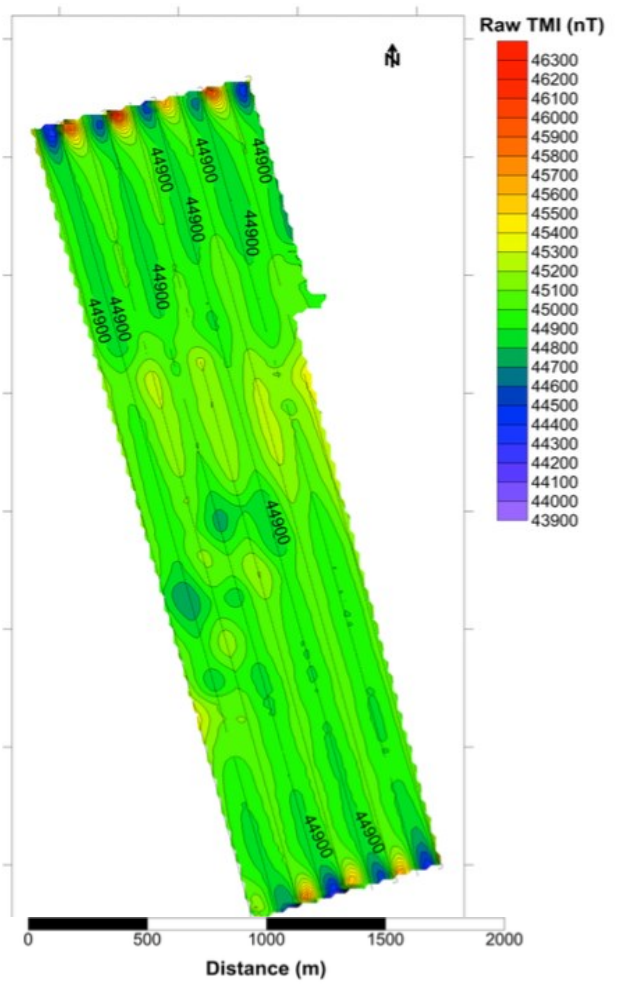
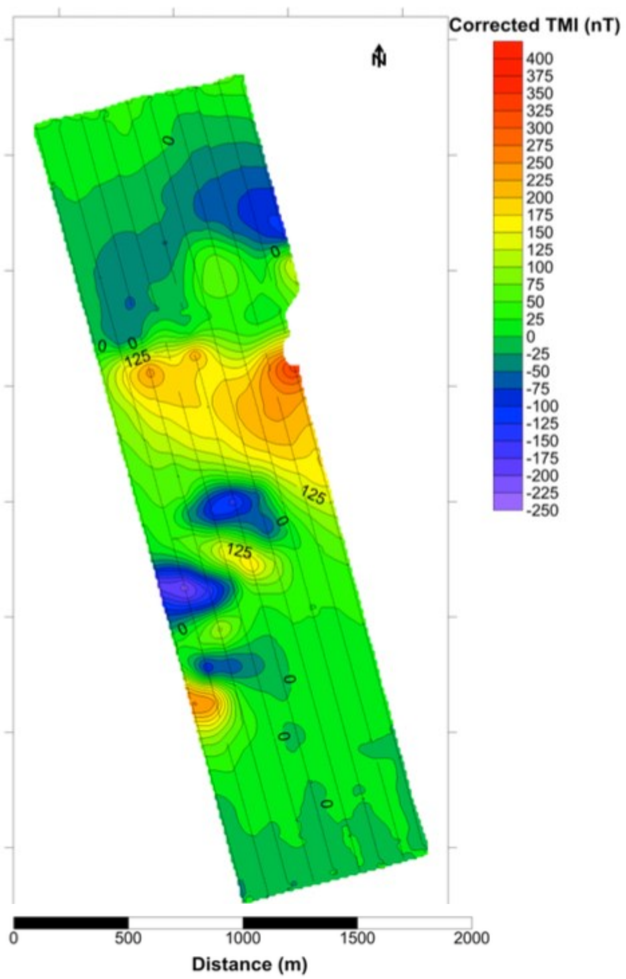


1. Calibration Maneuver
2. Compute Coefficients



3. Collect Survey Data



4. Realtime compensated Data

Bloomer, et al. (2014), in IEEE/OES Autonomous Underwater Vehicles

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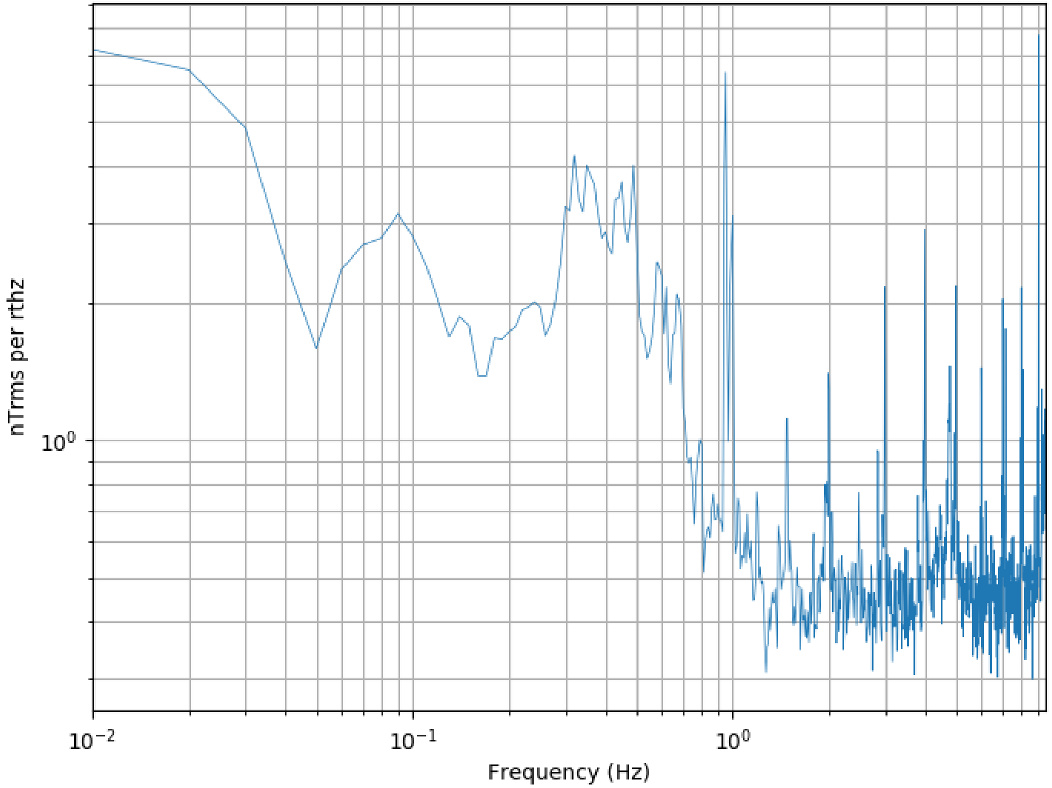
Magnetic Fields

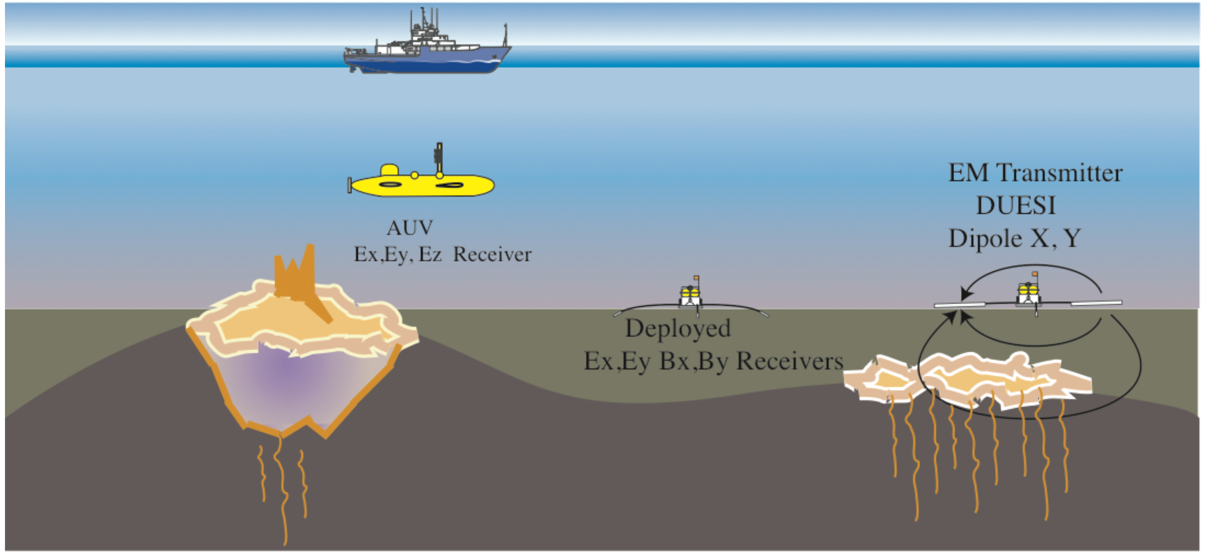
- Self Compensating Magnetometer Performance
  - Uses fluxgate sensor with base noise performance of ~0.04nTrms/rthz
  - Technique is amenable to lower noise sensors



SCM Power Spectra on AUV During Survey
5 hours of data used

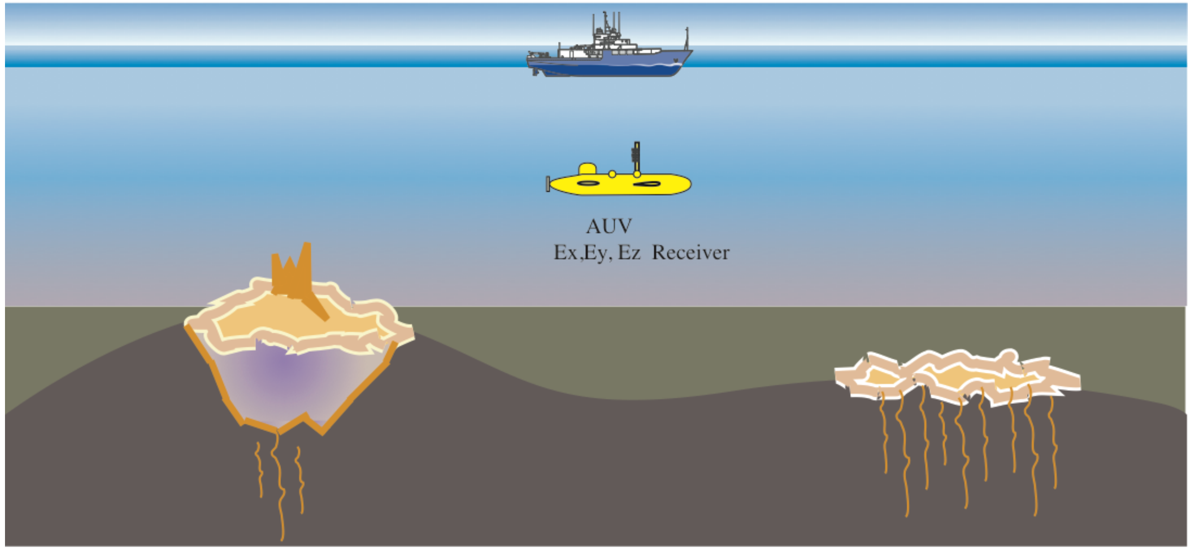
Geophysical Surveys

AUV-CSEM



1 engineering test
1 commercial survey

AUV-SP



1 engineering test and 4 commercial surveys
(e.g. NPD 3900 line kilometres with 3 AUV's)

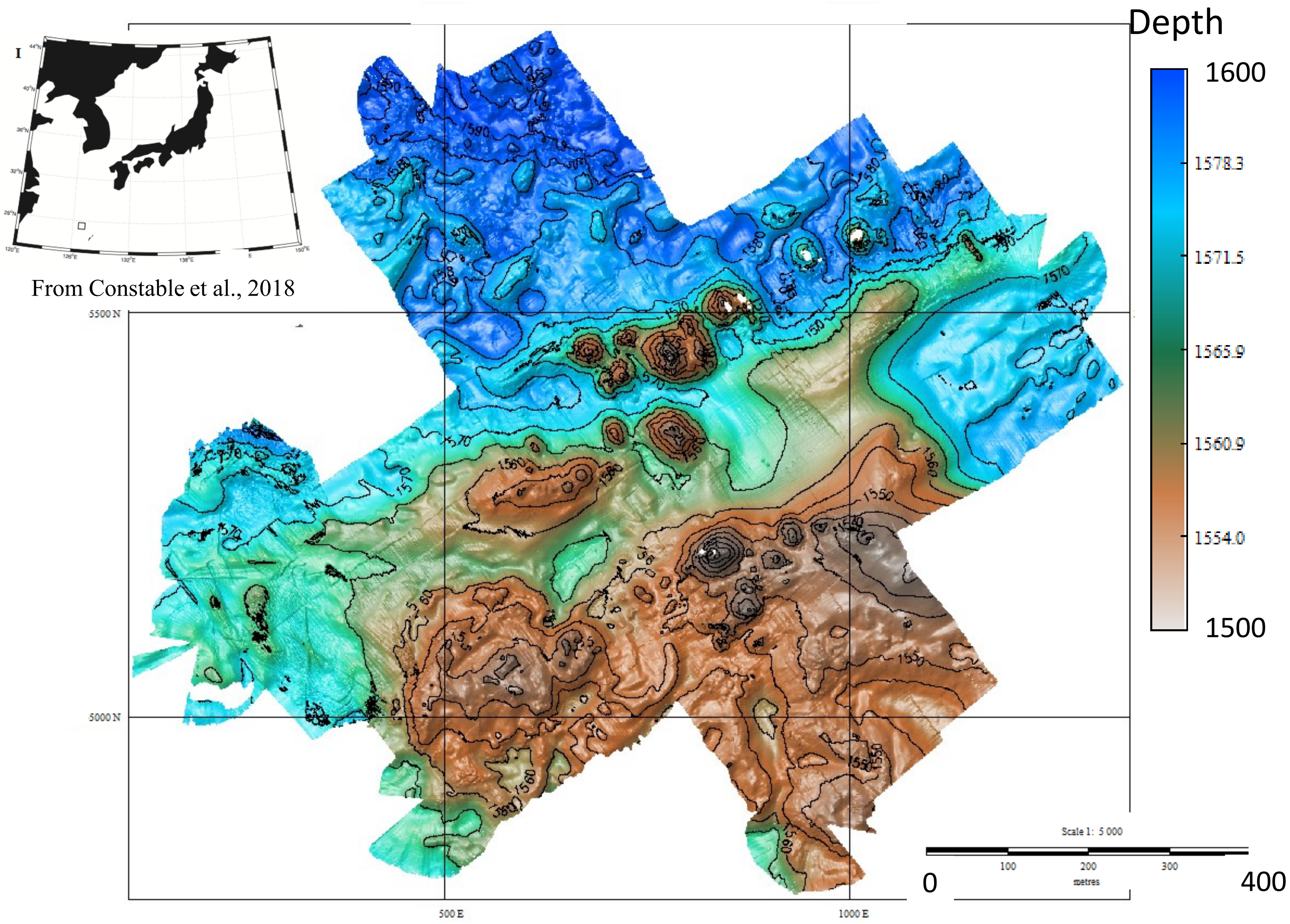
Example data set shown from Iheya area of the Okinawa Trough, off Japan as presented in:

Bloomer et al., 2018 IEEE

Constable et al., 2018 Geophysical Journal International

Constable et al., 2018 SEG International Exposition and 88th annual Meeting

Example Data Set from Iheya



From Constable et al., 2018

Development Partners

UC San Diego | Scripps Institution of Oceanography

Fukada Salvage & Marine Works Co., Ltd.

Final Engineering Tests of AUV-SP and AUV-CSEM

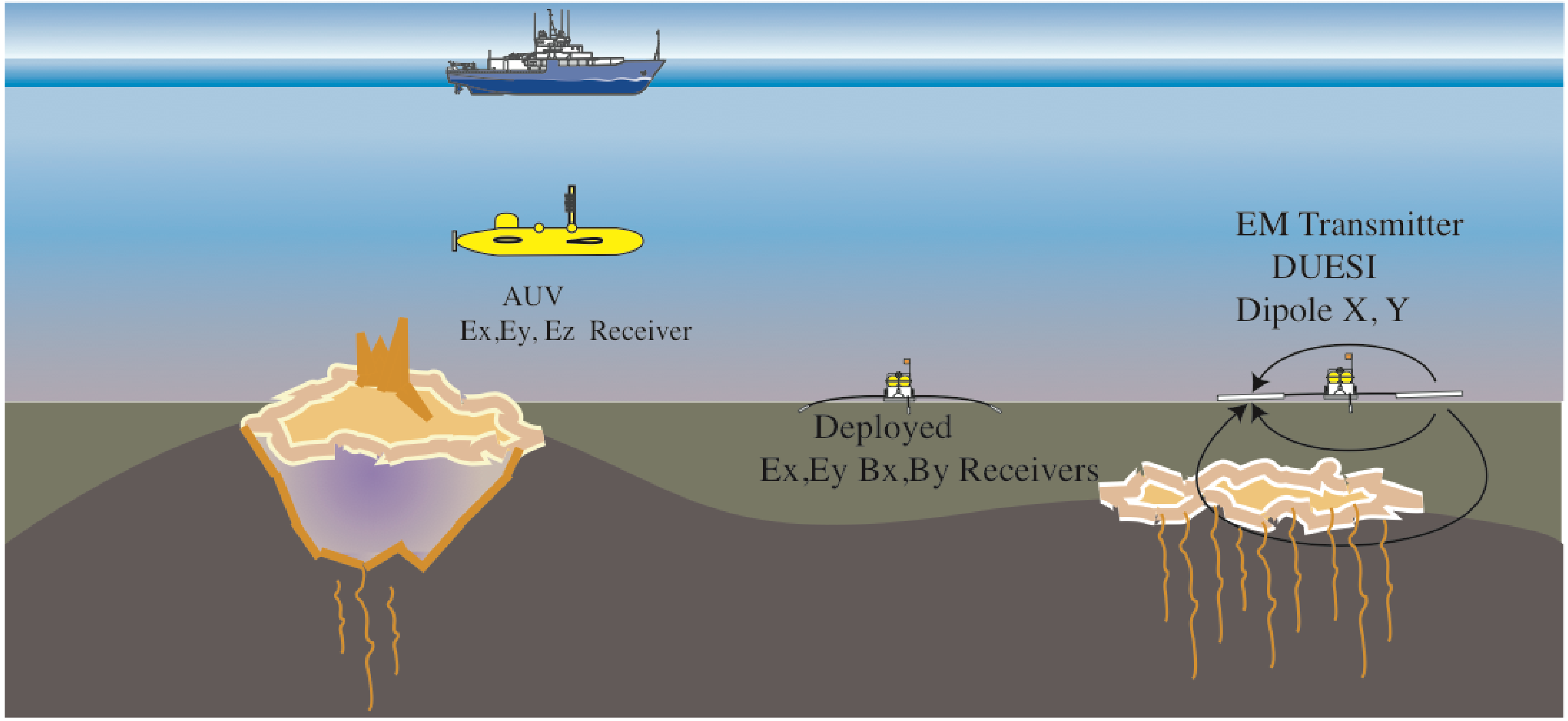
Collected typical AUV payload data:

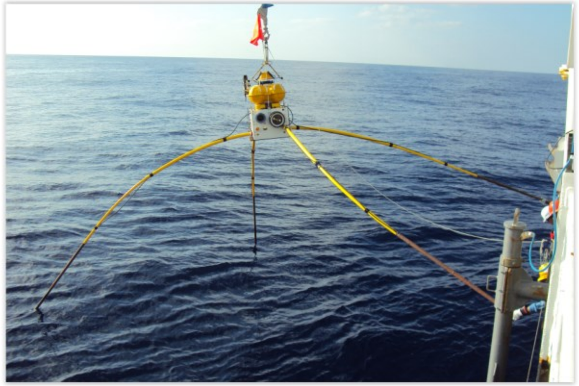
- multi-beam bathymetry (shown)
- side-scan sonar
- sub-bottom profiler
- water chemistry (pH/ORP) data
- magnetic field (SCM) data
- Turbidity data

Added a new sensor, the electric field sensor that collected both AUV-SP and AUV-CSEM data simultaneously.

Did three repeat passes over a 1200 m by 1100 m area.

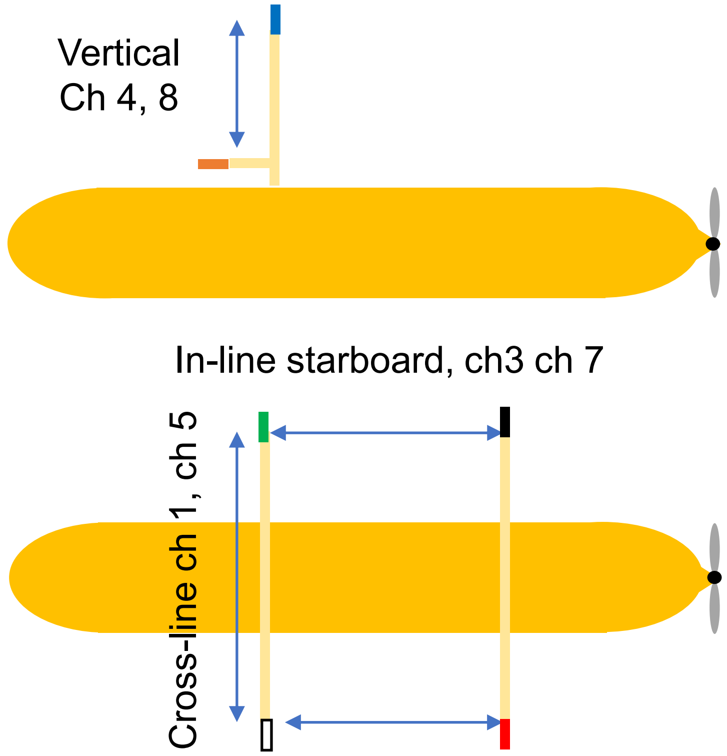
AUV-CSEM

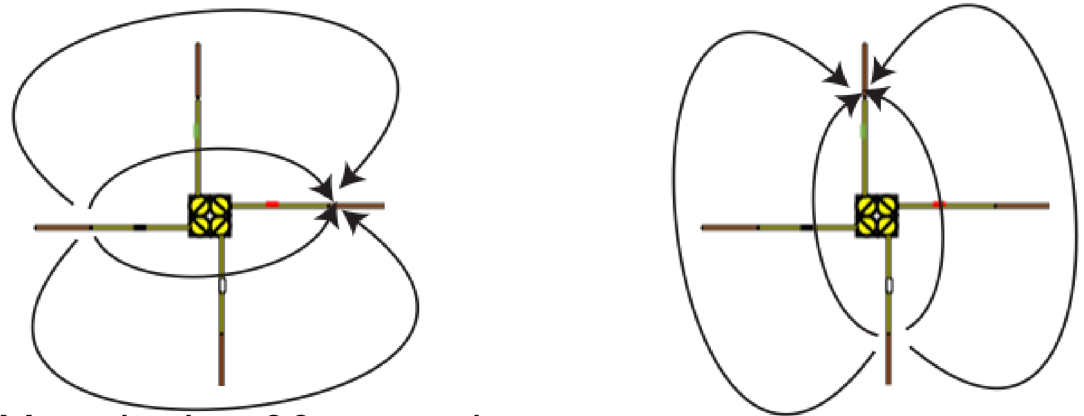




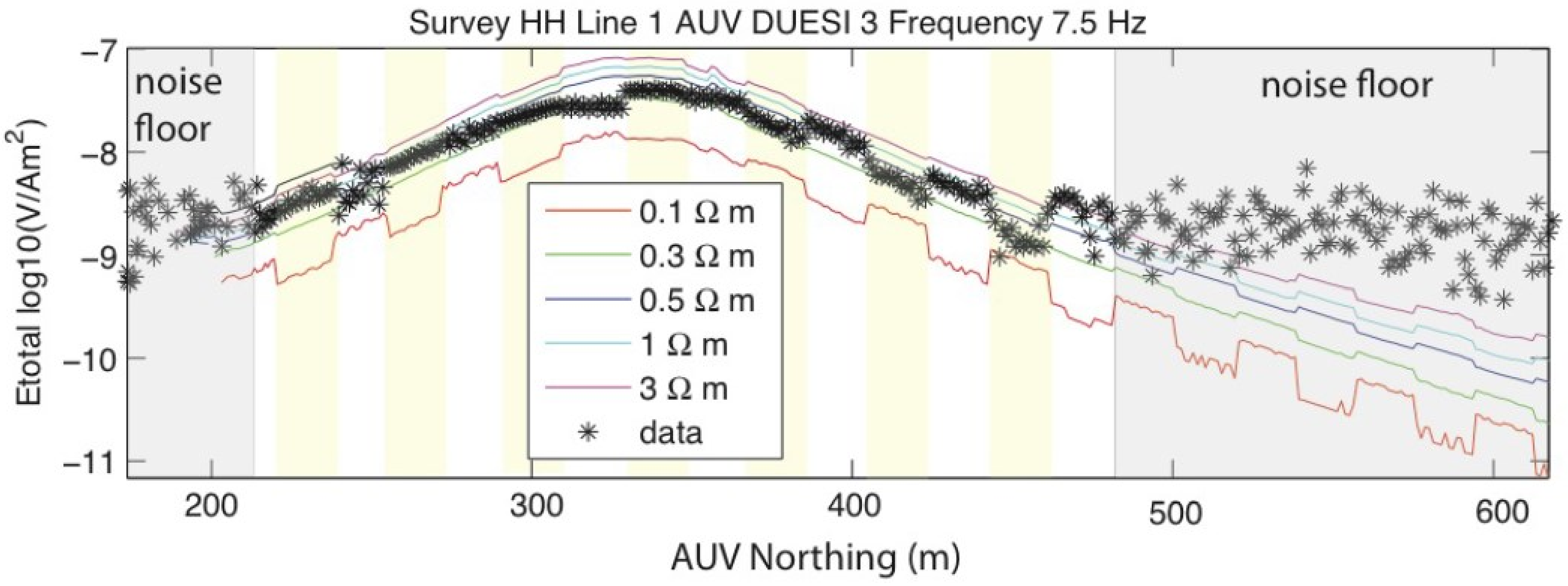
- For AUV CSEM one or more seafloor transmitters are deployed and the AUV acts as a mobile receiver
- Can also deploy fixed receivers.
- Collaboration between OFG, SIO, Fukada developed the AUV-CSEM methods
- First reported in Bloomer et al 2016 IEEE and refined since then.

AUV-CSEM





- Transmitter outputs a 20A D-wave from 10 m dipoles at specified frequencies ~1-10 Hz.
- Receiver observes how the response changes spatially as the AUV surveys an area.



AUV-CSEM Processing Workflow

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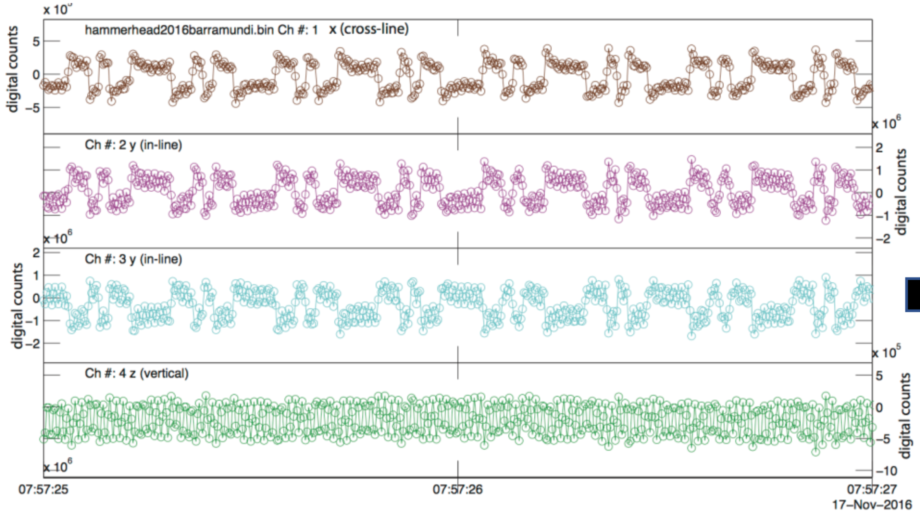
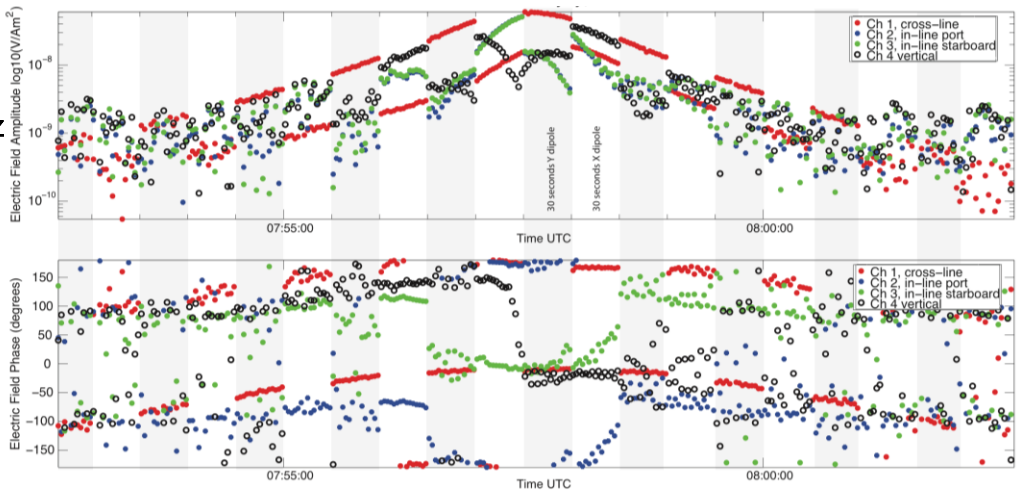
Time Series



2 sec FFT
(fundamental & harmonics)

Repeat for each DUESI: @ 2 Hz, 2.5 Hz
Correct for amplifier response
Normalize by SDM and ideal square wave coefficients
Receiver drift corrections
Transmitter drift corrections
clean

Amplitude and Phase



May stack data here 4, 8, 16, 30 seconds possible

Merge with navigation

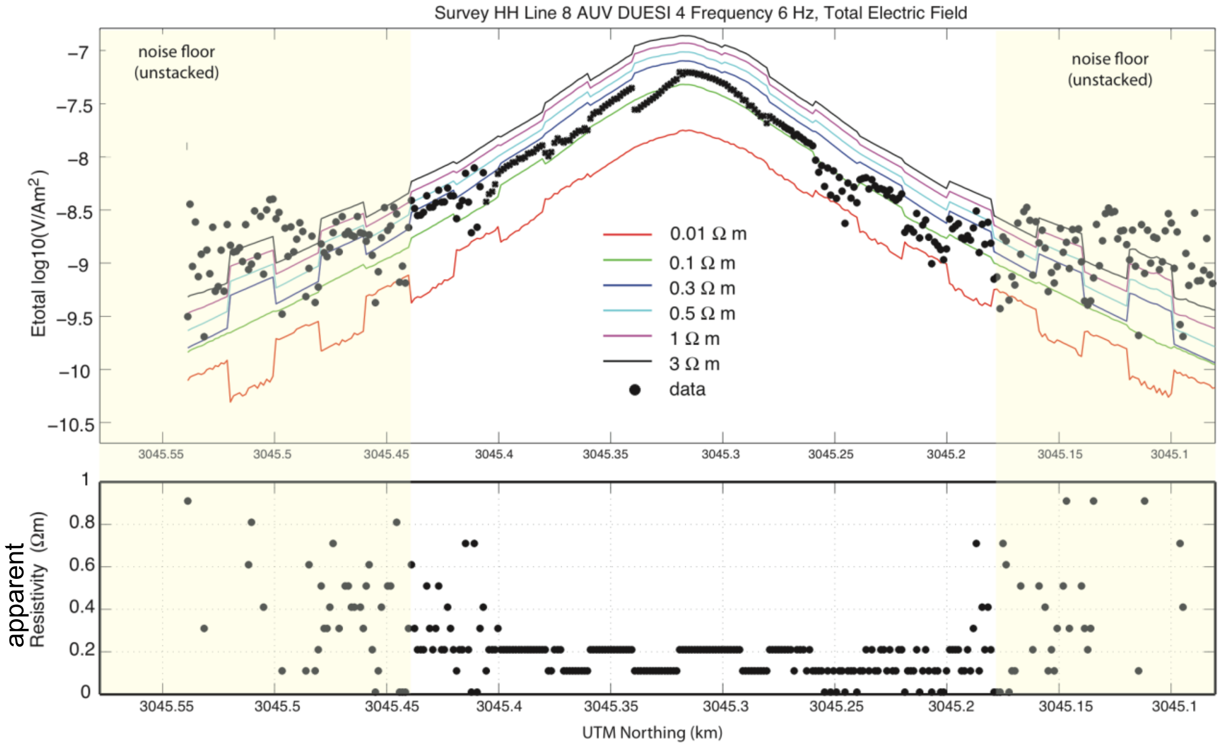
DUESI X, Y, Z, heading, pitch
AUV X, Y, Z, altitude, heading, pitch, roll
X, Y, Z all electrodes for Rx and Tx

1D half-space forward modelling

Using Dipole 1D (Key, 2009)
and Etotal or Pmax

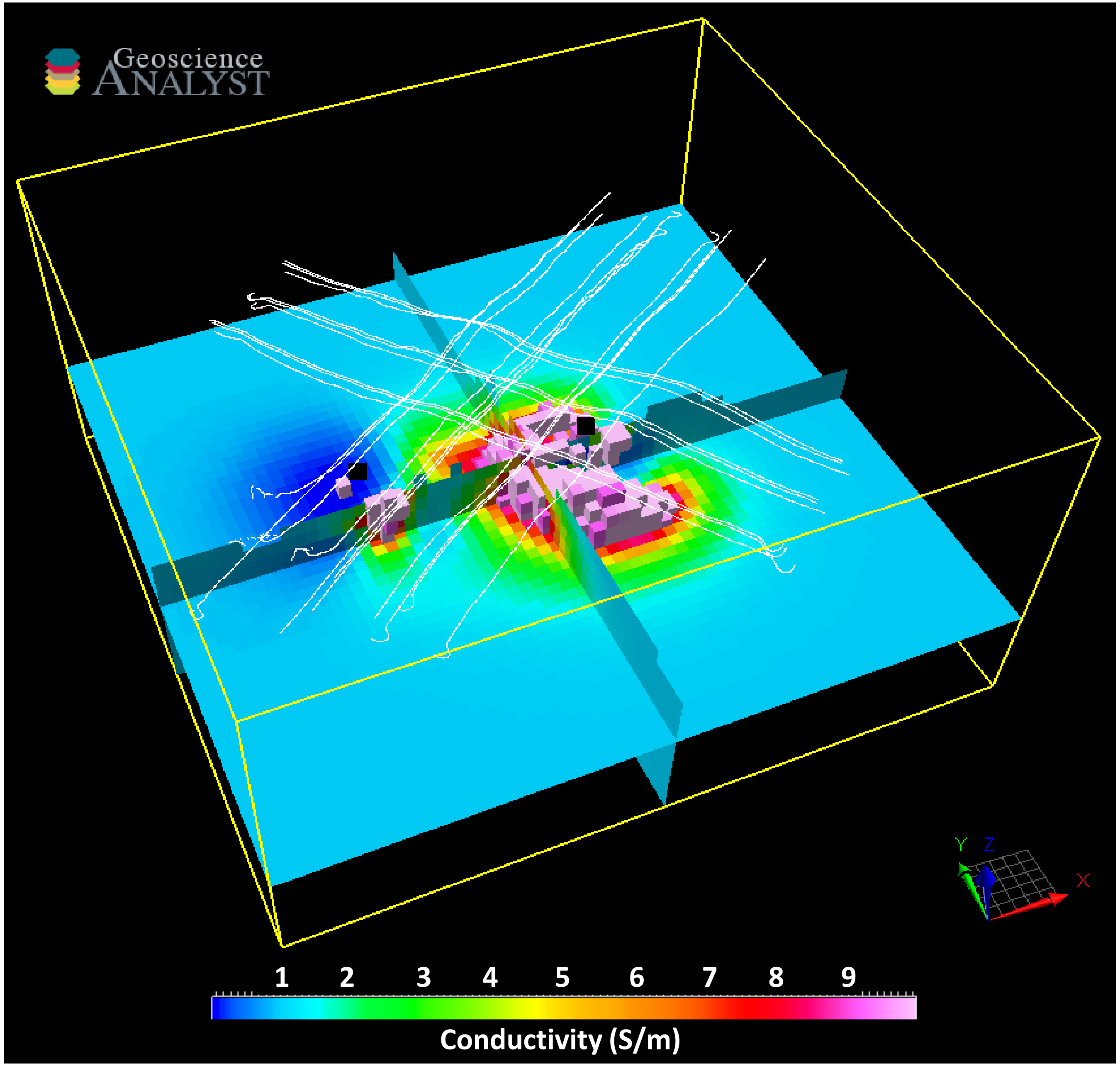
1D half-space forward modelling

1D apparent resistivity

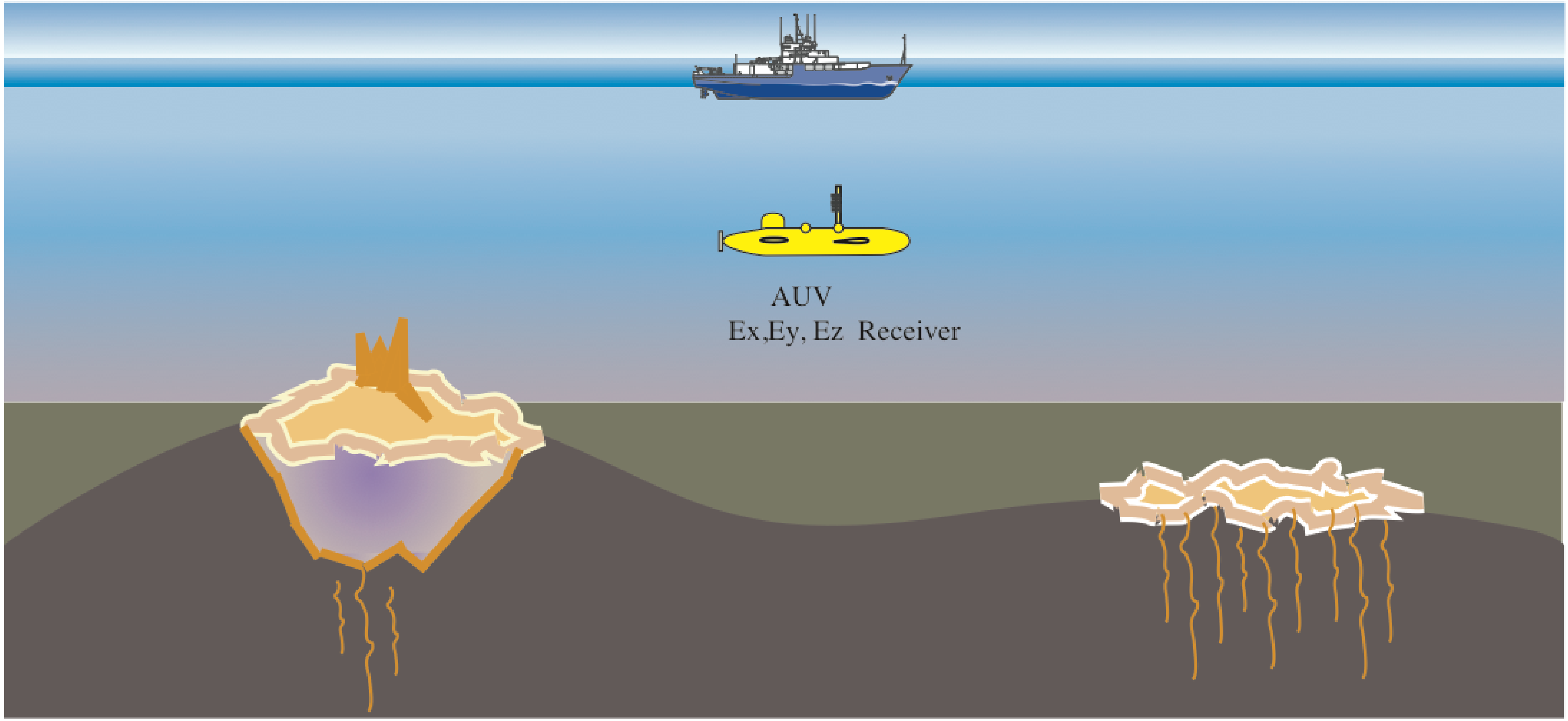


3D Conductivity Volume

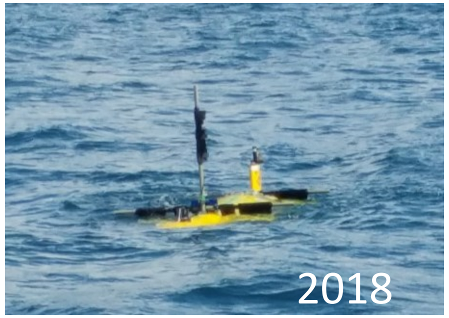
- Data processed by Constable
  - Frequencies: 2.0 Hz, 2.5 Hz, 6.0 Hz, 7.5 Hz, 14.0 Hz, 17.5 Hz, 26.0 Hz, 32.5 Hz
  - Ex, Ey amplitude only inversion.
- Data inverted by CGI
  3D conductivity model
- Pink iso-surfaces encompass conductivities from 8.9 -10 S/m.



AUV-SP



Mineralizing feeder structure, part of regional fault system and veining associated with mineralization



AUV-SP – Repeat Passes

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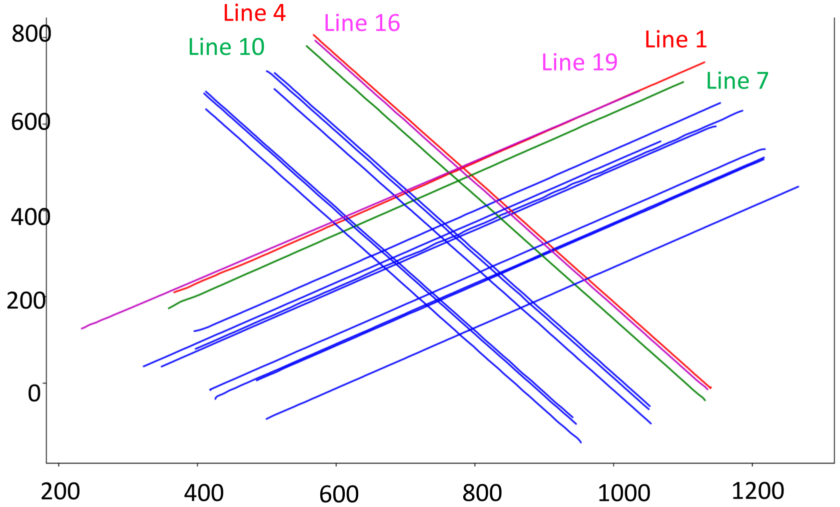
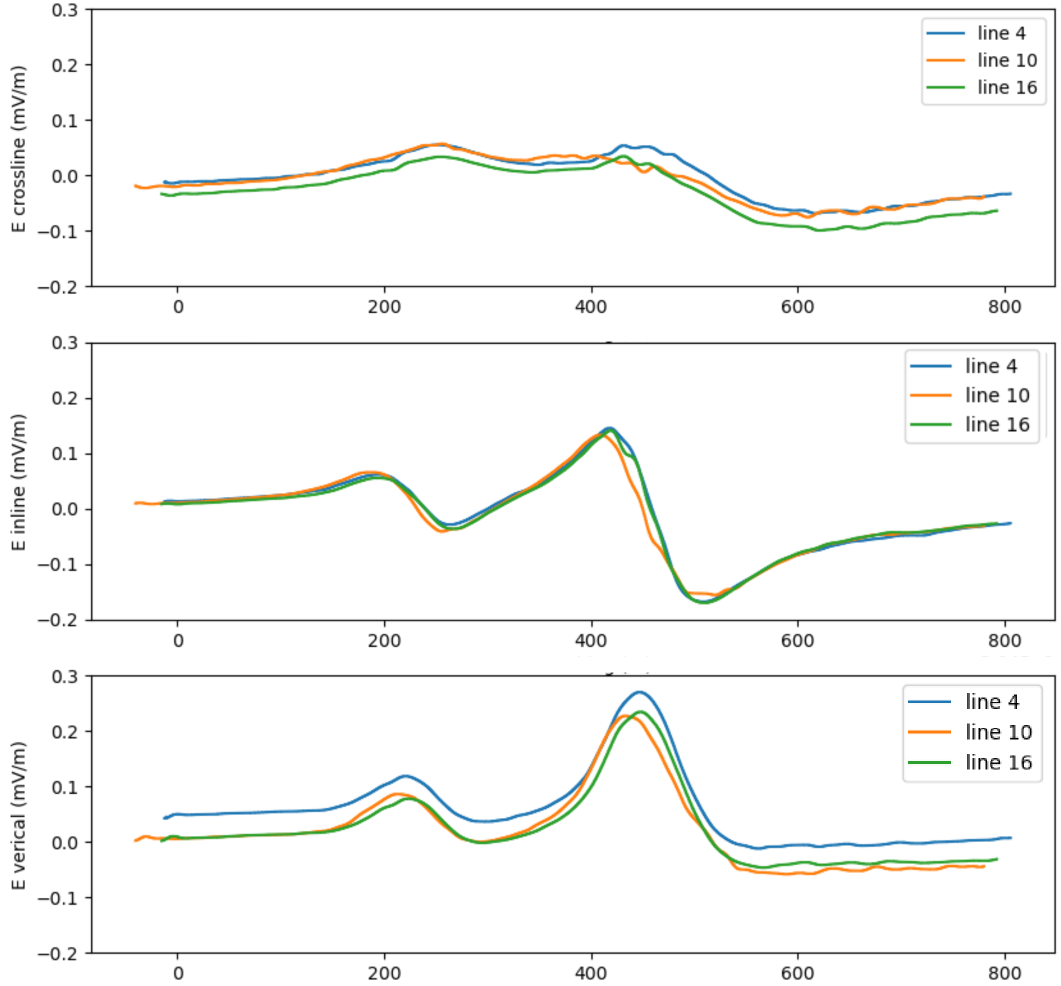
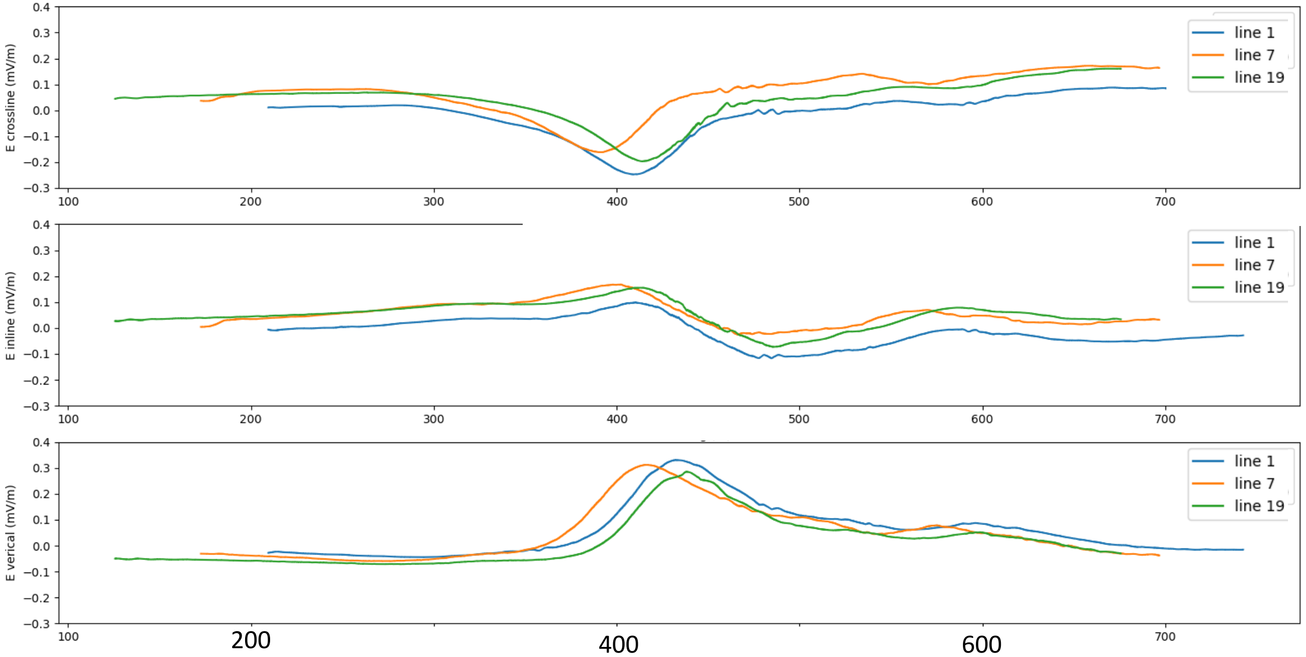
Three repeat passes of the same approximate Location with similar 3 component electric fields.





Northing distance (m)



Northing distance (m)

Similar to Fig 6 in Constable et al., GJI 2018

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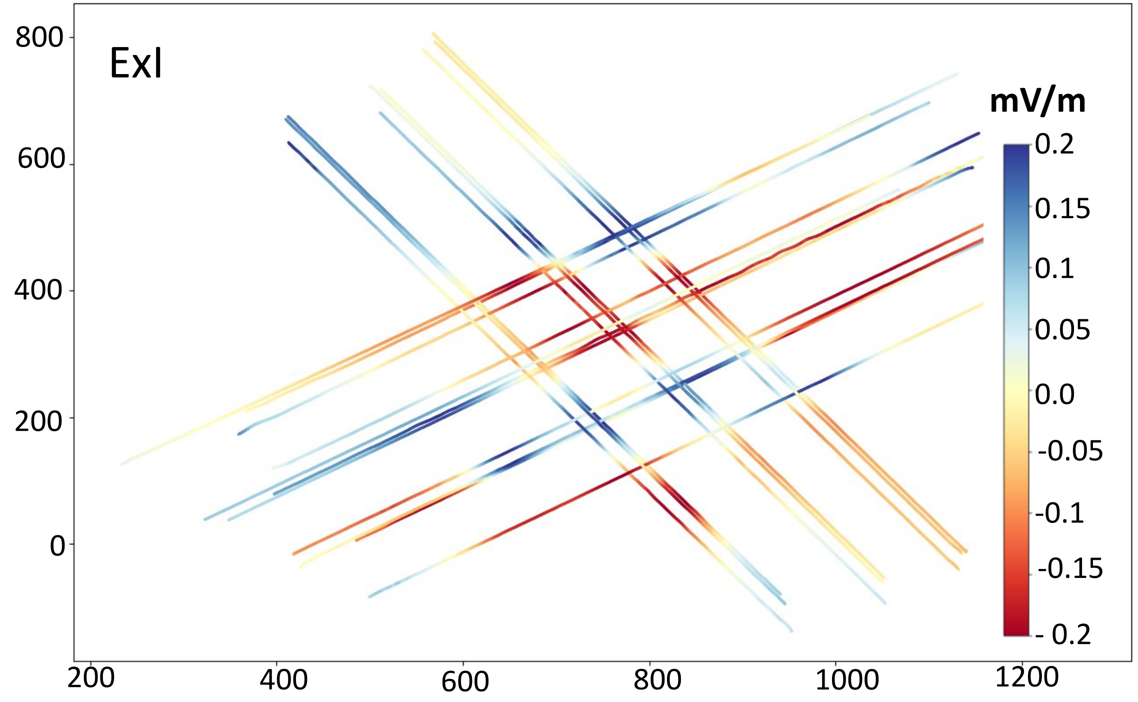
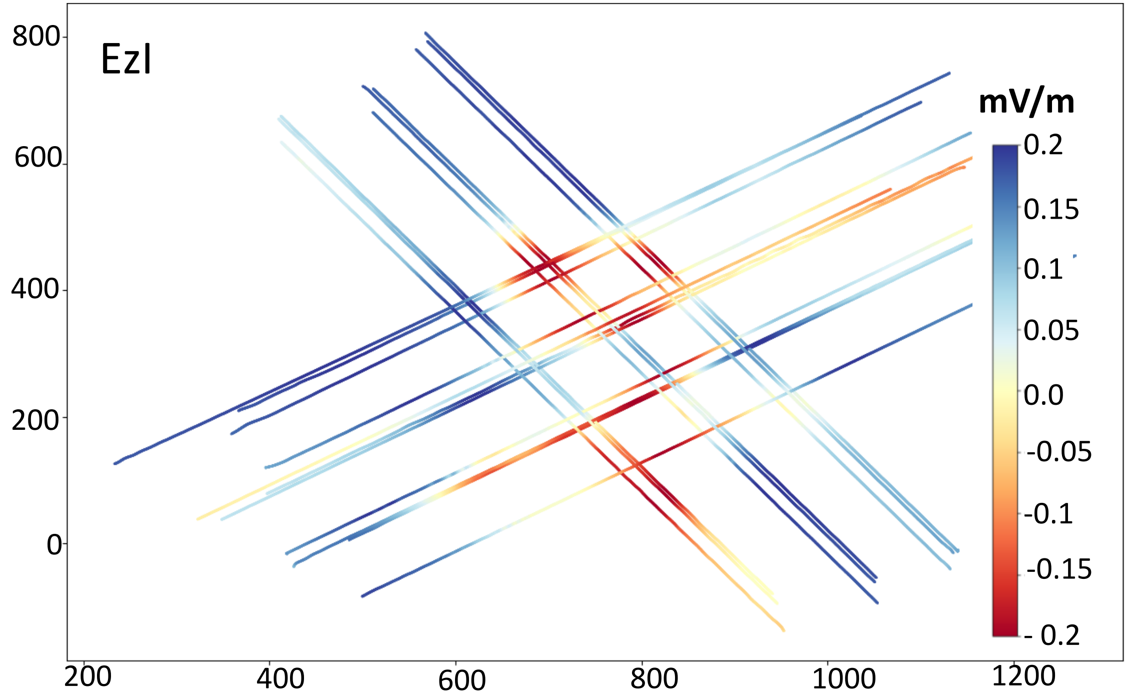
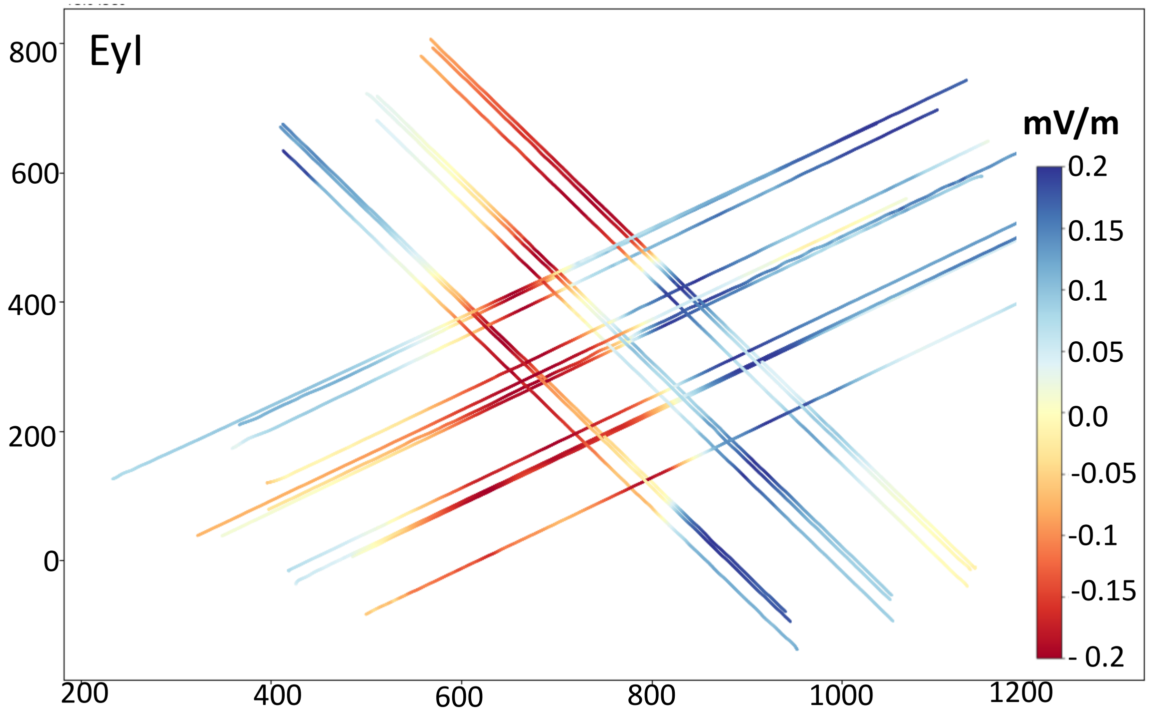
AUV-SP – Repeat Passes in Map View

Crosslines are in broad general agreement

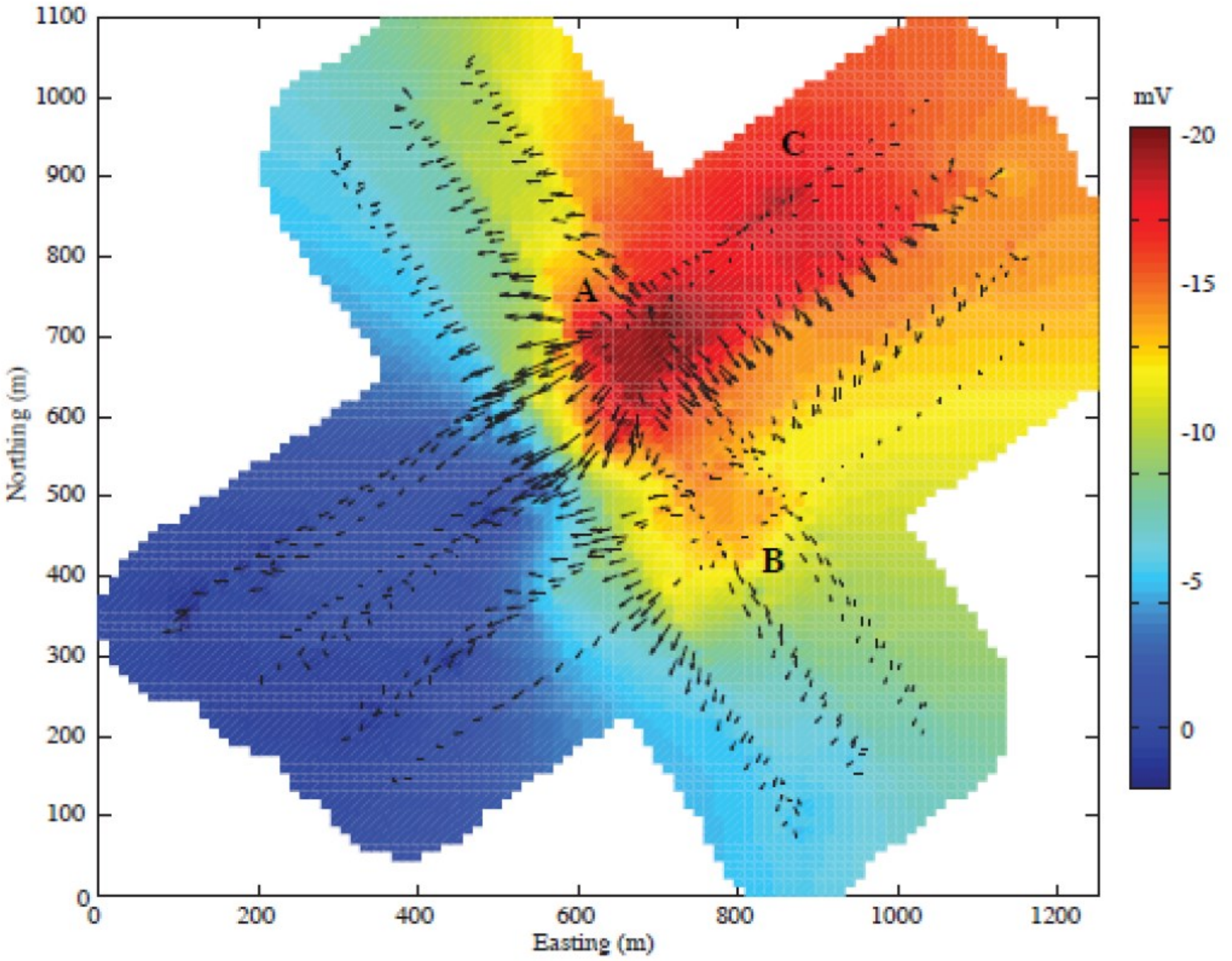






Self Potential Survey

- Also called Spontaneous Potential
- Is the potential difference that develops on the Earth's crust due to natural electric currents caused by oxidation and by hydraulic streaming potentials
- Can be used to map regions of hydrothermal venting, oxidizing massive sulfides, and seafloor geological structures disturbing the Self Potential current field.
- Vector components of Efields are crucial to constructing a potential estimate



SP collected in collaboration with SIO

S. Constable, P. Kowalczyk, and S. Bloomer, "Measuring marine self-potential using an autonomous underwater vehicle," *Geophysical Journal International*, vol. 215, no. 1, pp. 49–60, 2018.

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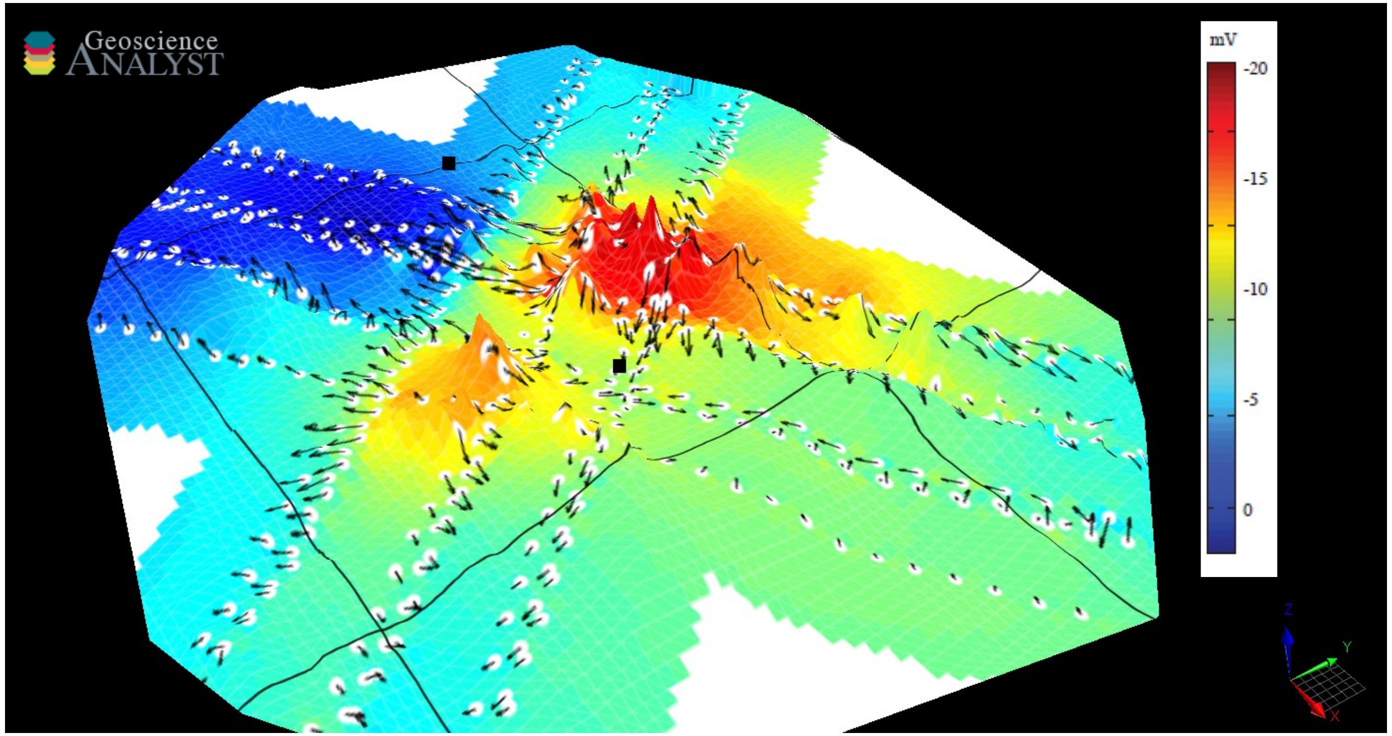
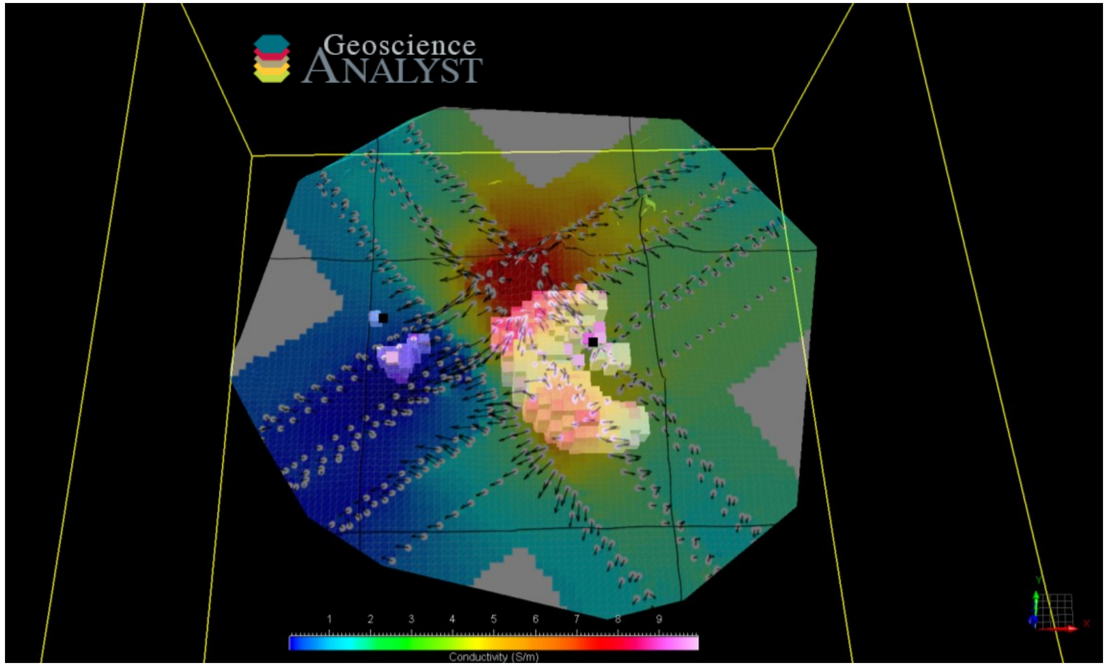
Self Potential and Conductivity model



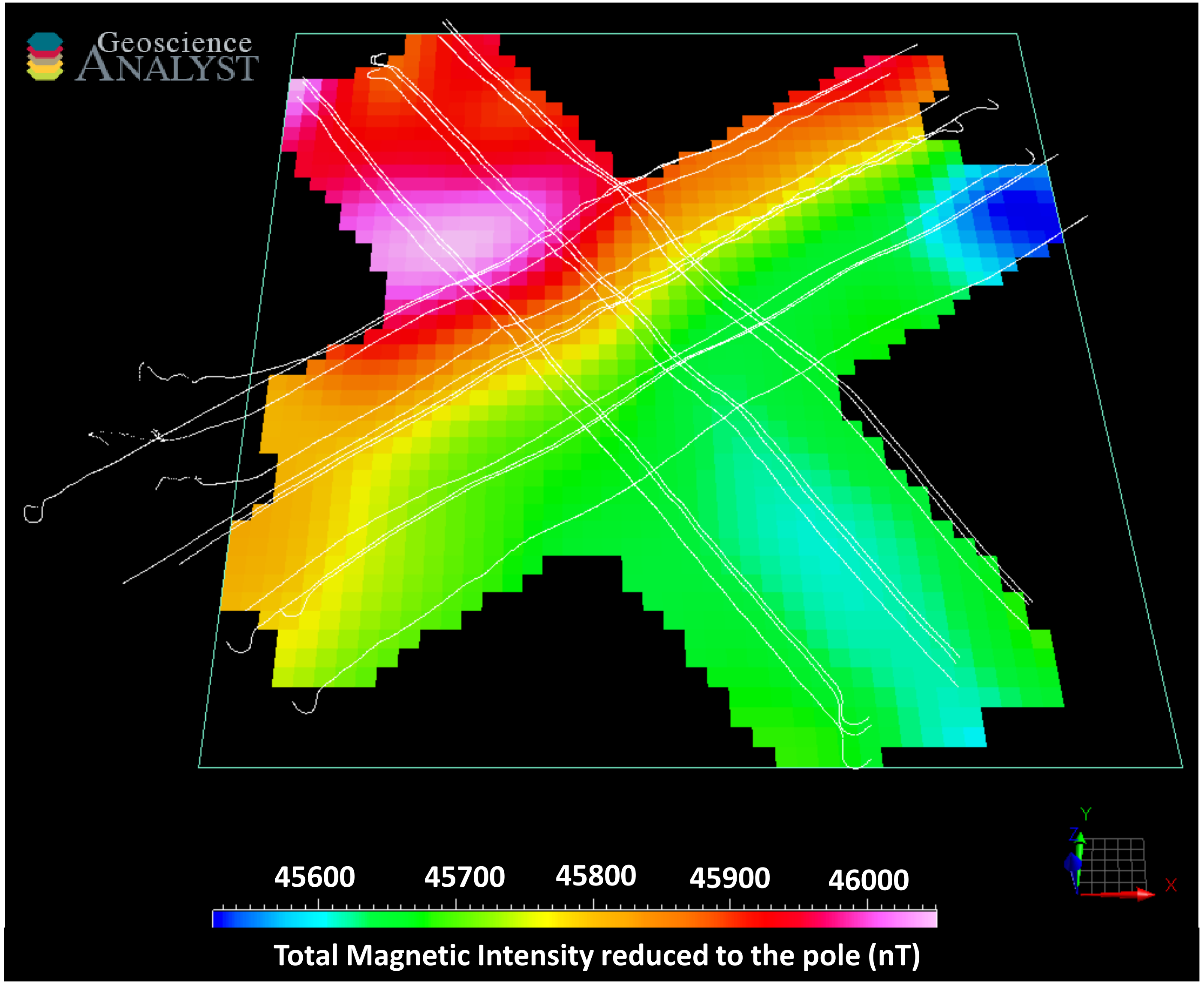
SP draped on bathymetry

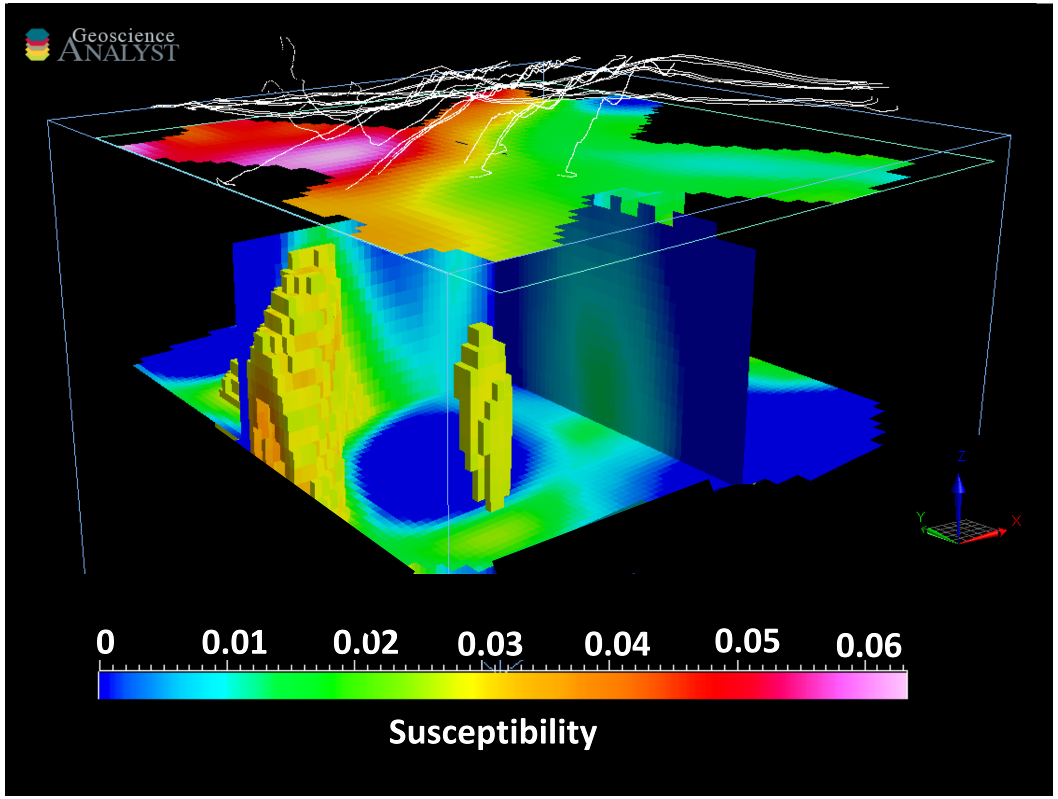


SP transparency with conductivity isosurface below.

From Bloomer et al., 2018 IEEE

Magnetic Data





- Data processed by Bloomer
    - TMI magnetic data reduced to the pole
- Data inverted using MGINV3D from Scientific Computing and Applications
    - 3D susceptibility model
- yellow iso-surfaces encompass susceptibilities from 0.027 – 0.039 (SI).

3D Model of AUV Survey Results from a Single Dive

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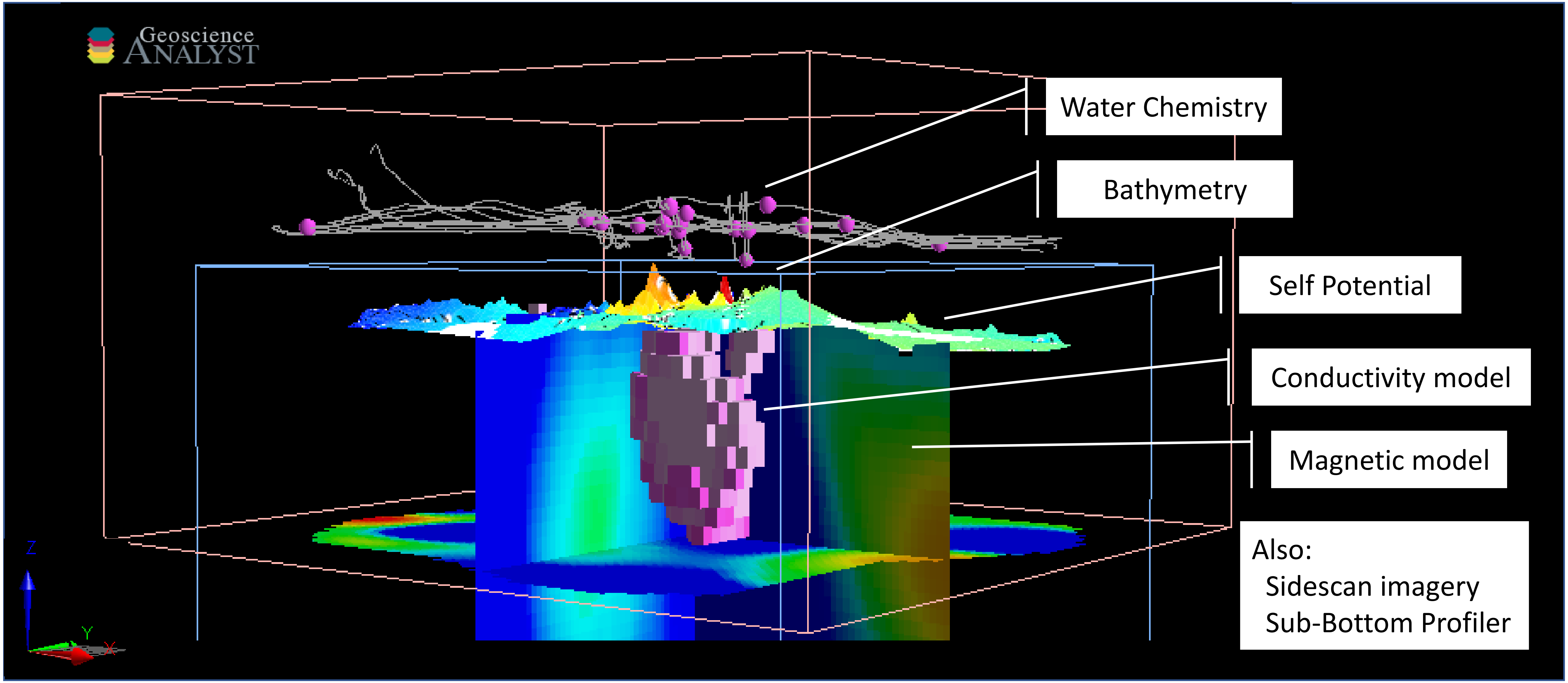


Modified From Bloomer et al., 2018 IEEE

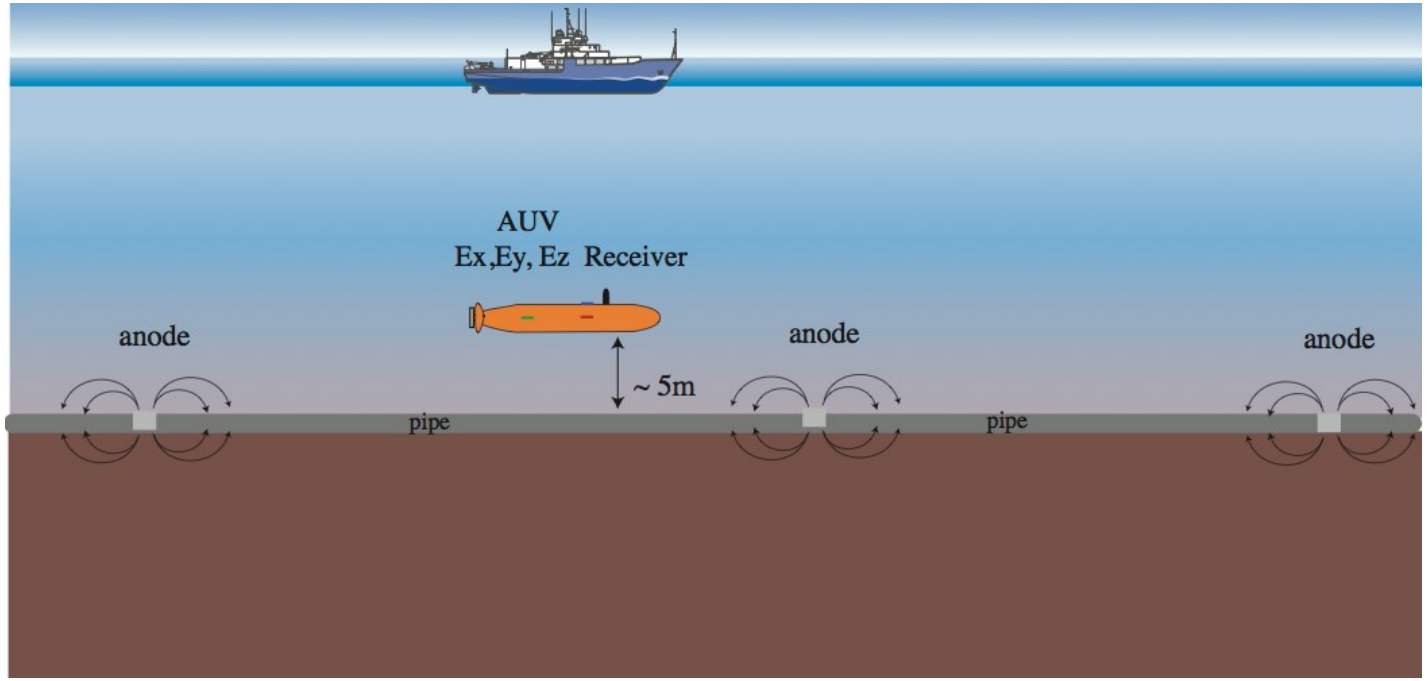
Development – Phase 2

Transition from using the system for seafloor mineral characterization to Subsea Structure Inspection - 2018

- Development of purpose built AUV hardware
- Tight integration of magnetometer and electric field sensors
- Benchmark against towed equipment
- Use on third party AUVs – 2019 to present
- Installed on more than 10 different AUVs to date

Structure Surveys

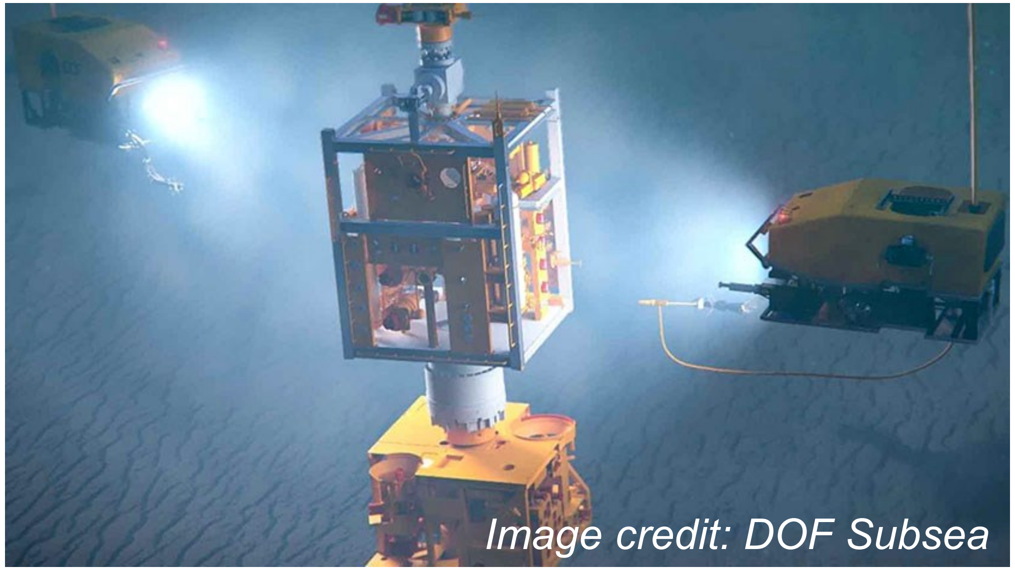
AUV-iCP



AUV-integrated Cathodic Protection

2 engineering tests
1 laboratory test
2 commercial surveys

ROV-iCP



Posted by Ocean News Published: 03 January 2018

https://www.oceannews.com/news/subsea-intervention-survey/dof-subsea-awarded-rov-contracts-in-brazil

1 engineering test
Completed remotely Nov 6-7, 2020

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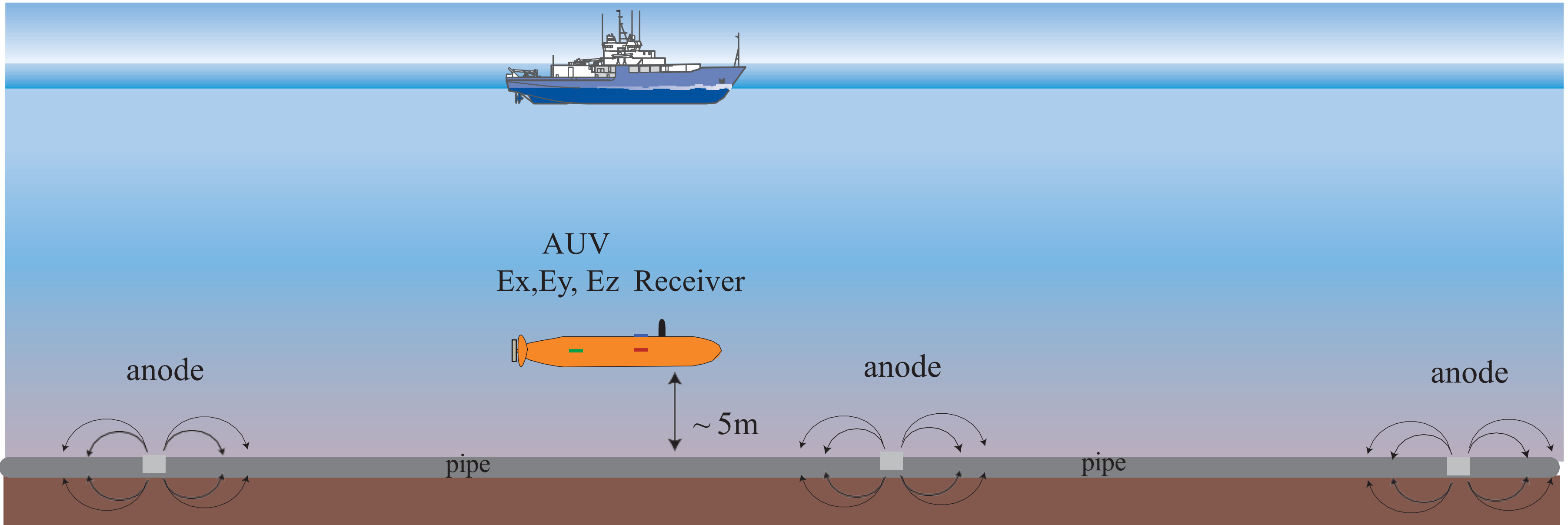
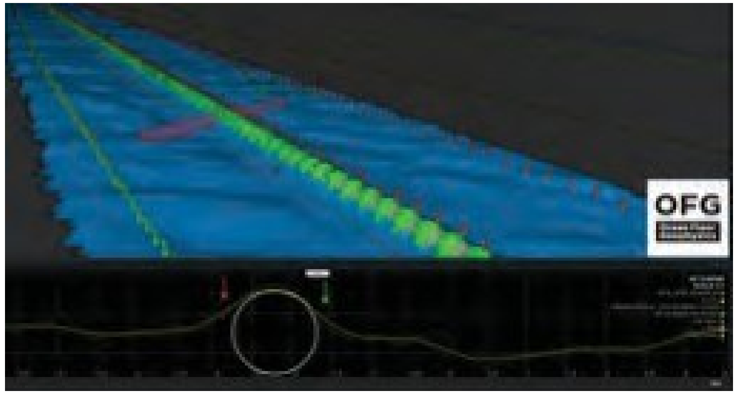
ISIES

Non-contact pipeline inspection



AUV mounted system for efficient inspection of a pipeline and its cathodic protection system.



Surveys collected in 2018-2020

Technology AUV mounted sensors

iCP - estimate current along pipeline Seafloor photography, Geochemistry, CTD

High resolution acoustic mapping (SSS, HISAS, SAS, MBES, SBP)

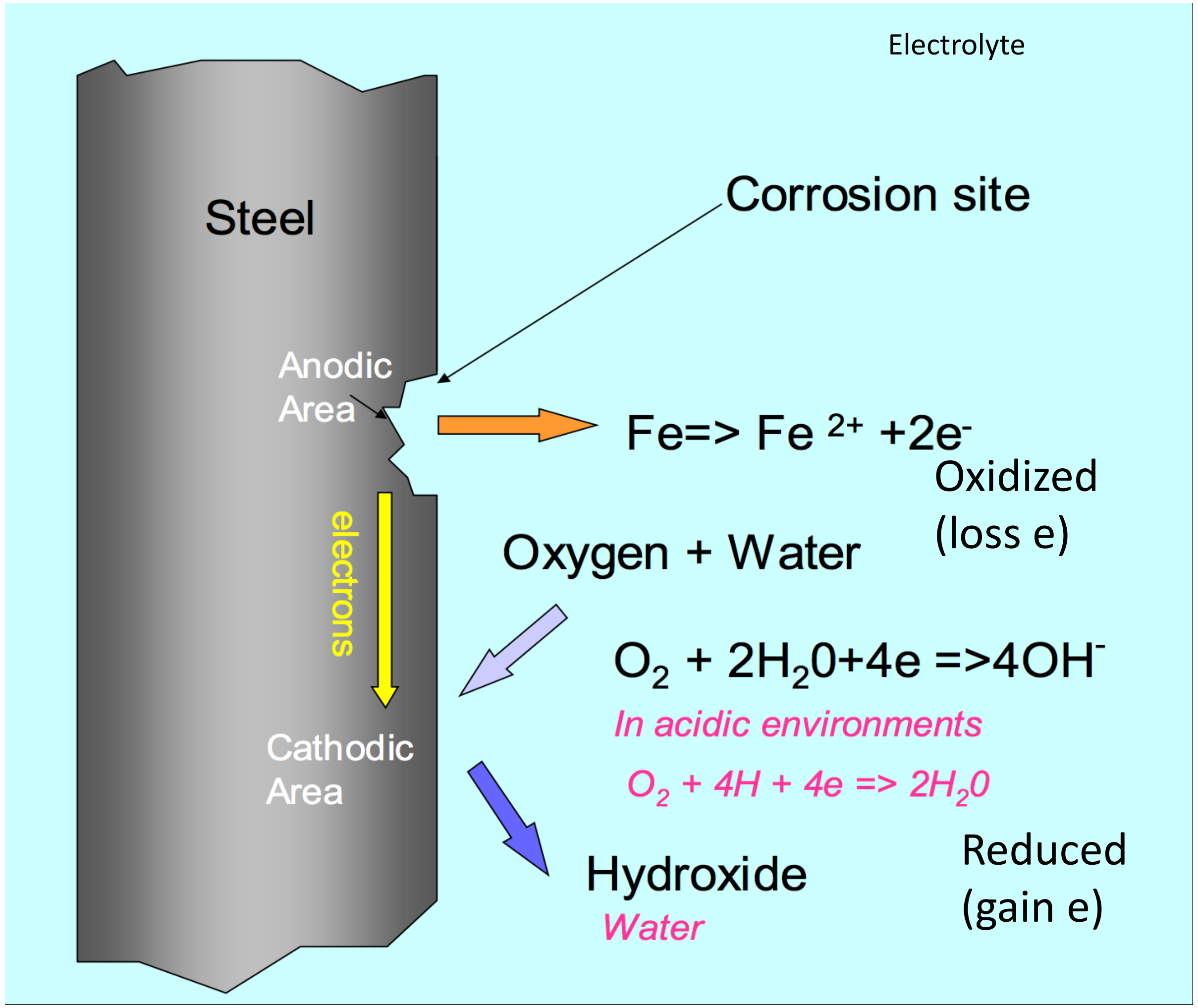
Corrosion

- A natural process that happens when a metal reacts with its environment. In this case rust, an iron oxide, is formed by the redox reaction of iron and oxygen in the presence of water. The iron structure weakens and disintegrates.
- In the presence of salt / seawater the rusting is accelerated because electrons can move more easily due to the presence of salt.

From https://kwikzip.com/using-spacers-to-mitigate-water-pipeline-corrosion/

Corrosion

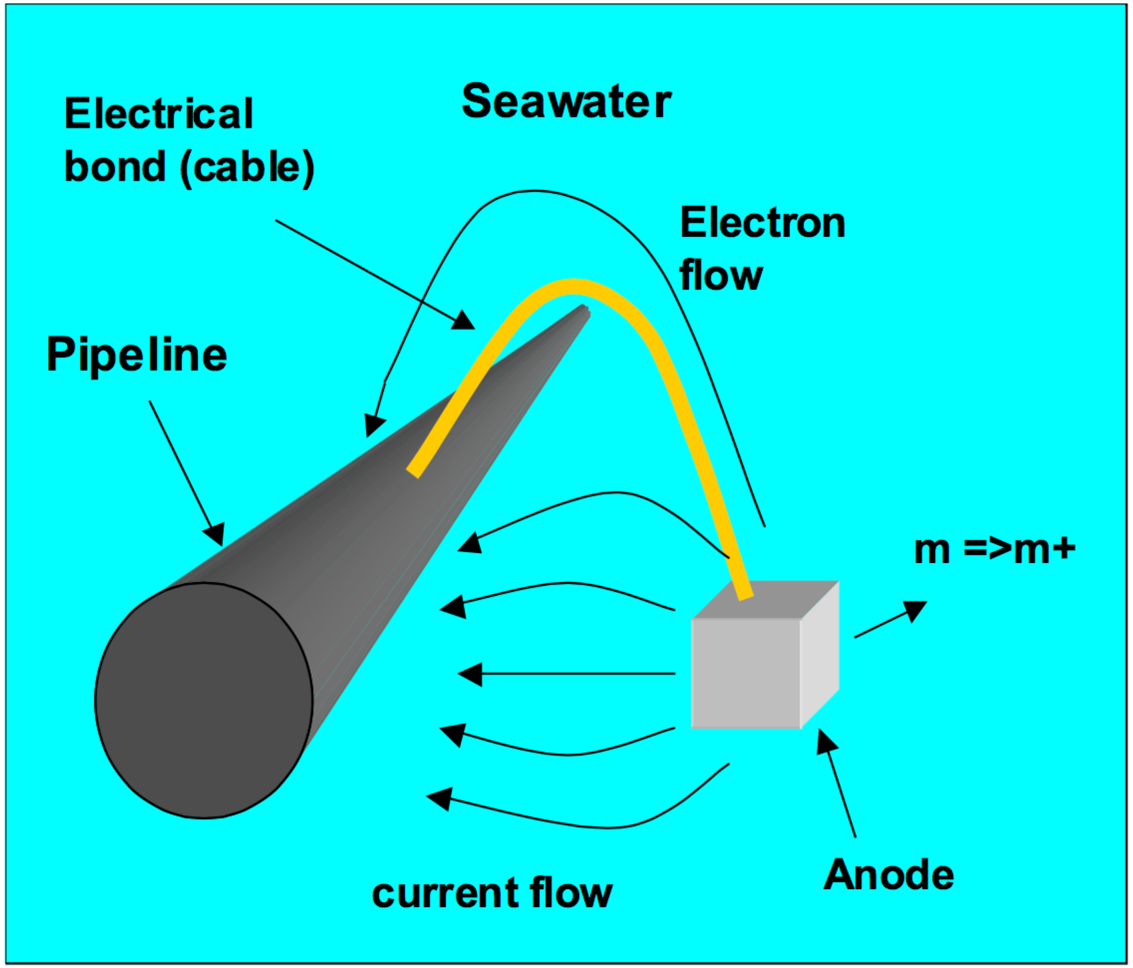
- Site for the reduction reaction to take place (cathode)
- Site of oxidation reaction to take place (anode)
- Electrical path – electrical continuity allows electrons to transfer from the corrosion site
- Ionic path – medium that allows the metallic ions to be transported



From ISES Theoretical Basis for data analysis system methodology and specifications

Cathodic Protection

- A technique used to control corrosion of a metal surface by making it a cathode in an electrochemical cell.
- Typically the metal to be protected is connected electrically to a more easily corroded ‘sacrificial metal’ that acts as the anode.
- The sacrificial metal corrodes instead of the metal.



From ISES Theoretical Basis for data analysis system methodology and specifications

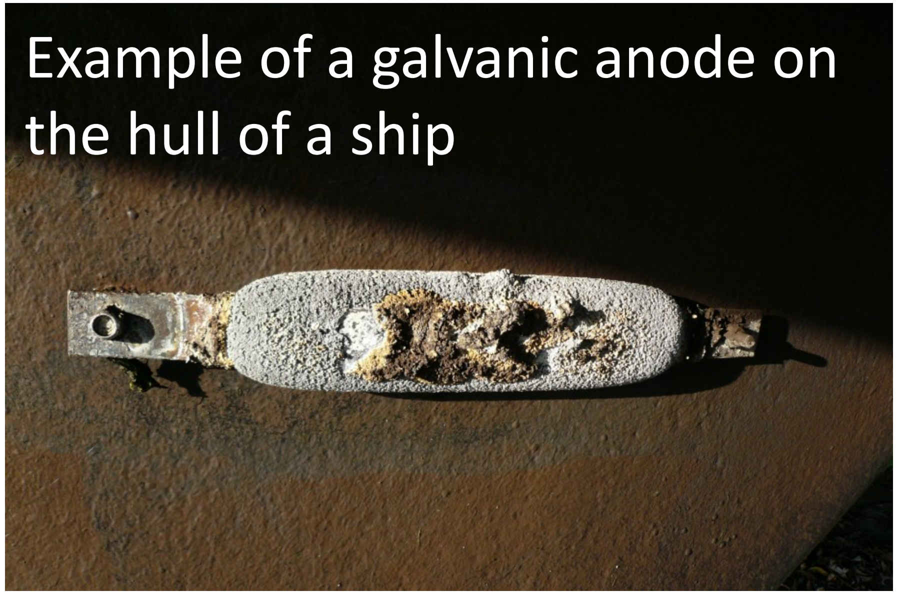
Sacrificial Anode

Zinc, an example of a sacrificial anode, prevents iron metal from "corroding".

Standard Reduction Potentials Table

Half-reaction: Oxidant	⇌	Reductant	$E°$ (V)	Ref.
$Zn^{2+} + 2e^-$	⇌	Zn(*s*)	−0.7618	[7]
$Fe^{2+} + 2e^-$	⇌	Fe(*s*)	−0.44	[5]

https://en.wikipedia.org/wiki/Standard_electrode_potential_(data_page)



The standard reduction potential of zinc is about -0.76 volts.
The standard reduction potential of iron is about -0.44 volts.

The difference in reduction potential between zinc and iron results in faster zinc oxidization than iron.

https://chem.libretexts.org/Bookshelves/Analytical_Chemistry/Supplemental_Modules_(Analytical_Chemistry)/Electrochemistry/Exemplars/Corrosion/Sacrificial_Anode

Prevent Corrosion

(specific to carbon steel pipelines and sacrificial anodes)

- Subsea pipelines are normally protected from corrosion by an external coating and by cathodic protection using galvanic/ sacrificial anodes.

coating

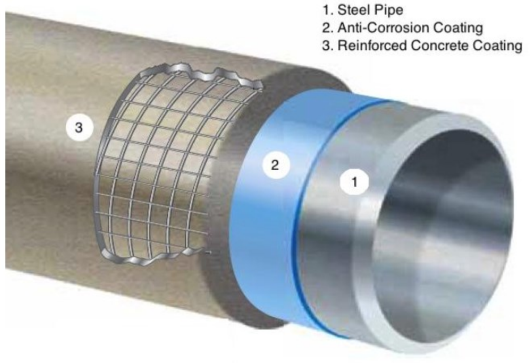


Figure 5: Hevicote™. Source: Bedero Shaw (2008)

From Shittu et al., AJER 2016

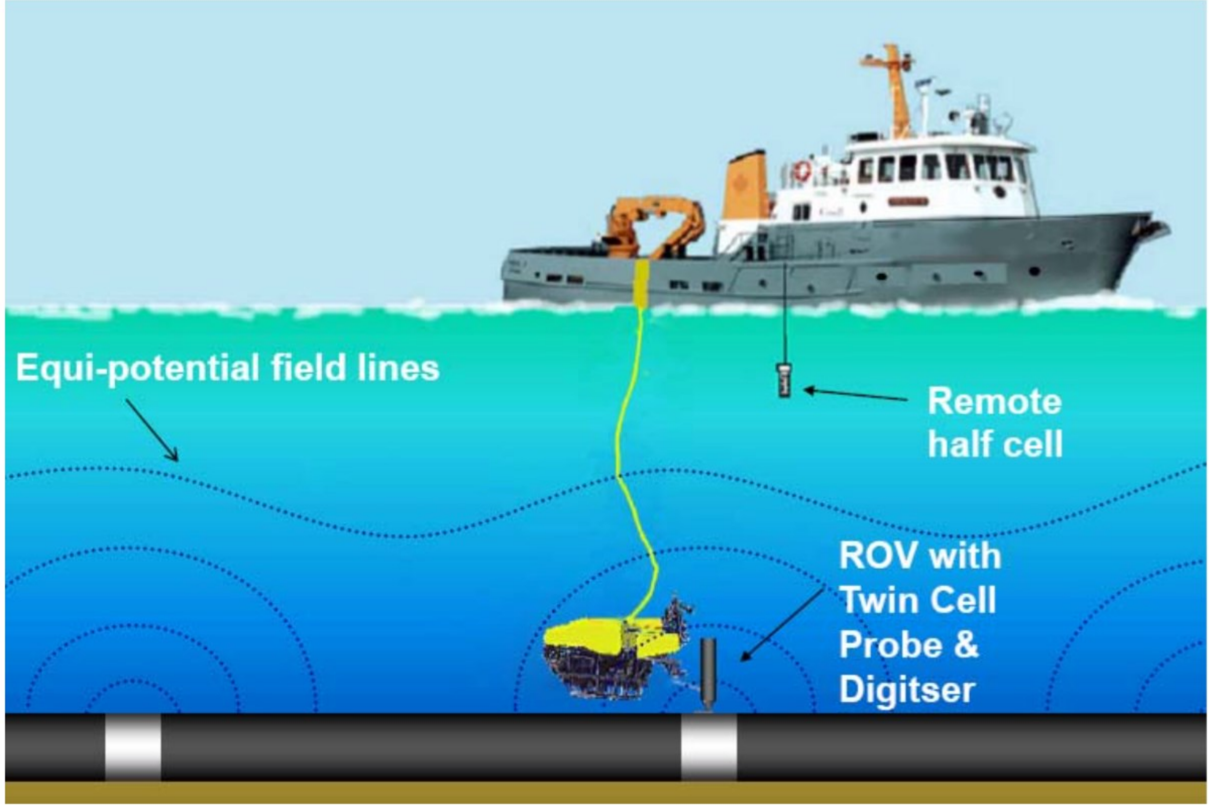
Bracelet Anodes

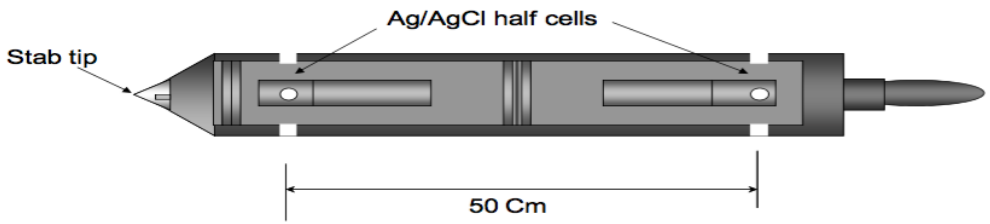
https://stoprust.com/products-and-services/bracelet-anodes/

- The specific design is dependent on the environment that the pipeline is located, subject to the temperature, salinity, water depth (in wave zone or deep water), other biologic, chemical (anaerobic), and physical factors etc…

Twin cell Contact Probe and Electric Field (FG) Survey

- Typical Method used to inspect the CP system of a marine pipeline
- Typically surveyed with ROV for visual assessment and stabs



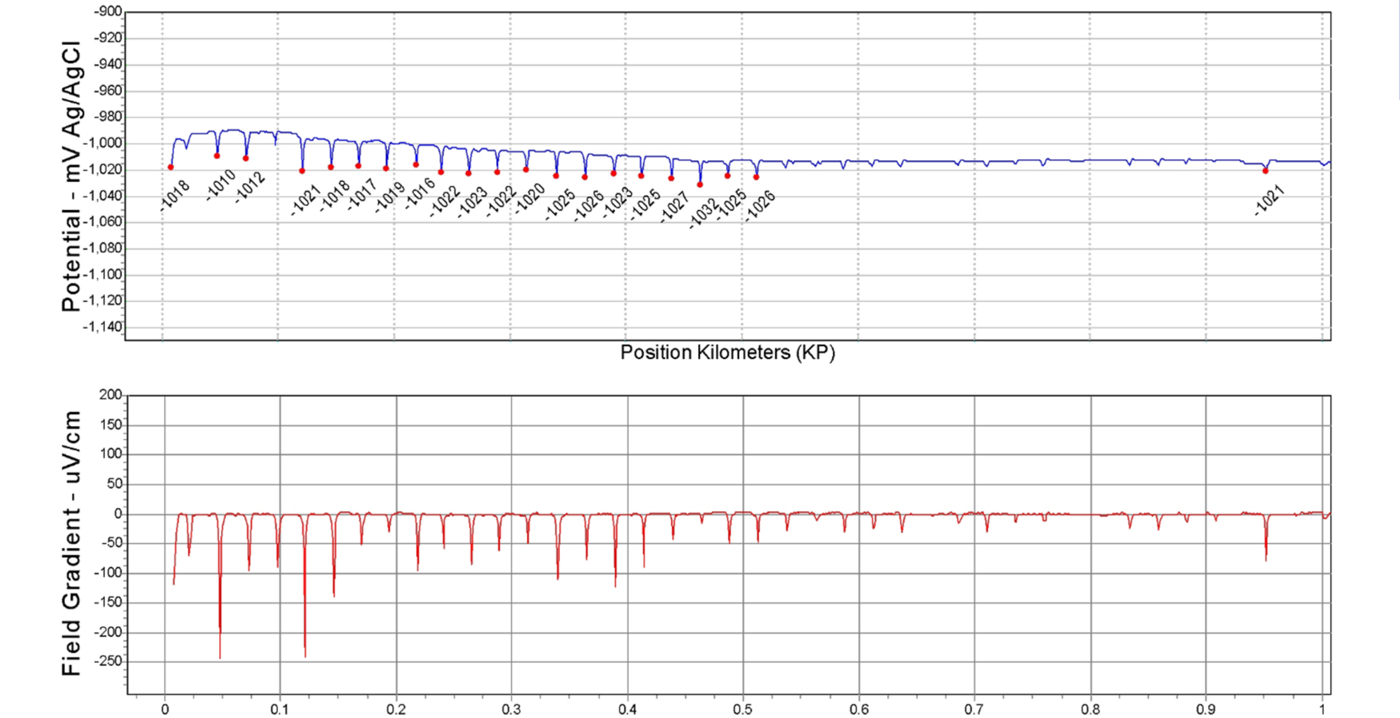


Example of twin half cell contact probe.

From ISES Theoretical Basis for data analysis system methodology and specifications

Motivation for the development of the OFG iCP inspection system

SYSTEM	MEASURES	CALCULATES	LIMITATIONS
ROV MOUNTED (TWIN CELL CP/FG SYSTEM)	• Contact Potential (CP) units: mV • Continuous CP/FG v KP. Industry terminology: Field Gradient (FG) Units: microvolts/cm • Sensitivity 1mV & 1µV/cm	• Anode current (mA) • Areas of current drain • Estimation of anode remaining life	• Slow survey speed ~0.5 knots • Regular calibrations contacts required • Probe orientation and distance can limit accuracy • Limited application on buried pipelines



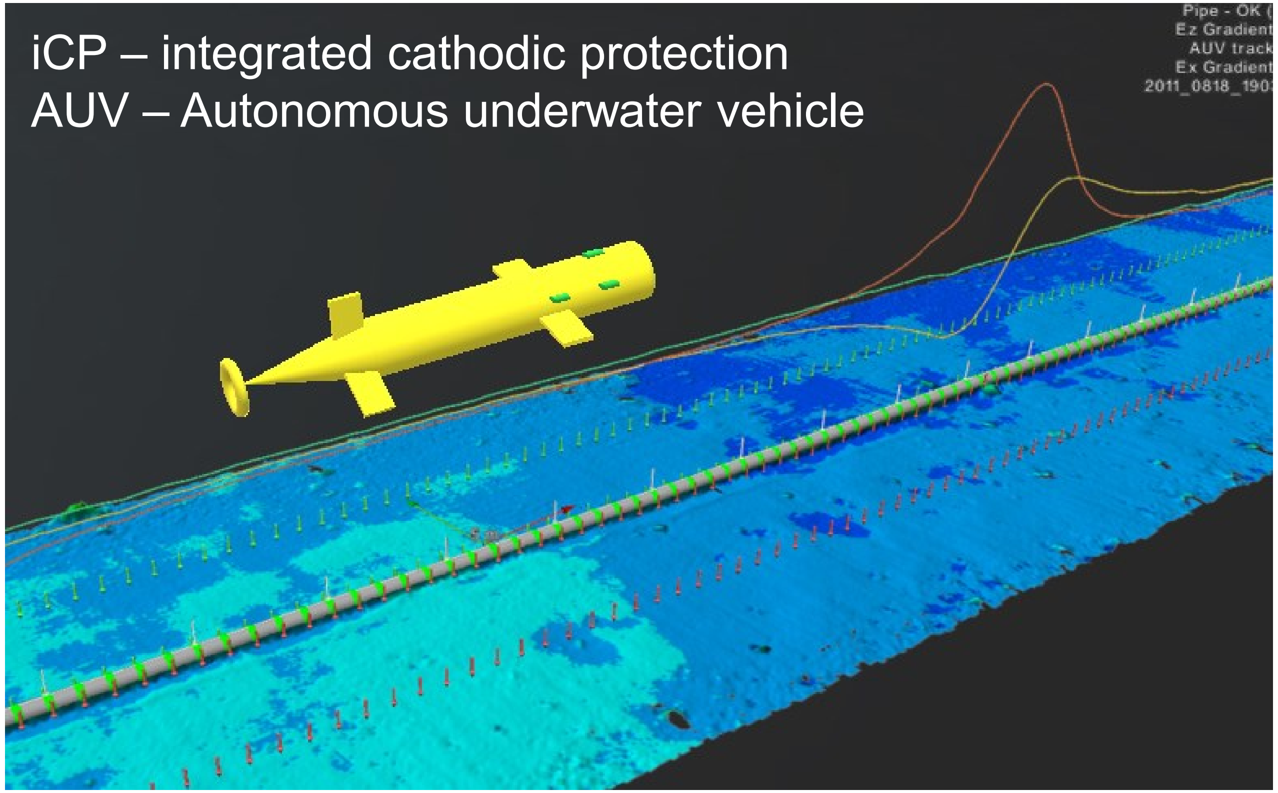
The AUV-iCP System

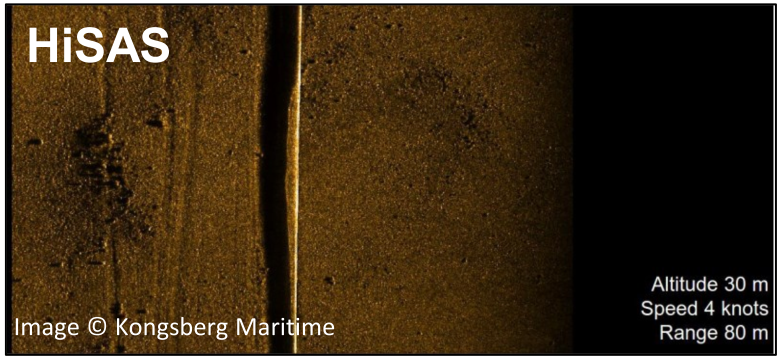
OFG Ocean Floor Geophysics

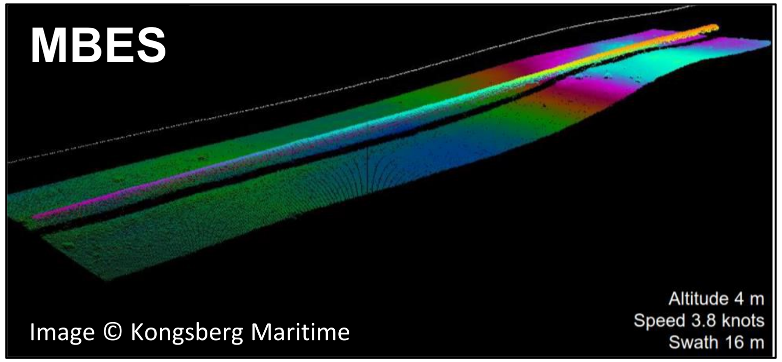
ISES

iCP uses AUV pipe tracking combined with E-Field system concurrently to accurately locate E-field measurements relative to pipe.

- High speed (~3-4 knots)
- High sensitivity (~0.01uV/cm)
- Accurate positioning relative to the pipe
- Measurement of fields for buried and rock dumped pipe
- In addition to pipe inspection and tracking using MBES, HiSAS, magnetometer (SCM), and photos







Why do Cathodic Protection Inspection?

Check the CP system's operational integrity

Detect any corrosion problems and to adjust/retrofit before any major failure

Collect data to reduce future inspection requirements

Adherence to Regulatory Authority Requirements

- Government Regulations
- DNV-RP-B401 *CATHODIC PROTECTION DESIGN JANUARY 2005 latest amendment April 2008*
- NORSOK STANDARD M-503 Edition 3, May 2007 *Cathodic protection*
- ISO 15589-2:2004 *Petroleum and natural gas industries -Cathodic protection of pipeline transportation systems -- Part 2: Offshore pipelines**
- NAMAS ; *National Accreditation of Measurement and Sampling* (or Equivalent)

From ISES Theoretical Basis for data analysis system methodology and specifications

The AUV-iCP System Inputs/Outputs

Precision Navigation
Real-time accuracy of ~2m with HiPAP USBL system

Pipe Tracking
Real-time tracking of pipe using HiSAS/MBES provides ~cm level positioning relative to pipe

Electric Field
Gradient measurements in 3-axes

Magnetic Field
Measurements in 3-axes

Seawater Conductivity

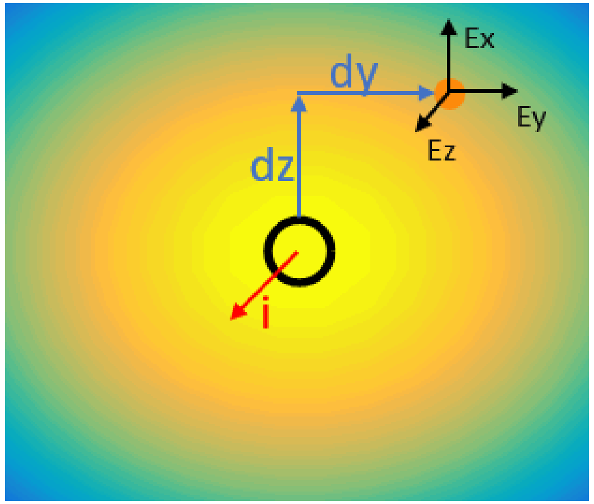
X/Y/Z

dx/dy/dz

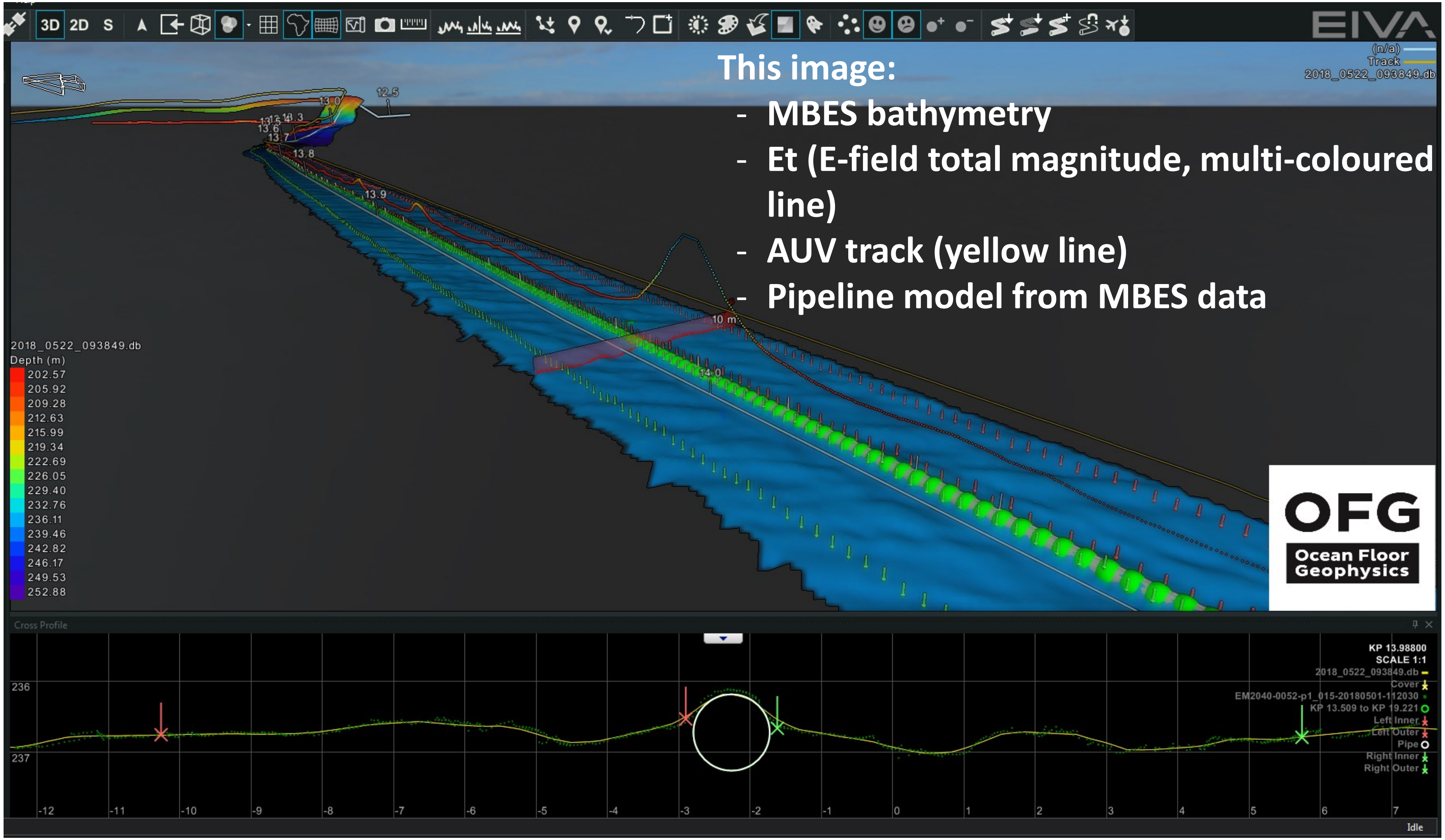
Ex/Ey/Ez

Bx/By/Bz

Cathodic Current Estimation i
By combining these systems the currents flowing through the pipe can be estimated



OFG AUV iCP tests results over North Sea pipeline



OFG Ocean Floor Geophysics

Subsea Structure Inspection

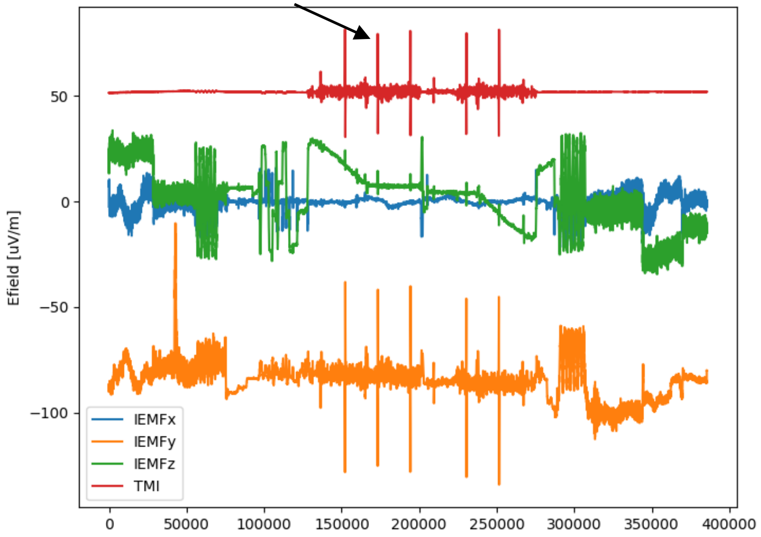
Importance of co-registered, compensated vector magnetic data

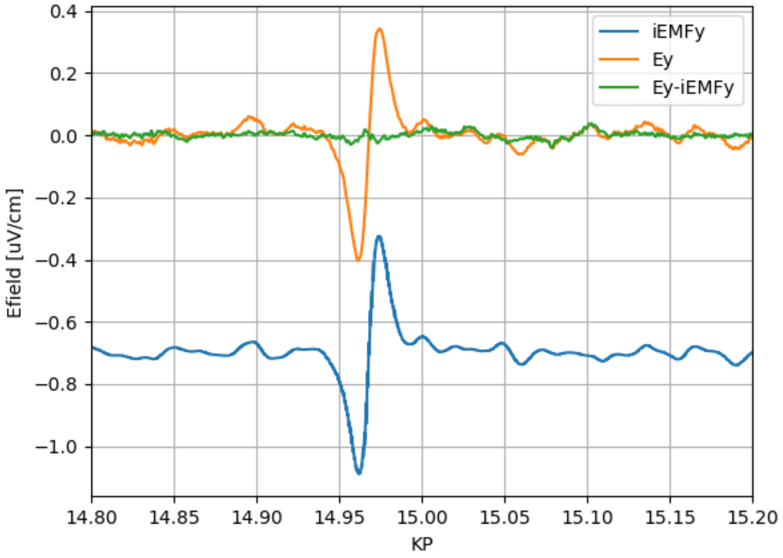
$$\mathbf{V}_{IP} = \mathbf{v} \times \mathbf{B}$$

Induced potential due to the motion of the electrode dipole through a magnetic field

Residual magnetism in subsea structures can be high

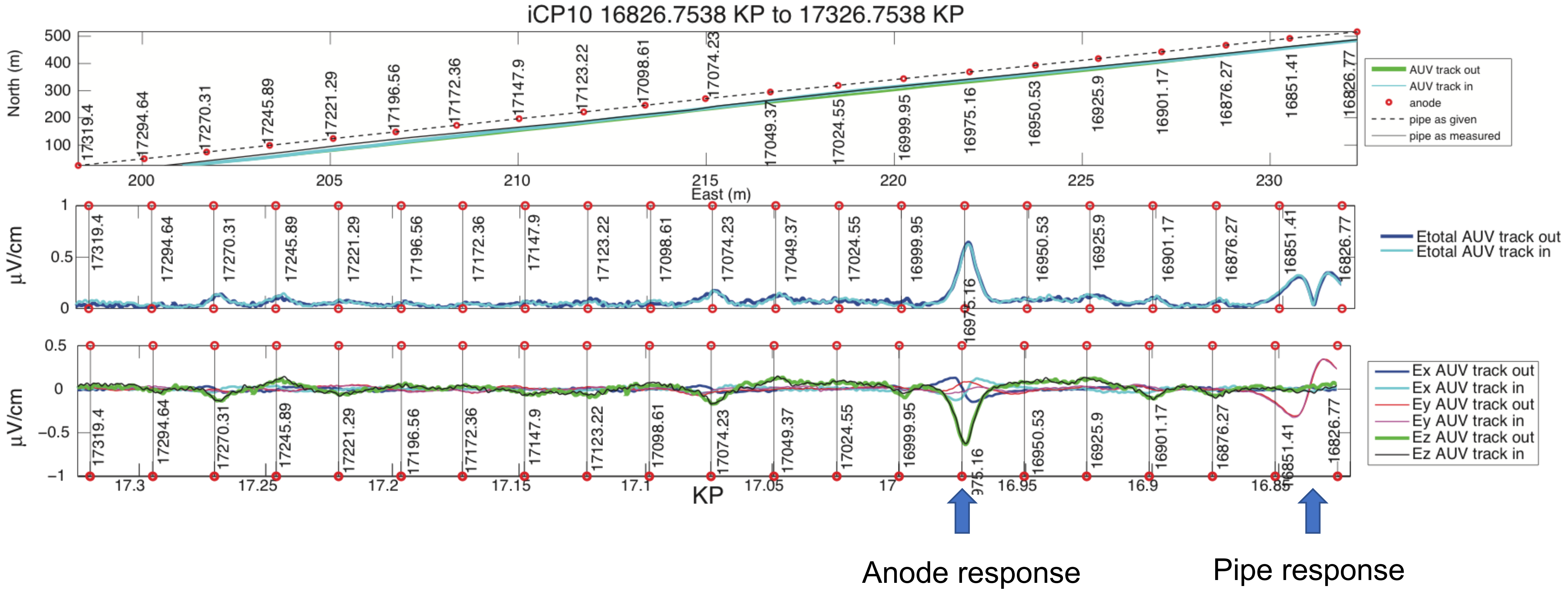
50uT anomalies from pipe





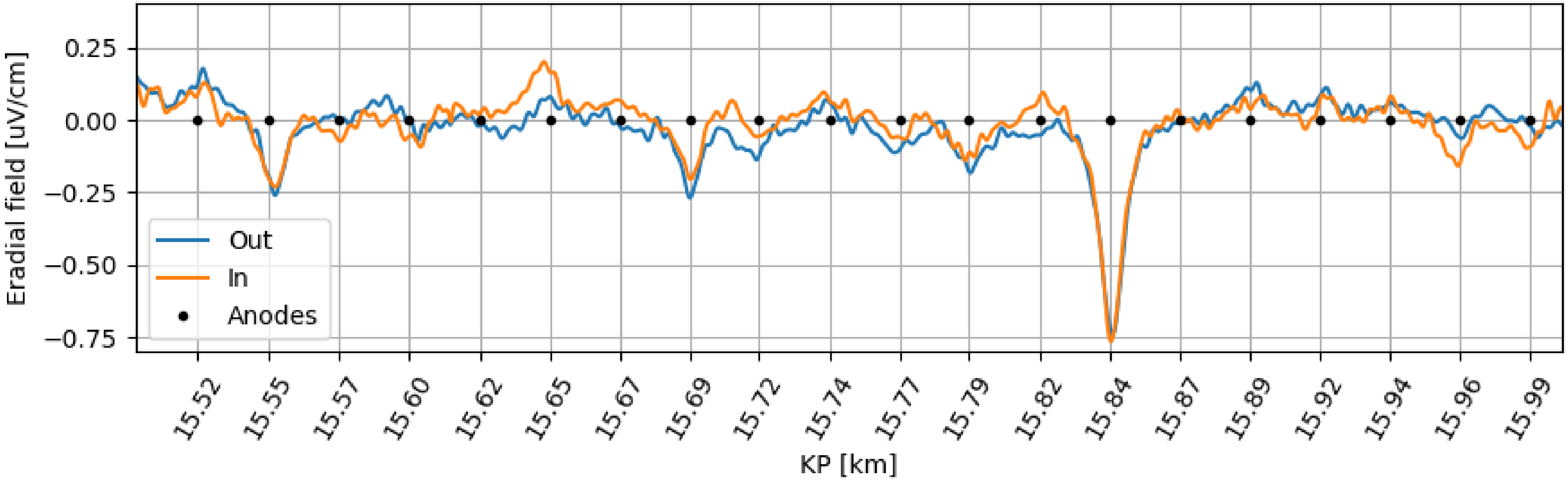
Plotted against pipe KP

Example of a ~ 500 m section of pipe



AUV Repeatability

- **OFG AUV iCP Accuracy ~ 0.01 µV/cm**
- Standard ROV twin cell CP/FG system +- 1 µV/cm
- Rotating sensor +- 0.1 µV/cm (as per publicly available information)



Measured data showing 2 survey runs in opposite directions along the pipeline

Subsea Structure Inspection

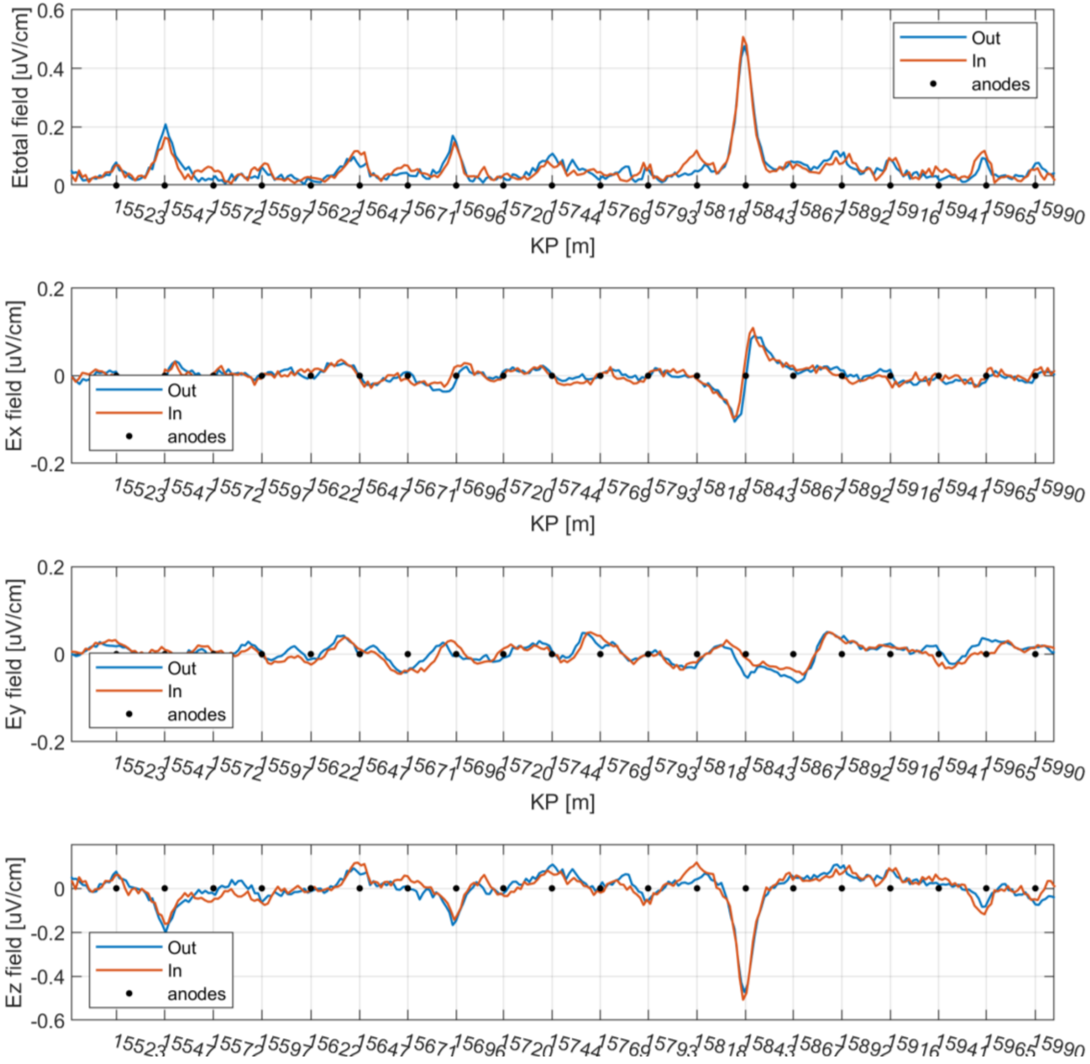
Measured data showing 2 survey runs in opposite directions

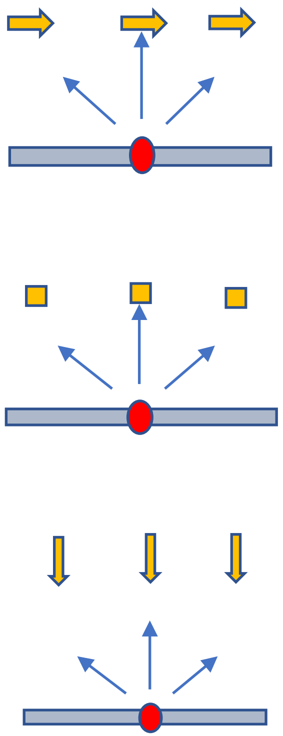
Standard deviation of difference between measurements in opposite directions:

Et = 0.021μV/cm
Ex = 0.012μV/cm
Ey =0.015μV/cm
Ez = 0.027μV/cm

Without correction for position, range, attitude. Corrected for range and attitude the difference is <0.01 uV/cm

*Difference is between entire length of pipe that was surveyed in both directions at the same altitude.

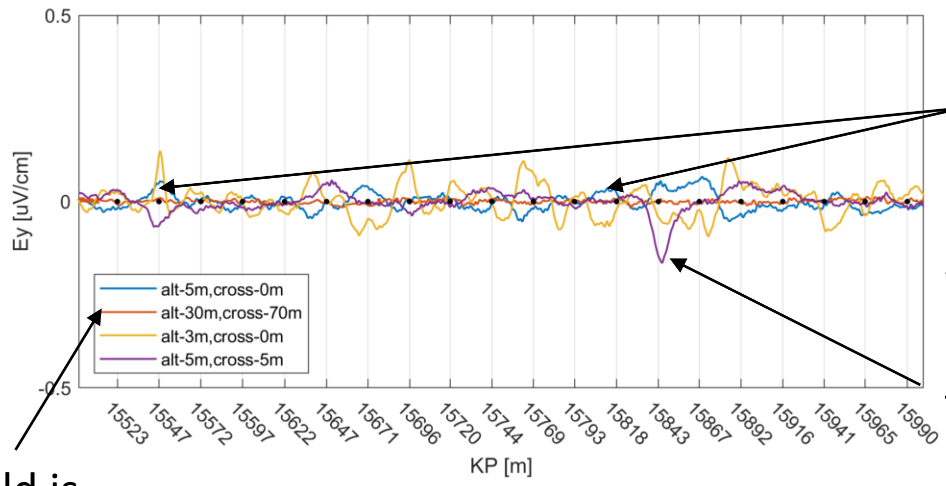




Subsea Structure Inspection

Measured data at different altitudes and cross track distance to the pipe

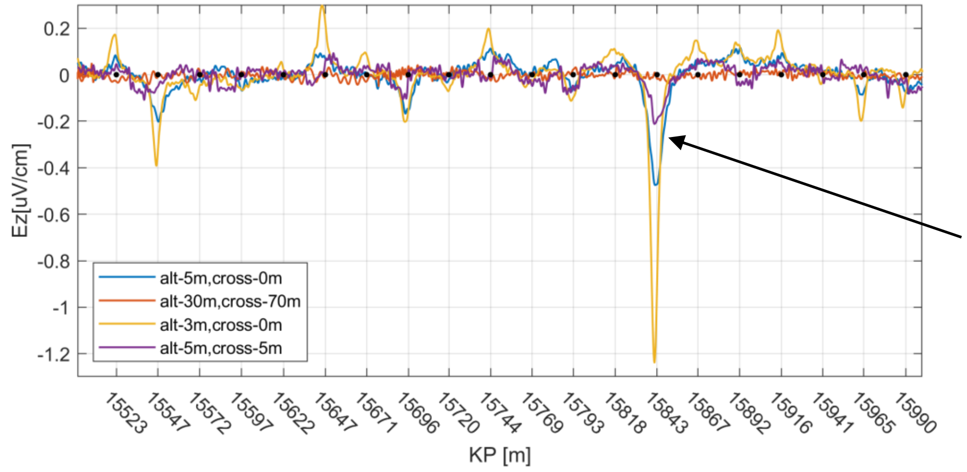
Altitude 30 m, cross 70 m
Altitude 5 m, cross 0 m
Altitude 5 m, cross 5 m
Altitude 3 m, cross 0 m



Sign of cross field component depends on which side of pipe the AUV is on

With cross track distance, some of the vertical is taken up in cross vehicle component

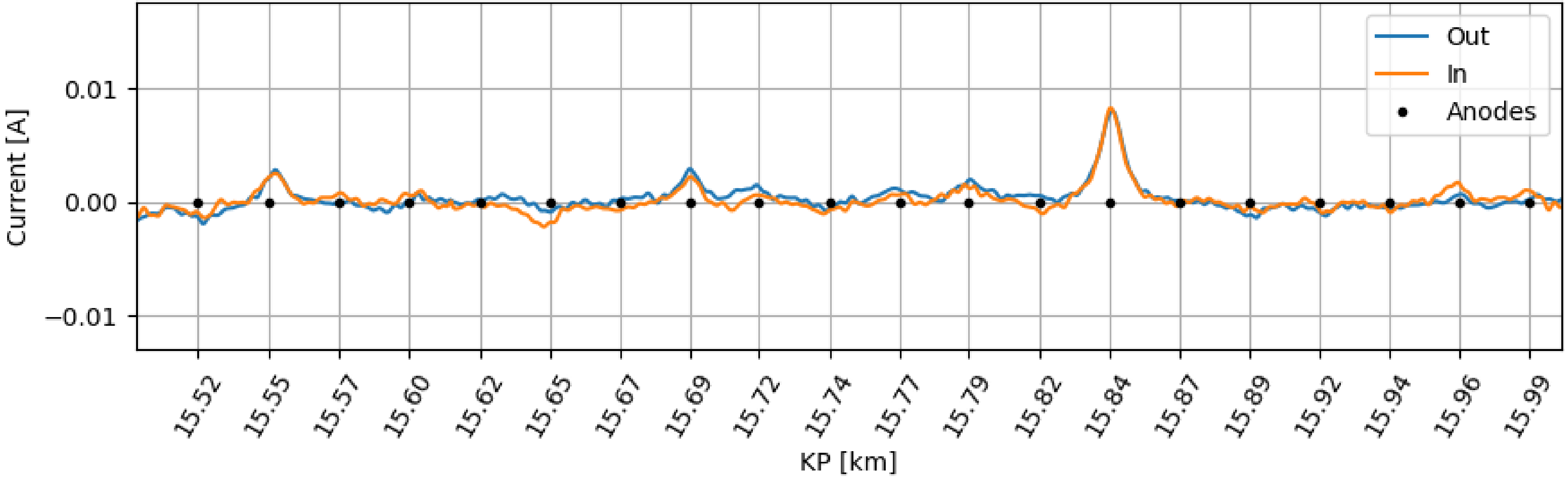
Farfield is zero



Size of signal scales with distance to pipe

Compute Anode Current

-**OFG AUV iCP** → Calculate anode currents → compute mass and energy remaining and **predict anode end-of-life much earlier**

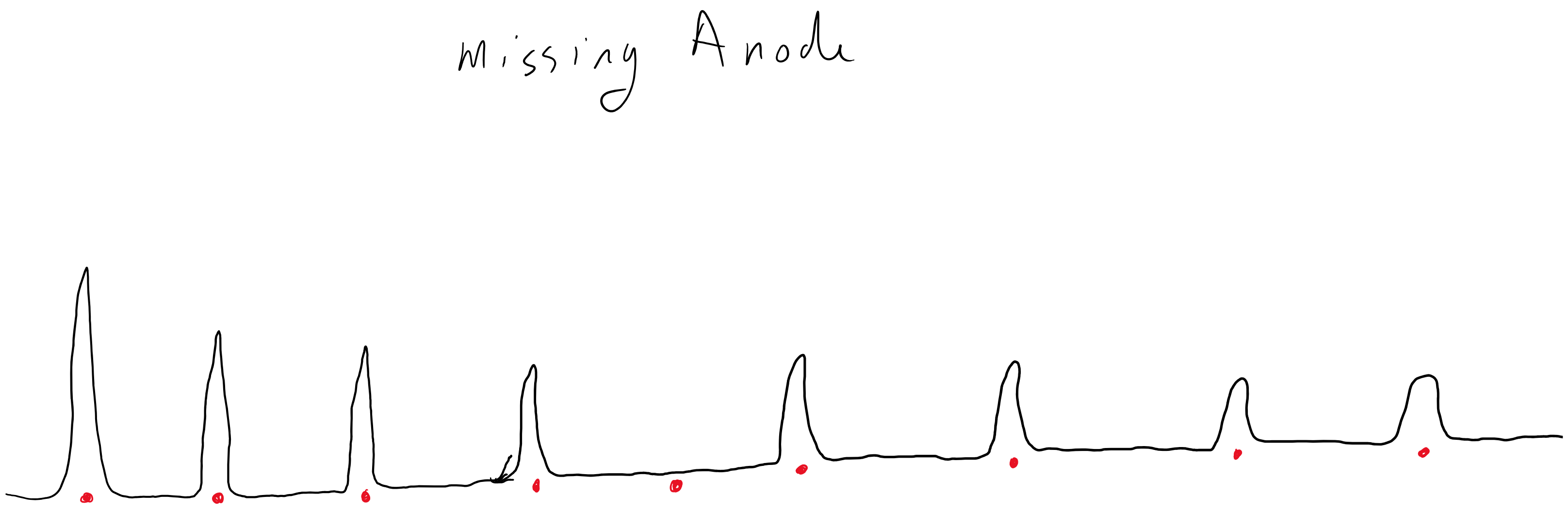


Can also compute anode wastage, and potential – not discussed here

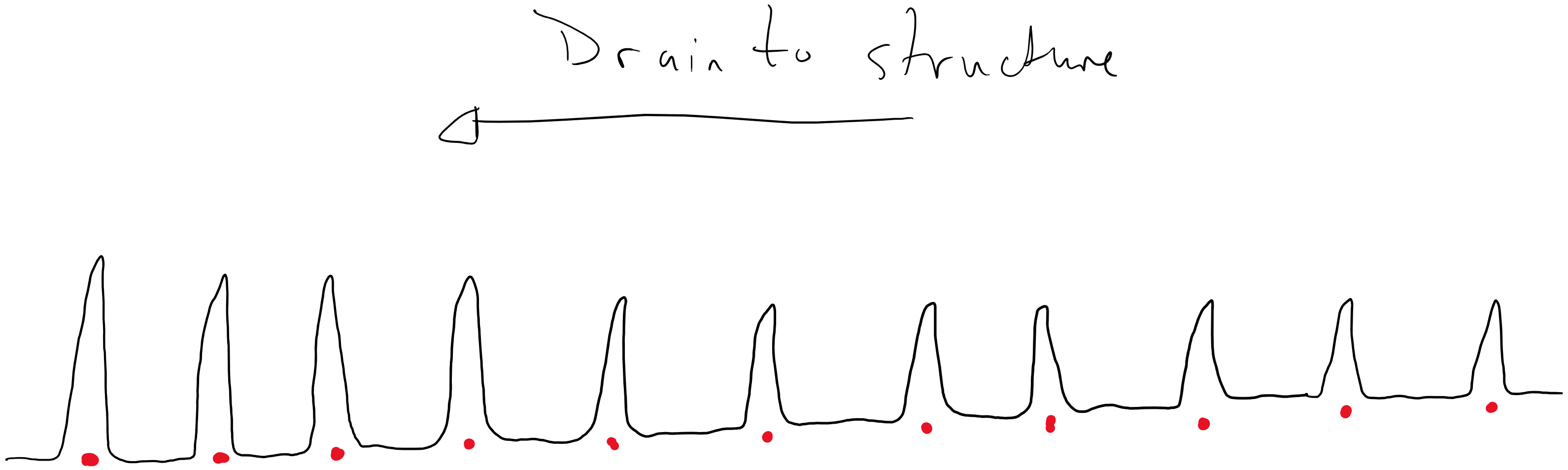
Sketches of Different AUV-iCP Observations

- Based on commercial survey in spring 2019
- Observe missing anodes
- Current drain to structures
- Short pipe response
- Missing anode
- Well protected long pipe

Missing anode

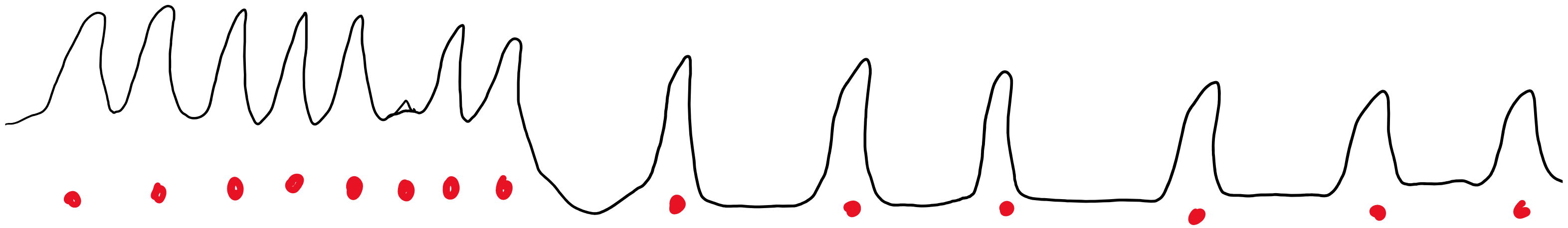


Current drain to structure



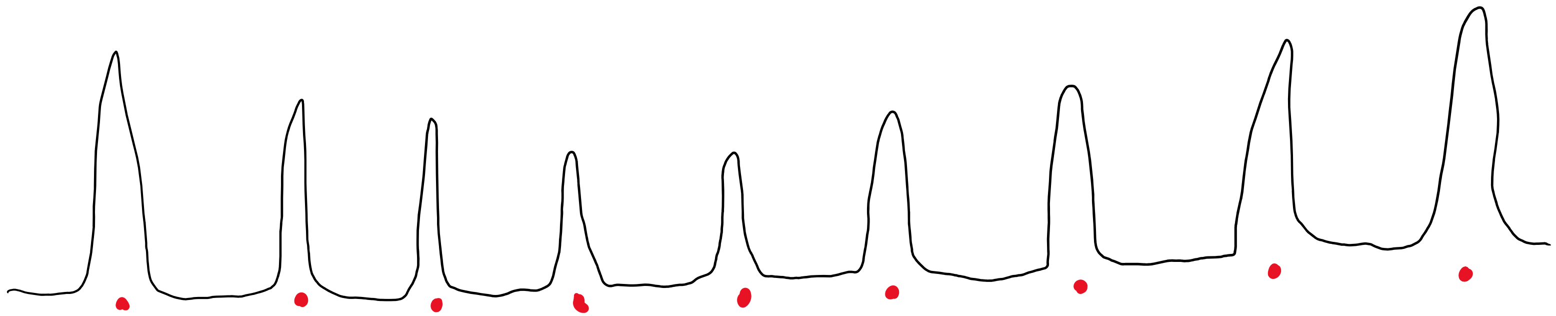
Missing Anode, close together

Missing Anode, close together



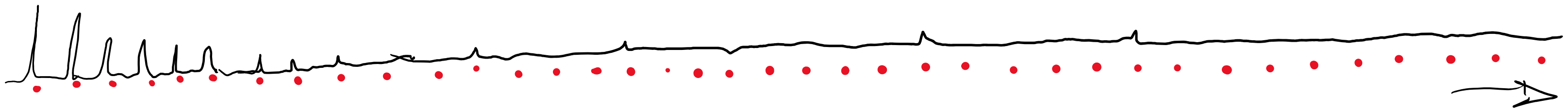
Typical short pipe response

Typical short pipe response w/
everything nominal



Well protected long pipeline

Well protected long Pipeline



Low electric field strength, low anode output current

OFG AUV iCP Usage Scenarios in a Pipeline Integrity Management Strategy

Scenario One **- Maintenance CP survey**

To **determine** if the pipeline cathodic protection system is performing as designed in terms of **protection levels** and **anode performance** and **anode life**.

Scenario Two **- Intervention CP survey**

The iCP system can be used to undertake a **rapid assessment** of the condition of the pipeline **after the event** has occurred to provide accurate information

Scenario Three **- Post lay baseline/tie-in CP survey**

The **OFG AUV iCP** system can be used to undertake ***high speed visual*** and **field gradient** measurements.

The AUV Electric Field Development Time Line

OFG Ocean Floor Geophysics

Development Partners

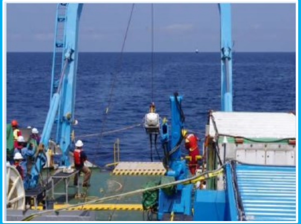
UC San Diego | Scripps Institution of Oceanography

Fukada Salvage & Marine Works Co., Ltd.

ISIES

2014

First commercial CSEM-Vulcan gas hydrate survey



Discussions about putting electric field sensor onto an AUV

2015

Second commercial CSEM-Vulcan gas hydrate survey

Field Trials of AUV outfitted with electric field sensor

2016

Engineering Test of AUV-CSEM and AUV-SP Surveys

2017

Noise test of electric field measurements on the OFG AUV 'Chercheur'

Third commercial CSEM-Vulcan gas hydrate survey

2018

Field trials of AUV-iCP on a North Sea pipeline using 'Chercheur'

First commercial AUV-CSEM and AUV-SP survey

2019

Test of AUV-iCP system on synthetic pipeline in a pool

Two Commercial AUV-iCP surveys

Two commercial AUV-SP surveys carried out

2020

Remote Field Trials of iCP and SCM on ROV for structure surveys

2021

Field Trials of iCP and SCM for EM ship signature characterization

AUV based Electric and Magnetic Field Measurements

OFG Ocean Floor Geophysics

- Efficient collection of multiple data sets simultaneously.
- AUV-SP and AUV-iCP is suitable for both focused and regional scale studies.
- AUV-CSEM is suitable for focused studies.
- Other applications include ship signature characterization to allow for a “mobile” range rather then fixed ranges.
- Completed trial of a structure survey with electric and magnetic field sensors integrated with an ROV.